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# Comparative Analysis of HEATNETS for Geothermal Network Performance

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## ABSTRACT

Thermal energy networks (TENs), also known as 5th generation district energy systems, or more specifically geothermal networks when exchanging heat with geothermal boreholes, are an important technology for efficient utilization of thermal energy. In these networks an ambient loop connects buildings and thermal sources, such as a borehole field, to exchange energy and maintain a desired loop temperature. Water-source heat pumps are used at the buildings to connect to the ambient or thermal loop to meet to the building heating and cooling loads and maintain comfort. A semi-transient, reduced-order technical model and techno-economic model, called HEATNETS, has been developed at NREL that captures the flow of energy around a TEN.

In this work, a comparison of the HEATNETS technical model and a well-known coding platform used for modeling geothermal networks, TRNSYS, has been completed for a proposed geothermal network as a verification and validation process. Hourly data provided from the TRNSYS simulation included building loads, pumping power, heat pump power, temperature entering and leaving the borehole field, and mass flow rates. The hourly borehole temperatures were used to create a linear regression model utilized in HEATNETS to estimate the borehole field heat exchange. The building loads and mass flow rates were direct inputs to HEATNETS while the pumping power, heat pump power, borehole temperatures, and coefficients of performance were all simulated and calculated by HEATNETS, allowing for direct comparison of the thermal energy transfer. HEATNETS considers the full process from design inputs to economic outputs and can provide modeling options for high-level initial system design and operational optimization. This study focuses on validation of HEATNETS using results from TRNSYS. HEATNETS is not intended to replace other modeling tools but instead enhance modeling capabilities by providing an open-source, high-level, and rapid model. A comparison with TRNSYS demonstrates that HEATNETS can be a unique and fast approach to capturing performance of a full geothermal network system.

## 1. INTRODUCTION

Thermal energy networks (TENs) have the potential to aid in the integration and efficient utilization of electricity for heating and cooling of buildings. These networks, and specifically 5G district energy systems, are becoming more widely accepted as a path for integrating with a renewable electric grid (Simpson et al. 2024). In these networks the ground acts as a heat sink and source for exchanging energy to and from building loads. The subsurface maintains a stable temperature and provides a more consistent heat transfer medium than the air, which is used in air-source heat pump systems. Liu et al. (2023) found benefits, such as reducing power costs and reduction in annual electricity consumption, when converting existing building heating and cooling systems to geothermal heat pumps.

Generally, geothermal boreholes have been studied for many years in various application spaces (Tang et al. 2022) as a reservoir for exchanging energy with the components on the system loop. The main attributes of a TEN typically include an ambient temperature loop that connects buildings (commercial or residential) and load balancing sources (such as boreholes) to each other. The buildings then exchange heat with the thermal loop through water-source heat pumps, and the flow is maintained via a centralized circulation pump (or various pumps through the system). A benefit of this scheme is that the ambient temperature loop allows for buildings to consume heat from the system and produce heat for the system (Buffa et al. 2019).

While tools exist to model geothermal networks, the models typically take significant time to set up and run. Some models that are most often used for design of TENs are the commercial code, TRNSYS, or the open-source code Modelica Buildings Library (TRNSYS, Lawrence Berkeley National Laboratory, n.d). These codes are complex and can be computationally expensive. Additional models have been researched for specific interest in specific systems or subcomponents, such as storage or borehole heat exchange (del Hoyo Arc et al., 2018, Quirosa et al. 2022, Heim et al. 2024). However, as mentioned in Simpson et al. 2024, there is still a need for an open-source, fast, reduced-order model that can capture the main components and behavior of a TEN and predict the economics.

A few of these systems have been installed throughout the United States such as at Colorado Mesa University (EPRI, 2021; Xcel Energy, 2023), and Whisper Valley housing development in Texas (Oh & Beckers, 2023; Wolfson & Mapel, 2020). These systems can provide a framework moving forward for this technology. Additionally, the Learning from the Ground Up (LeGUp) project, led by the Home Energy Efficiency Team (HEET) is studying one of the first utility-scale pilot geothermal networks installed in Massachusetts. This project is unique in that it is a utility-led community retrofit project. Working with HEET, NREL has been developing an open-source model of the pilot installation which will be used to inform the optimization of designing and operating a geothermal TEN.

This work was produced by NREL as a part of the LeGUp project, where this paper explores a reduced order model (ROM) written in Python to capture the energy flow for a geothermal network (Simpson & Zhu, 2024). The benefit of the ROM is the quick runtime as well as the ability to make changes to the design quickly. The ROM in combination with a techno-economic analysis (TEA) model is called HEATNETS (Heat Analysis Tool for NEtworked Thermal Systems). HEATNETS is designed to be an open-source code for modeling and predicting performance for thermal energy networks. HEATNETS uses either measured or modeled building loads to simulate and predict parameters such as the borehole field temperatures and heat pump power which are all connected via the ambient thermal loop.

The focus herein is to compare the ROM results with the established modeling tool called TRNSYS. The inlet and outlet borehole temperatures, pumping power, and heat pump powers are compared between these two different models which both simulate the same geothermal network. The comparison shows the validity of the new ROM.

## 2. METHODS

The geothermal network modeled here consists of multiple buildings, a borehole field, a pump station, and an ambient loop which carries fluid to and from the main components. Figure 1 shows a diagram of the main loop, relevant components, and whether the data was directly input to the ROM (blue boxes) or calculated from the ROM (red boxes). The goal of this simulation is to estimate the movement of energy through the network including buildings, boreholes, and the ambient loop.

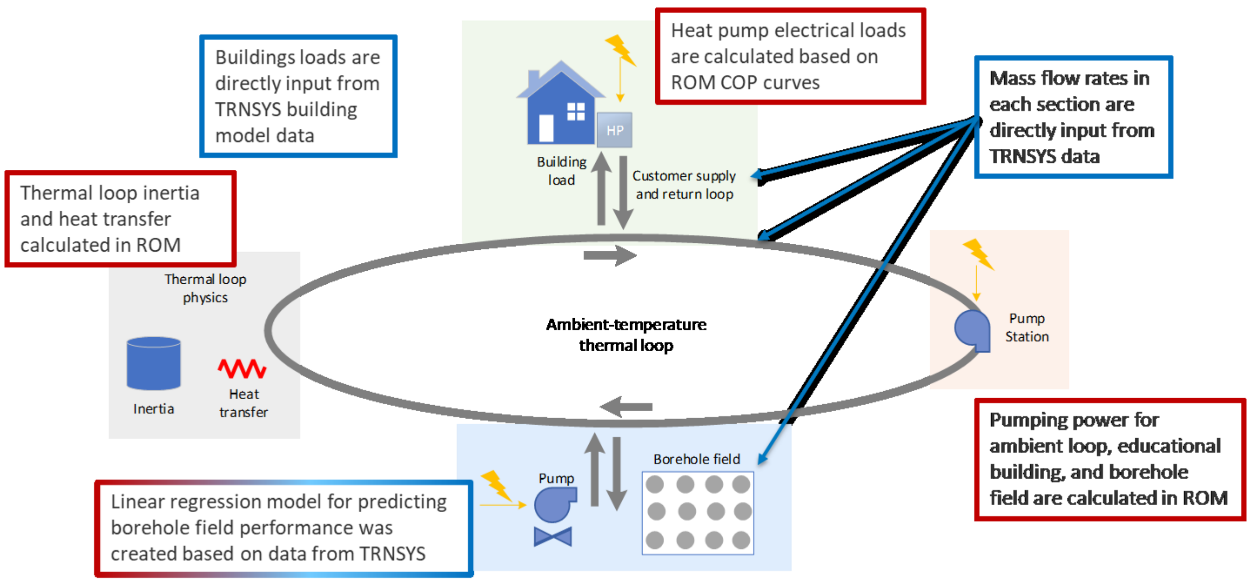


**Figure 1. Diagram of the thermal energy network where the ambient thermal loop carries fluid that exchanges energy with the other components around the system. The red boxes indicate parameters calculated by the ROM, while the blue boxes indicate data directly input from the TRNSYS data.**

The ROM inputs real building loads, mass flow rates, pumping efficiencies, and heat pump coefficients of performance (COPs). Using the data, we calculate the temperatures into and out of the buildings, as well as the borehole temperatures, estimate the overall heat exchange through the system, and determine the system COP. For this analysis, as alluded to in Figure 1, the building load and mass flow rate data were directly read into the ROM from the given TRNSYS data. While the borehole inlet and outlet temperature were used to create a linear regression model, the remaining given data (pump power and heat pump power) were used as a comparison between the ROM and TRNSYS. An additional detail of this loop, not explicitly shown in the figure, is an educational building with a high load that is on a separate loop with its own pump, and therefore mass flow rate. Results shown will be split into the ambient loop, the educational building, and the borehole loop.

Generally, the heat flow equation for the fluids is given by $\boldsymbol{Q} = \dot{\boldsymbol{m}}\boldsymbol{C_p}(\boldsymbol{T_{in}} - \boldsymbol{T_{out}})$
Equation 1 shown below.

$$\boldsymbol{Q} = \dot{\boldsymbol{m}}\boldsymbol{C_p}(\boldsymbol{T_{in}} - \boldsymbol{T_{out}}) \quad \textbf{Equation 1}$$

Where $\boldsymbol{Q}$ is the heat transfer, $\dot{\boldsymbol{m}}$ is the mass flow rate, $\boldsymbol{C_p}$ is the specific heat of the fluid, $\boldsymbol{T_{in}}$ is the inlet temperature, and $\boldsymbol{T_{out}}$ is the exit temperature. This equation is used, for example, to calculate the outlet temperature of the buildings by rearranging the equation based on the known inputs (mass flow rate, building loads, and inlet temperatures).

$$\boldsymbol{T_{out}} = \boldsymbol{T_{in}} - \left(\frac{\boldsymbol{Q}}{\dot{\boldsymbol{m}}\boldsymbol{C_p}}\right) \quad \textbf{Equation 2}$$

### 2.1 Borehole Temperature Regression Model

Temperature into and out of the borehole field and mass flow rates into the borehole field were provided from the TRNSYS model. This data was used to create a regression model to predict the outlet temperature of the borehole field. Regression models are useful when trying to predict the outcome from two or more inputs (Linear Regression, 2024).

The regression model used took in the inlet temperature to the boreholes, the ground temperature, and the mass flow rate into the boreholes, therefore $T_{out} = f(T_{in}, T_{ground}, \dot{m})$. The ground temperature was estimated using the inlet and outlet borehole temperatures provided calculating the energy to the boreholes and subsequently predicting the ground temperature from that energy exchange. The results provided a somewhat sinusoidal temperature profile with a lower ground temperature in the winter months (~11.5°C) and a higher temperature in the summer months (~12°C). A polynomial was then fit, and the regression model was used, via a Python package, to predict the outlet borehole temperature (Pedregosa et al., 2011). Figure 2 shows the regression model output given the inlet temperatures, estimated ground temperatures, and mass flow rates, versus the provided TRNSYS outlet temperature data.

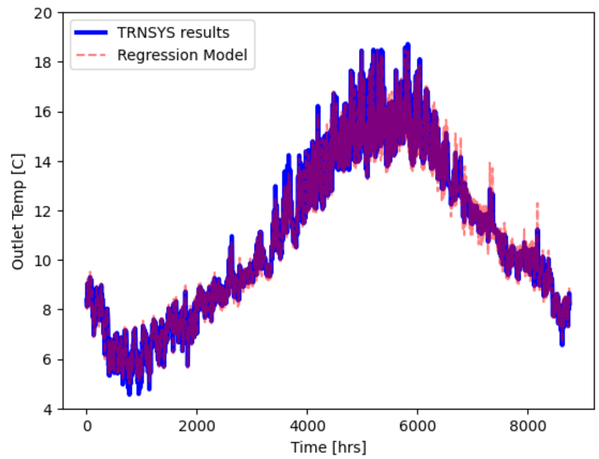


**Figure 2. Regression model prediction using a portion of the TRNSYS inputs as training data and then the rest of the TRNSYS inputs as validation data.**

In the ROM the regression model is called each time step to predict the outlet borehole temperature given the ROM calculated inlet temperature, estimated ground temperature, and provided mass flow rate.

### 2.2 Pump power and heat pump power calculations

Pumping power and heat pump power were also provided from the TRNSYS model for comparison. In the ROM these values are calculated based on flow and heat transfer physics around the loop and assumed efficiencies for the pumps and heat pumps. Pressure losses through the system—from pipe roughness, bends in the pipes, and valves, for example—all contribute to the pumping power as well. With a high resistance in the pipes the pumping power will increase. Therefore, it was important in the simulation to estimate the pumping losses accurately. $\Delta \boldsymbol{P} = \frac{f\rho L V^2}{2D} + \sum \frac{K(\rho V^2)}{2D}$ Equation 3 shows the basic equation for calculating pressure losses of a fluid through a pipe.

$$\Delta \boldsymbol{P} = \frac{f\rho L V^2}{2D} + \sum \frac{K(\rho V^2)}{2D} \qquad \textbf{Equation 3}$$

Where $\Delta \boldsymbol{P}$ is the pressure differential (from one location to the next), $\boldsymbol{f}$ is the friction coefficient (a function of the pipe roughness and fluid velocity), $\boldsymbol{L}$ is the length of the pipe, $\boldsymbol{V^2}$ is the fluid velocity, $\boldsymbol{D}$ is the pipe diameter, and $\boldsymbol{K}$ is the friction coefficient for components such as valves. The pump power is then calculated from the following equation.

$$\boldsymbol{P}_{power} = \frac{\dot{V}\Delta P}{\eta} \qquad \textbf{Equation 4}$$

Where $\dot{\boldsymbol{V}}$ is the volume flow rate, and $\boldsymbol{\eta}$ is the efficiency of the pump. Finally, the coefficient of performance (COP) of the full system is calculated based on $\boldsymbol{COP}_{system} = \frac{\text{Total building loads}}{\text{Total electrical loads}} = \frac{\sum |\text{building loads}|}{\sum \text{electrical loads}}$ Equation 5.

$$\boldsymbol{COP}_{system} = \frac{\text{Total building loads}}{\text{Total electrical loads}} = \frac{\sum |\text{building loads}|}{\sum \text{electrical loads}} \qquad \textbf{Equation 5}$$

The COP provides an estimate of the overall performance of the system, where the greater the efficiency of the system the higher the COP. An efficient system, should in theory, have a lower operational cost and have a higher COP.

## 3. RESULTS AND DISCUSSION

The results show that the ROM can take in specific components for a thermal loop and transient data and produce annual results. While there is some discrepancy between the ROM and TRNSYS, the ROM shows it can be used as a tool for simulating geothermal networks.

The mass flow rates for the three distinct flow patterns—the ambient loop, the educational building, and the borehole loop—were all directly read into the ROM from the provided TRNSYS data. Figure 3 shows the comparison of the mass flow rates, indicating that the data was read in correctly.

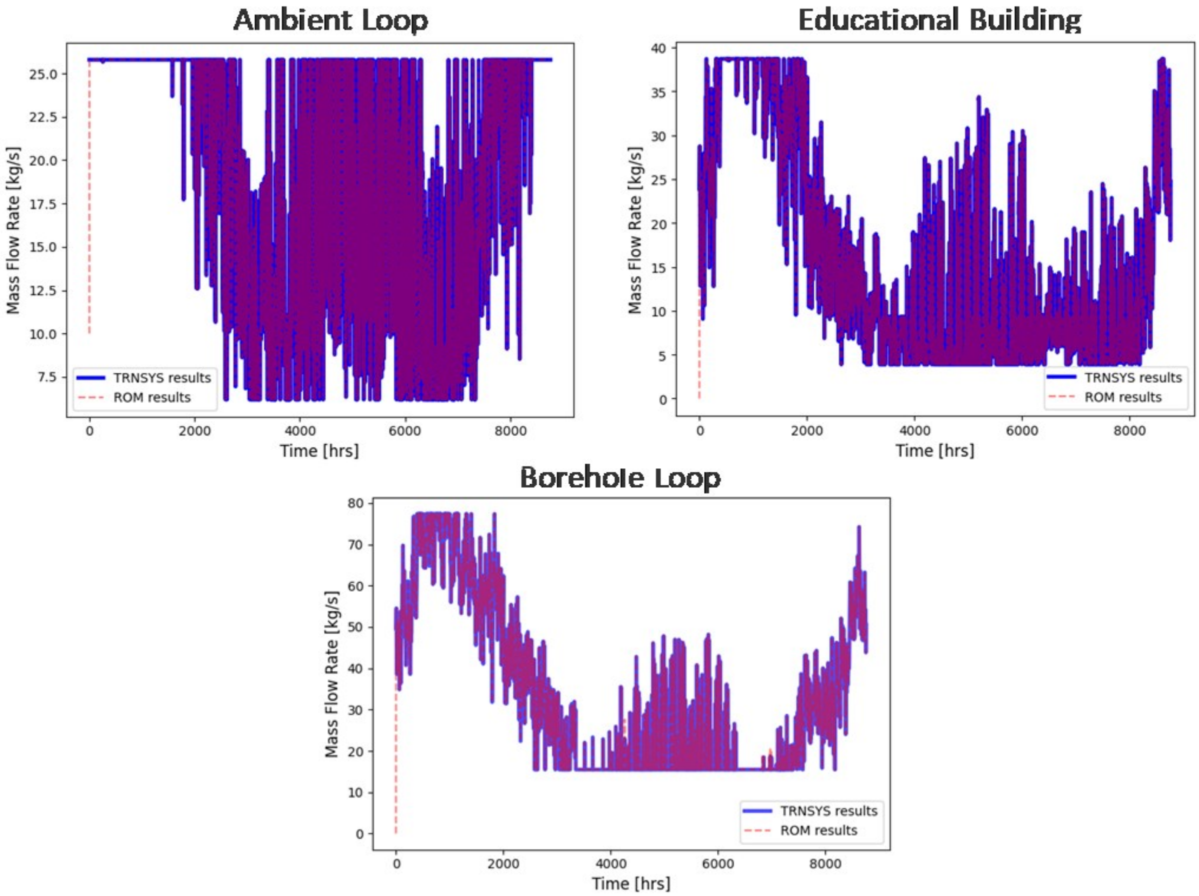


**Figure 3 Mass flow rates for the ambient loop, educational building and borehole loop.**

**The inlet and outlet borehole temperatures compared to TRNSYS can be seen in Figure 4. The temperatures do not match exactly; however, the error between the temperatures is small. The mean square error (MSE), similar to the variance for data, for the inlet temperatures is 1.58 (in Celsius squared) while for the outlet temperatures is 0.288, providing confidence that the**

**ROM can predict borehole temperature and heat exchange using the regression model explained previously. Further,**

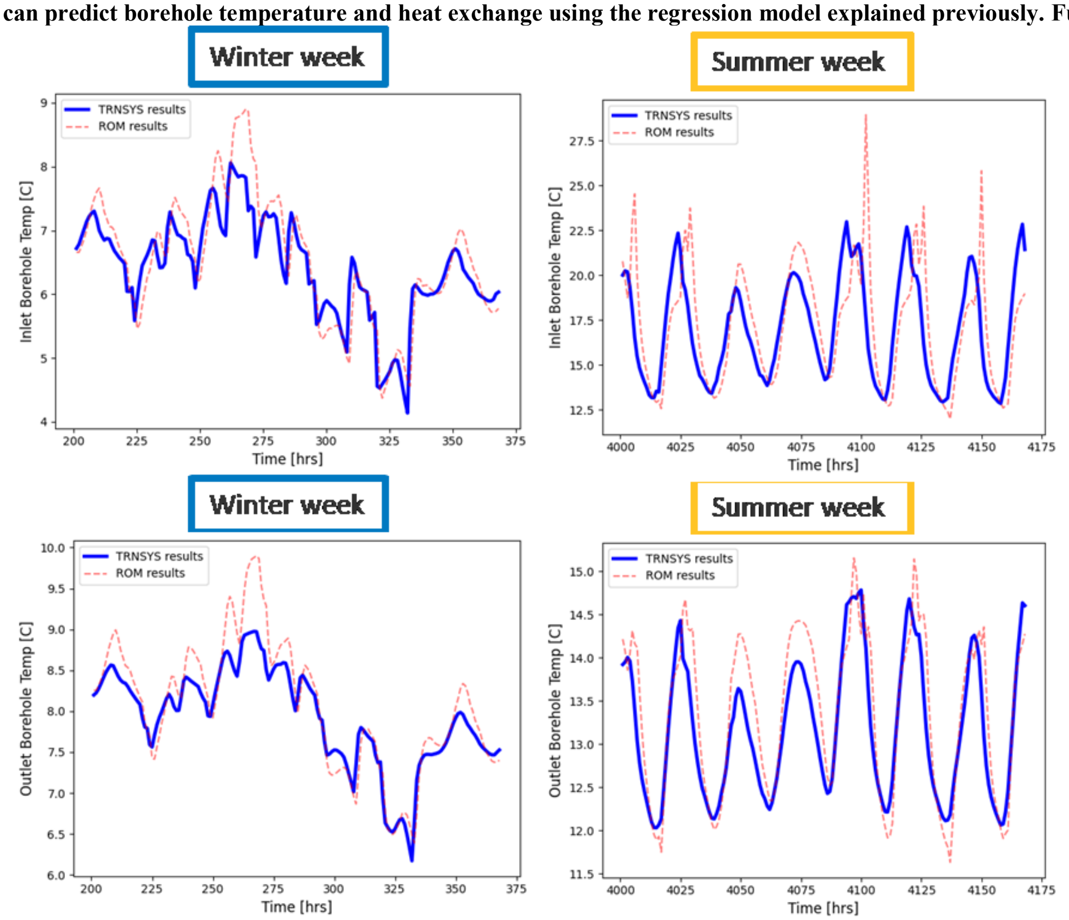


Figure 5 shows a winter and summer week for both the inlet and outlet temperatures. It can be seen from these figures that more discrepancy occurs in the summer months (hours 3500 to 6500) versus the winter months. This discrepancy could come from variations in fluid properties between the models, or differences in ground temperature estimations. In addition, Figure 6 (a) shows the temperature differences between the ROM and TRNSYS models and Figure 6(b) shows the temperature difference (inlet – outlet) for both models. This figure highlights more where the models agree and where they differ.

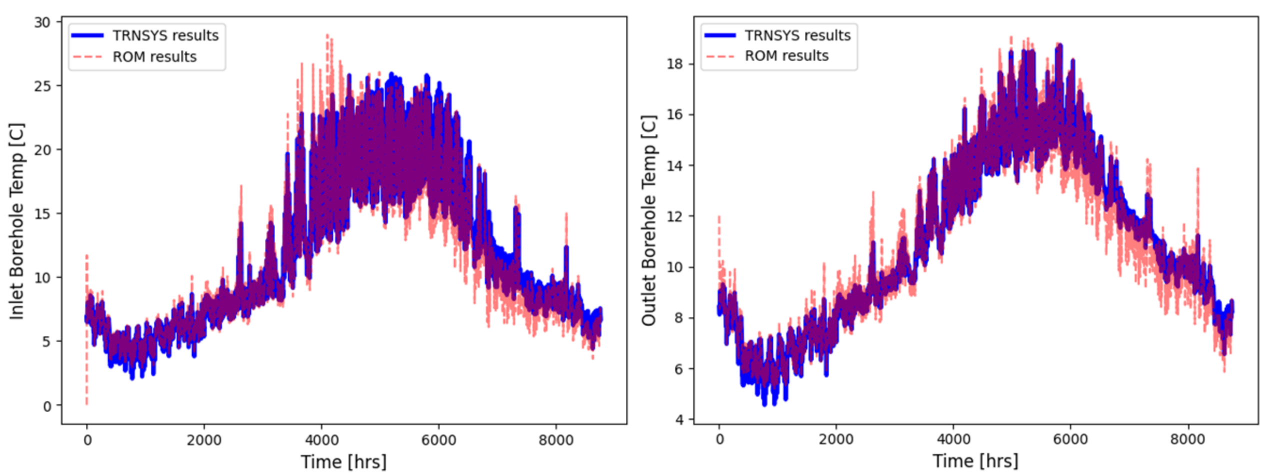


**Figure 4. Inlet and outlet borehole temperatures predictions from the ROM and TRNSYS.**

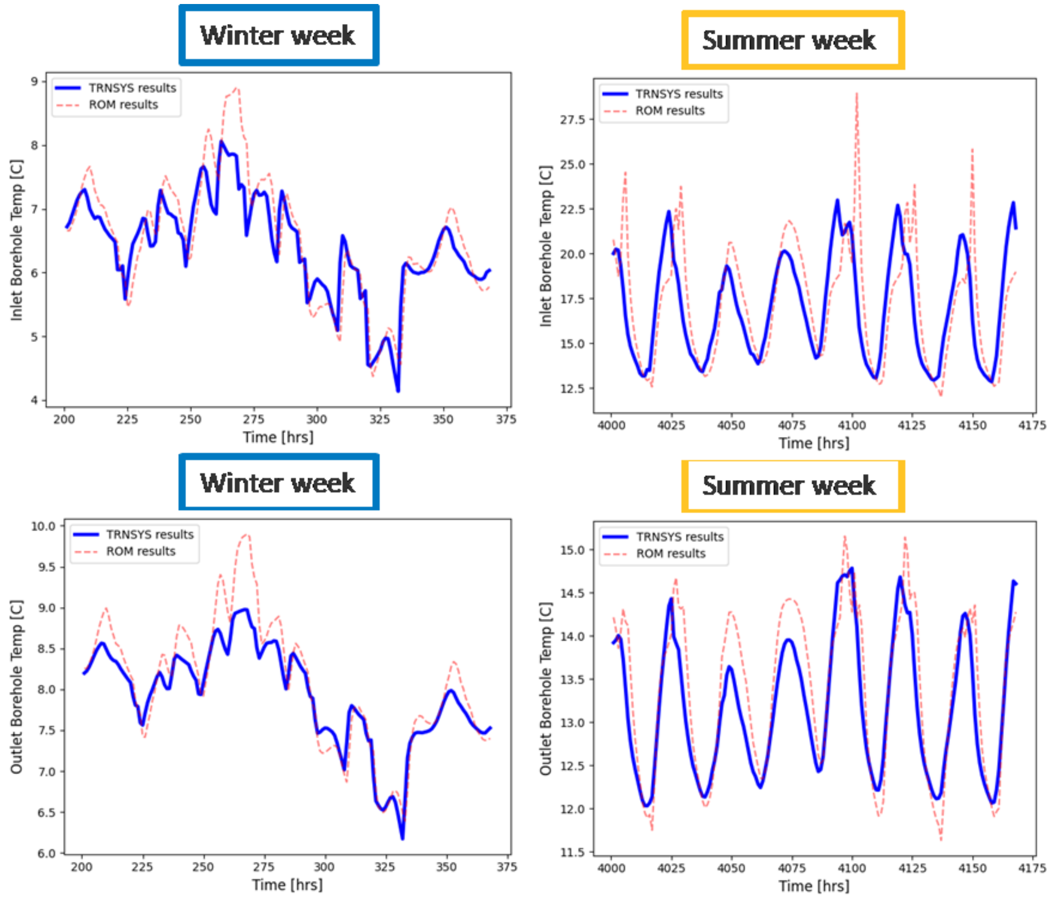


**Figure 5 A winter and summer week for the inlet and outlet temperatures for the ROM versus the TRNSYS model.**

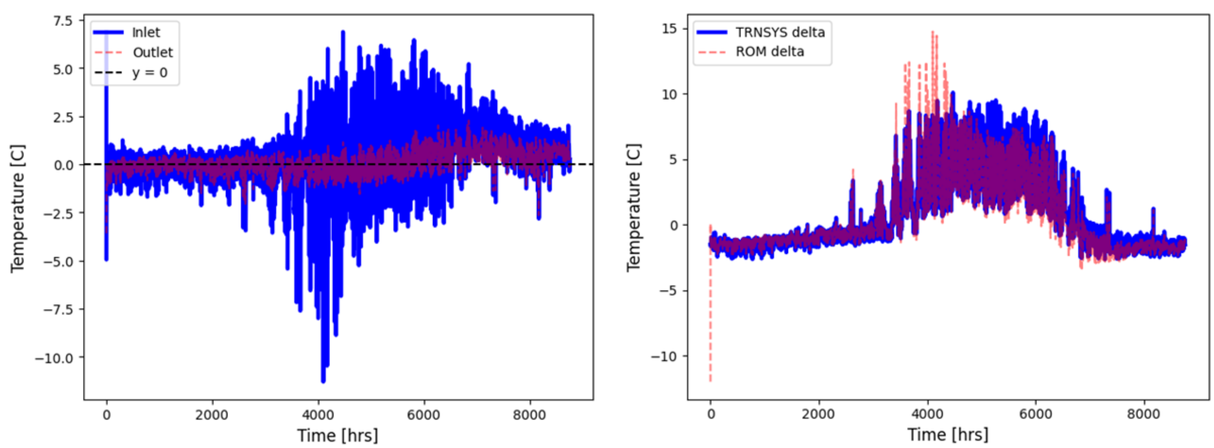


**Figure 6. (a) Temperature differences between ROM and TRNSYS from Figure 4, (b) temperature differences between inlet and outlet.**

To estimate the overall efficiency of the system and therefore cost (in the future) it is important to understand the circulation pumping power and heat pump power for the system overall. Three different pumping powers were provided from TRNSYS, similar to the mass flow rates, for the three different sections of the loop. In the ROM the pump power is calculated and influenced by the pump losses through the system, the mass flow rate, and the temperatures in the fluid. Figure 7 shows the pumping powers for the ambient loop, the educational building, and the borehole loop.

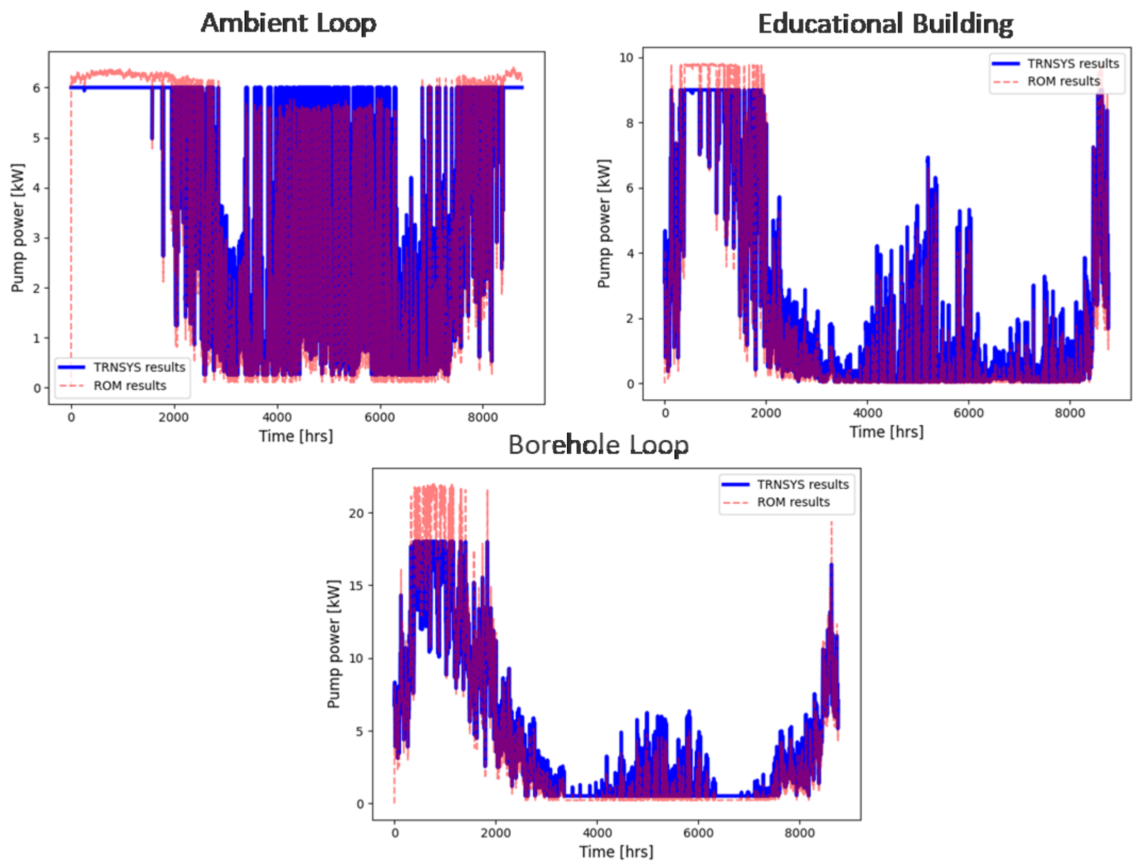


**Figure 7. Pumping power for the ambient loop, the educational building, and the geothermal borehole loop.**

The figures show some differences in the model outputs, however the percent difference for each pumping power is very low, shown in Table 1.

**Table 1 Average percent difference for the pumping power ROM calculations versus TRNSYS data.**

| Pump | Percent Difference |
|---|---|
| Ambient Pump | 4.8% |
| Educational Building Pump | 8.4% |
| GHX Pump | 2.4% |

Some of the variations in pumping power can be attributed to estimations in pressure losses through the system, the temperature variations (which could cause variations in fluid properties), and the pump efficiency estimations.

Data for the heat pump electrical loads were also compared between the ROM and TRNSYS. The heat pump electrical loads are calculated in the ROM based on estimated heat pump efficiencies, mass flow rates, and fluid temperatures. HEATNETS shows very good agreement with TRNSYS on an annual and hourly basis for the heat pump electrical loads, with an overall percent error of <1%, seen in Figure 8 and Table 2.

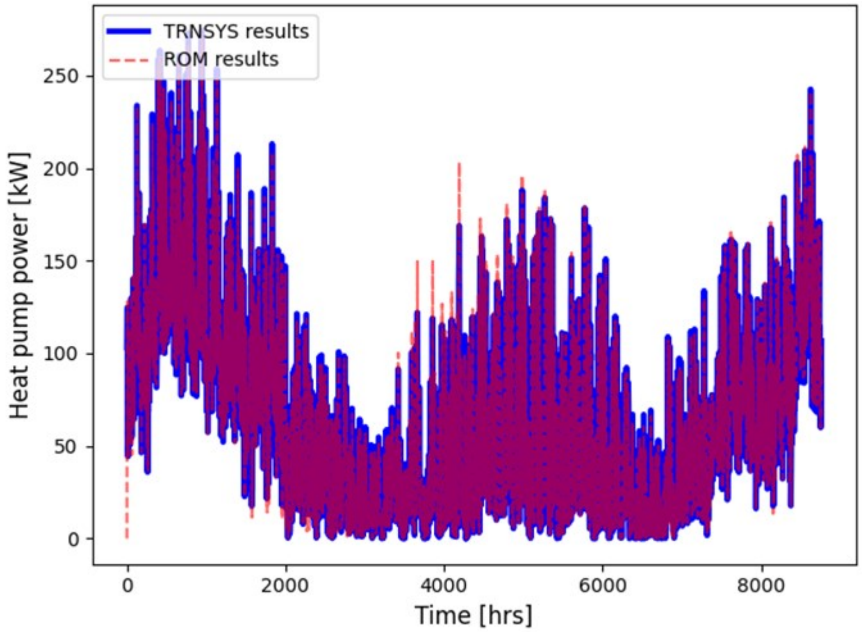


**Figure 8 shows the heat pump power for the ROM and TRNSYS data as well as the annual loads and percent error.**

**Table 2 Annual heat pump loads for the ROM and TRNSYS.**

| | |
|---|---|
| TRNSYS HP [kWh] | 553,810 |
| ROM HP [kWh] | 549,674 |
| Percent error [%] | 0.7 |

Finally, the COP of the system overall was determined and compared with TRNSYS as well. The COP for both datasets is calculated based on the total building load power divided by the total electrical loads (both heat pump and circulation pumps). The ROM COP was 3.87, while the TRNSYS COP was 3.82.

On an hourly basis the inlet and outlet borehole temperatures between the ROM and TRNSYS models differ slightly, which could cause the variations in the other discussed results. The temperature differences could come from many factors in the models that affect the borehole performance, including the linear regression model, ground temperature estimations, heat transfer equations, etc. Results show that the ROM temperatures differ more significantly from the TRNSYS temperatures when the system switches from mostly heating to mostly cooling (around hour 4000), which also points to potential discrepancies in temperature (and therefore fluid property) estimations.

## 4. CONCLUSION

This study proved that the ROM can take in hourly data and produce results that closely match a well-known and accepted model, TRNSYS. HEATNETS (ROM + TEA) is an opensource model alternative to TRNSYS and is particularly useful as more TENs are built for considering initial design tradeoffs. Additional investigations on the hourly performance of specific parameters, such as the pump power, temperature estimations, and borehole performance would likely show further improvements to the ROM.

This research demonstrates the capability of modeling a thermal energy network with multiple building loads and boreholes throughout the system. The ROM used in this study was compared with the well-known model TRNSYS and produced accurate results with the ROM and TRNSYS having 0.7% difference in the COP and up to 8.4% difference in the pumping power. The future of this ROM is to increase the modeling capabilities, and to model various design networks in short periods of time to aid with decision-making in the design process. Future work also includes further integrating the ROM and economic models within HEATNETS which will provide cost analysis and metrics for the desired system.

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