HEAT PIPE INTEGRATED HEAT PUMP SYSTEM FOR LOW-ENTHALPY GEOTHERMAL RESERVOIR UTILISATION

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ABSTRACT

Global reliance on fossil fuels for energy generation has led to severe environmental consequences, including greenhouse gas emissions, environmental degradation, and resource depletion. Transitioning to sustainable energy systems is critical to mitigate these impacts. The study proposes a renewable-driven heat pump system integrated with a geothermal heat pipe to exploit underutilised low-enthalpy geothermal reservoirs for residential and industrial heating applications. The system was mathematically modelled and simulated to evaluate its feasibility and performance. The results demonstrate the system's ability to provide high-temperature output while minimising electrical energy consumption. The integrated system is adaptable to various geothermal conditions ensuring robustness and high efficiency across diverse operating ranges, highlighting its role in balancing performance with environmental sustainability. Comparative analyses against different heat pump systems reveal improved operational efficiencies which show in a higher coefficient of performance (COP), while also being able to satisfy high-temperature heating needs. By prioritizing low-carbon thermal networks, this work advances the decarbonization of heating systems and provides a replicable and scalable model for regions with great and limited geothermal potential.

Keywords: Heat Pump, Heat Pipe, Sustainability, Domestic Hot Water, Modelling

1 INTRODUCTION

The increased energy demand, driven by fast economic and population growth, has emerged as a pressing concern of our era. In the year 2024, the global demand for energy experienced a significant increase, reaching a growth rate of 2.2%. This figure is more than double the average increase observed over the past decades. Concurrently, fossil fuel reserves are undergoing significant depletion, posing a substantial threat to the energy supply [1], [2]. This unsustainable path demands a crucial transition towards efficient, renewable energy systems to limit further resource depletion and ecological degradation [3]. Heat pump technologies are a pivotal solution in this transition to a sustainable future. In recent developments, conventional heat pump systems have been enhanced and modified to reach much higher efficiencies and operate in integrated net-zero carbon systems [4]. The development of advanced heat pump systems, integrating renewable energy sources such as solar, wind, and geothermal energy, is a current focus in the field [5], [6]. Geothermal heat pump systems achieve exceptional performance through ground-source energy exchange, with optimized COP values reaching values over 5.0 [1]. This study introduces a heat pump system integrated with a super-long heat pipe extracting geothermal energy. A notable characteristic of heat pipe systems is its exceptional heat transfer efficiency, which facilitates the transfer of heat at near-zero temperature differences. In recent years, considerable interest has been expressed by the scientific community in the advancement of geothermal heat extraction through the utilization of super-long gravity heat pipes [7]. While heat pipe-heat pump integration has been demonstrated for direct heating applications, its potential for modern district heating networks with variable demand profiles remains largely unexplored. The present paper developed a comprehensive modelling framework for a system utilizing low-potential geothermal reservoirs through an 1800-meter-deep heat pipe with R717 working fluid. The approach enables the exploitation of low-potential geothermal reservoirs, which are characterized by lower temperatures in comparison to the majority of deep boreholes located within geothermal active regions. The framework incorporates depth-dependent heat transfer calculations, thereby enabling the generation of high-temperature district heating water or meeting district heating needs during periods of peak demand.

2 METHODS AND MODEL

In the present study, a geothermal heat pipe coupled heat pump system is presented and evaluated. The modelling was done in MATLAB and additional validating simulations were conducted in Aspen Plus V14.

The model consists of two interconnected parts: the heat pump compression cycle and the heat pipe. It works as a conventional heat pump system with the addition of high-temperature heat source coming from the heat pipe. The system scheme is presented in Figure 1 (a) with the corresponding pressure-enthalpy (p-H) diagram (b). The heat pump compression cycle and the heat pipe work under the following assumptions:

- The heat pump cycle operates in steady state
- No heat loss in heat pump cycle or connecting pipes
- Heat pipe time dependent heat loss is not considered
- Pressure loss only occurs inside the heat pipe
- Heat pump compressor has a constant isentropic and mechanical efficiency of 72% and 100%, respectively

The main goal of the study is to show the feasibility of coupling the heat pipe to a heat pump system and additionally evaluate the performance metrics, such as the coefficient of performance (*COP*) and volumetric heating capacity (*VHC*):

$$COP = \frac{Q_{\text{COND}}}{W_{\text{LP-KOMP}} + W_{\text{HP-KOMP}}} \quad (1)$$

$$COP+ = \frac{Q_{\text{COND}} + Q_{\text{PREHEAT}}}{W_{\text{LP-KOMP}} + W_{\text{HP-KOMP}}} \quad (2)$$

$$VHC = \frac{Q_{\text{COND}}}{m_{\text{ref}} \times \nu} \quad (3)$$

$$VHC+ = \frac{Q_{\text{COND}} + Q_{\text{PREHEAT}}}{m_{\text{ref}} \times \nu} \quad (4)$$

Where Q_{cond} is the condenser heat flow, Q_{preheat} is the heat flow available for preheating, $W_{\text{LP-COMP}}$ and $W_{\text{HP-COMP}}$ represent the low-pressure (LP) and high-pressure (HP) compressor work, m_{ref} is the refrigerant mass flow and ν is the specific volume at the compressor inlet conditions.

2.1 Heat pipe design

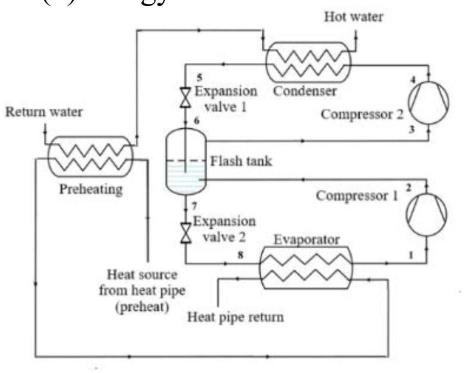
The heat pipe operates as a gravity driven system with internal circulation control and vapor extraction capability. Geothermal energy evaporates the working fluid (R717) in the evaporator section, creating vapor that rises through the adiabatic section to the top. The internal circulation is completely driven by natural convection and gravity. The heat pipe is self-regulated with an internal spray nozzle.

During operation, vapor is extracted at the top supplying the heat pump. In the process it condenses and is returned through an internal pipe to a spray nozzle located at depth. The spray nozzle provides automatic pressure control: as heat pump demand increases, more vapor is extracted, reducing the heat pipe pressure. Simultaneously, increased condensate flow rate increases the liquid column height in the internal pipe. When the hydrostatic pressure above the spray nozzle exceeds the vapor pressure in the heat pipe, the spray nozzle activates, injecting liquid back into the system. On the contrary, during low heat pump demand, higher heat pipe pressure prevents nozzle activation, allowing liquid to accumulate in the internal pipe while vapor pressure naturally increases due to continued geothermal heating and evaporation. This self-regulating mechanism ensures pressure balance without external control systems.

2.2 Model Operation

The model follows a sequential energy cascade logic: (1) geothermal input calculation using existing Slovenian borehole data shown on Figure 1 (c.), (2) heat pipe thermal mass heating during startup, (3) working fluid circulation and activation of the heat pump at target temperature, (4) heat pump operation with hysteresis control, and (5) energy redistribution between heat pump and water preheating based on available capacity.

a.)



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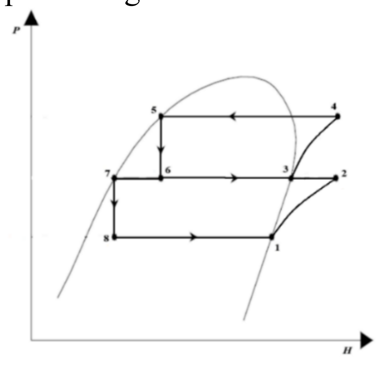

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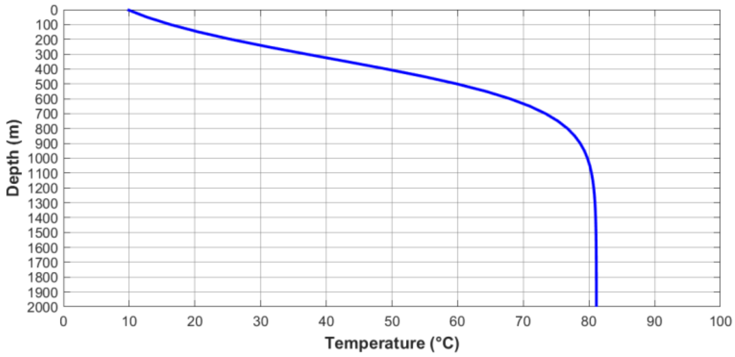


Figure 1 Process scheme of the integrated heat pump system (a.), its pressure-enthalpy diagram (b.), and the geothermal gradient (c.)

3 RESULTS

Different key performance characteristics of the integrated system were analysed under variable demand conditions. Figure 2 demonstrates the exceptional energy utilization efficiency of the integrated geothermal heat pipe-heat pump system across multiple operating scenarios. The temperature evolution Figure 2 (a.) shows stable temperature control at the target 60 °C, confirming robust thermal control and reliable heat pump operation within the designed hysteresis band. This prevents heat pump cycling while maintaining extraction temperature above the threshold for 65 °C hot water supply. It is evident that the system responds to demand change without oscillatory instability. The temperature evolution shows the vapor temperature at the top of the condenser, meaning the temperature where the working fluid can be extracted.

The energy flow analysis on Figure 2 (b.) and (c.) reveals the system's ability to maintain total energy utilization from the geothermal source. With changing heat pump demand, preheating adjusts to maintain a constant energy output. This inverse relationship demonstrates intelligent energy redistribution rather than waste, with preheating compensating perfectly for reduced heat pump demand. For example, when the heat pump demand decreases from 36 kW (t=1500 min) to 12 kW (t=2000 min) preheating automatically increases from 38 kW to 62 kW, maintaining a constant energy output. Importantly, the heat pump maintains a constant outlet temperature of 65 °C regardless of demand variations, with demand control achieved through variable water mass flow rather than consumer supply temperature.

The performance metrics (d.) showcase the system's true potential when operating with surplus geothermal capacity. The base COP of 3,08 represents conventional heat pump efficiency, while COP+ values reach up to 14,0 during extreme low demand periods. At t=2000 min the heat pump demand is only 12 kW while 62 kW of excess geothermal energy remains available for preheating, creating these artificially high COP+ values. These extreme values are realistically possible but in usual operation the COP+ values are reaching 5,3-9,6 as shown in other time points. During peak-shaving demand the system operates at COP+ values near or slightly above conventional two-stage heat pump systems. The VHC improvement follows the same principle as COP: during low demand periods, the fixed geothermal input provides both heat pump demand and substantial preheating within the same heat pump refrigerant mass flow, dramatically increasing volumetric heating capacity. Noted, the VHC are provided based on the interior heat pump refrigerant circulation to be consistent with COP calculations.

Extended operational analysis Figure 2 (e.) and (f.) reveal the system's thermal storage capabilities during minimal demand periods. By reducing preheating to minimum levels during low-demand periods (constrained by working fluid flow bounds), most geothermal energy redirects to thermal mass heating. The system achieves higher temperatures up to 66 °C at the extraction point, creating a temporary high-temperature capacity for peak shaving potential. This thermal mass 'charging' shows the dual-functionality potential needed for 5th generation district heating and cooling (5GDHC) implementations.

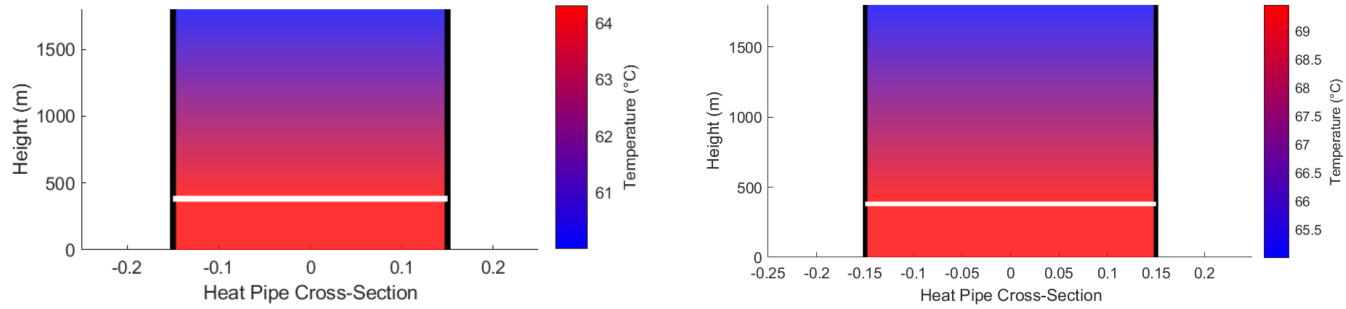
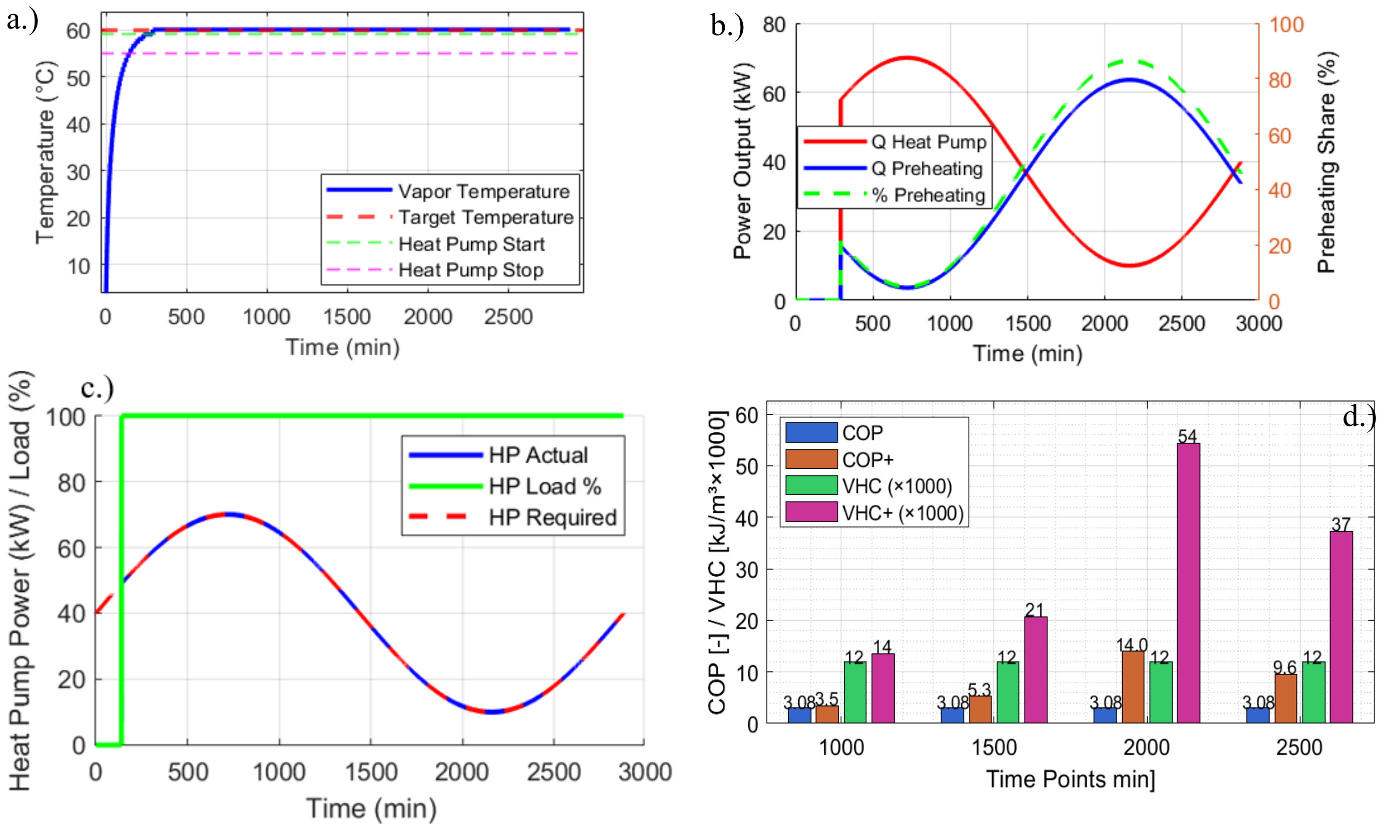


Figure 3 shows the complete thermal stratification along the 1800m heat pipe depth under both normal operation (a.) and thermal storage mode (b.). Three distinct zones are apparent: isothermal liquid region, transitional vapor region with gradual temperature decrease, and the extraction zone. The 4°C temperature difference results from hydrostatic pressure effects across the vapor column. The system is designed to prevent temperature crossovers in the preheating unit. Heat pipe extraction occurs at approximately 60°C, with a maximum temperature approach of 10°C compared to the 65°C heat pump outlet under normal operation. During thermal storage mode, the extraction temperature rises to 66 °C, creating peak-shaving potential. This ensures certain heat transfer in most cases, with potential crossover only occurring during extreme preheating scenarios when excess geothermal energy is available.



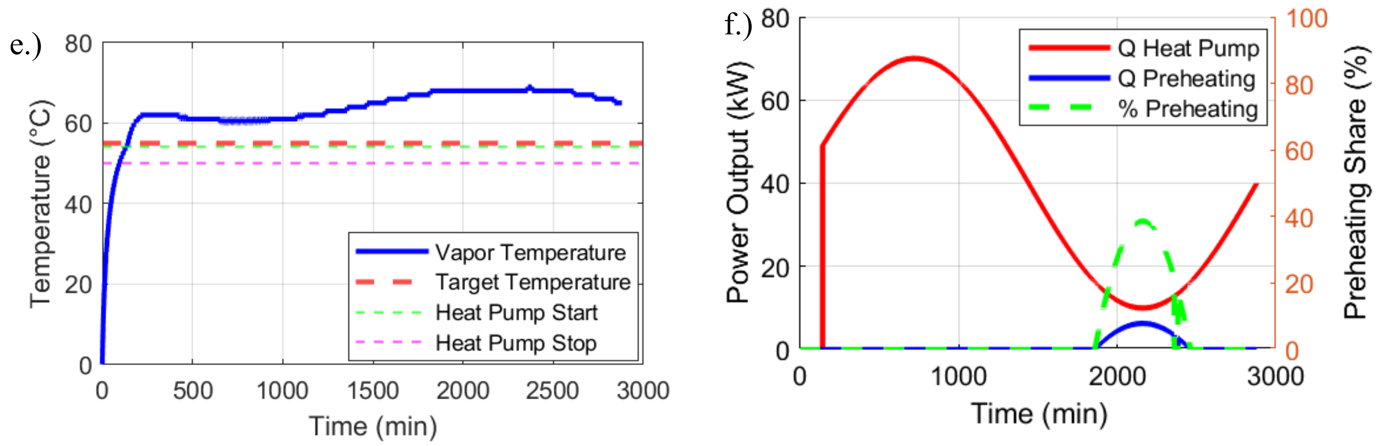


Figure 2 System performance under variable demand operation: (a) temperature evolution and hysteresis control, (b) energy flow redistribution, (c) heat pump load management, (d) system performance metrics, (e) temperature evolution during thermal storage mode operation, (f) heat pump load management during thermal charging

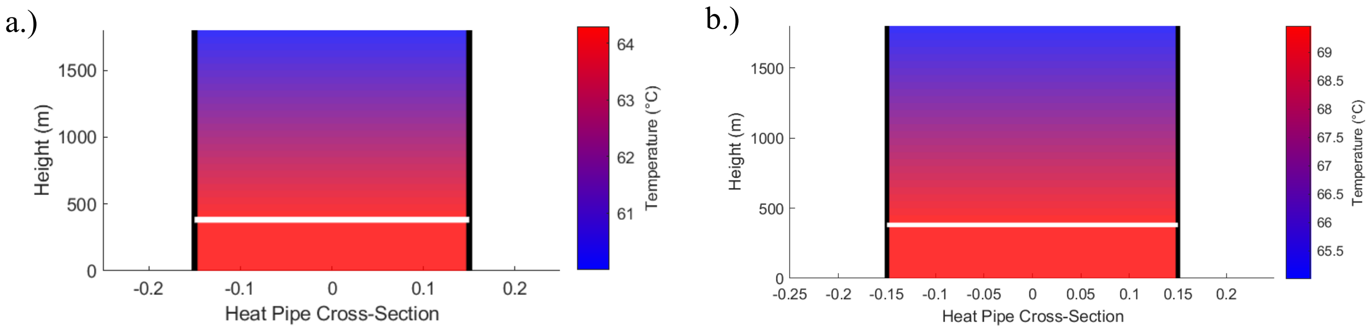
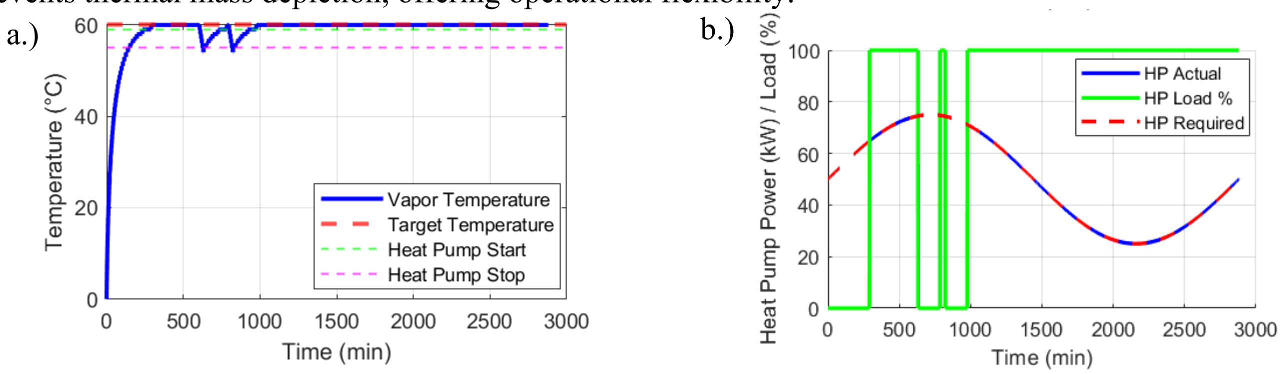


Figure 3 Temperature profile during normal operation (a.) and under low-demand and limited preheating (b.)

Figure 4 shows the system's behaviour when thermal demand exceeds available geothermal input, showing its adaptive capabilities and limitations. The system initially maintains the required 100% load by drawing energy from thermal mass, causing temperature to decline from equilibrium to 55 °C which marks the heat pump shut down threshold, as seen on Figure 4 (a.). During temperature recovery periods Figure 4 (b.), the heat pump deactivates, and all geothermal energy is committed to thermal mass reheating, with no preheating capability available. Alternatively, Figure 4 (c.) demonstrates demand limiting, where the working fluid is restricted to match the maximum available geothermal input, maintaining constant temperature in the heat pipe but not satisfying 100% heat pump load. This approach requires backup heating to meet full demand but prevents thermal mass depletion, offering operational flexibility.



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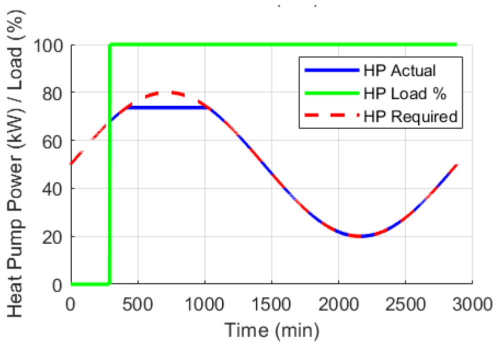

Figure 4 High demand temperature evolution (a.), heat pump and preheating heat flow against time and the overall preheating percent share for case with full 100% load (b.) and limiting demand (c.)

3.1 Implementation possibilities and limitations

While heat pipes have achieved remarkable progress and are not a novelty, super-long gravity arrangements coupled with heat pump focus mainly on direct geothermal extraction. Current systems operate as standalone geothermal sources with single-purpose heat extraction. There are very limited studies conducted with heat pipe systems integrated into 5th Generation District Heating and Cooling (5GDHC). The proposed system addresses critical gaps in 5GDHC implementation. Unlike conventional underground thermal energy storage (UTES) systems requiring separate storage and extraction components, a super-long heat pipe system provides dual functionality - active geothermal extraction during peak demand periods and passive thermal storage during low-demand periods (e.g., nighttime). This could solve two infrastructure problems with one implementation: active heating supply and passive energy storage.

The large thermal mass of a super-long heat pipe enables underground thermal energy storage without additional infrastructure. During low heat pump demand, excess geothermal energy increases the thermal mass temperature, effectively storing energy for later extraction. This secondary storage effect occurs passively, maintaining high system efficiency even during demand fluctuations.

This preliminary modelling framework enables new thinking about integrated geothermal systems by demonstrating how single infrastructure can serve multiple district heating functions. The sequential energy cascade logic automatically optimizes between immediate heating supply and thermal storage, providing insights for 5GDHC network design and operation, either increasing the hot water supply or heating up with the excess energy. This integrated multiple-choice system comes with some unignorable issues as:

- High drilling costs for 1,800m installation
- Complex construction and maintenance requirements
- Peak demand sustainability limited by geothermal source capacity
- System performance depends on consistent geothermal input availability
- Model requires experimental validation for practical implementation

4 CONCLUSION

This preliminary study demonstrates the technical feasibility of integrating super-long gravity heat pipes with heat pump systems for enhanced geothermal energy with consideration for variable heat demand. The developed model achieves sustainable COP+ values up to 9,6 during low heat demand operation while maintaining sustainable base-load performance with COP values of 3,08 at high-demand operation through appropriate energy redistribution.

The temperature stratification analysis confirms feasible operation while utilizing low-potential geothermal reservoirs. The 60°C extraction temperature with 5-10°C approach to heat pump delivery ensures reliable heat transfer while preventing temperature crossover under usual operating conditions. Demand analysis reveals that exceptional COP+ performance is possible for low-demand operation while short-duration peak shaving is also possible. Continuous high-load operation deteriorates the efficiency up to the point where the COP+ values approach values comparable to a conventional two-stage heat pump, making the system particularly suitable for district heating networks with variable demand profiles.

The system's dual functionality addresses possible 5GDHC implementation and tackles challenges by providing both active heating supply and passive underground thermal energy storage within single infrastructure. The 1,800m depth heat pipe enables energy storage during low-demand periods while maintaining continuous extraction capability, solving two district heating infrastructure problems with one implementation. The automatic load balancing between primary heat pump operation and secondary water preheating demonstrates the potential for transforming underutilized low-enthalpy geothermal resources into high-efficiency heating systems.

Future work should focus on enhanced heat pipe modelling with detailed dynamics and flow physics. Furthermore, the modified heat pipe model needs actual integration studies with existing 5GDHC infrastructure. This work establishes the groundwork for developing practical solutions that combine geothermal extraction, heat pump enhancement, and underground thermal storage in unified district heating applications yet a lot more work is needed.

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