Development of a Sizing and Modeling Platform for District Energy Systems with Geothermal Heat Pumps

Preprint

Jing Wang, Matt Mitchell, Tanushree Charan,
Brian Ball, Nathan Moore, and Shadi Abdel Haleem

National Renewable Energy Laboratory

Presented at IGSHPA Research Conference 2024
Montréal, Canada
May 28, 2024

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Conference Paper
NREL/CP- 5500-88178
May 2024

Contract No. DE-AC36-08GO28308

Development of a Sizing and Modeling Platform for District Energy Systems with Geothermal Heat Pumps

Preprint

Jing Wang, Matt Mitchell, Tanushree Charan,
Brian Ball, Nathan Moore, and Shadi Abdel Haleem

Suggested Citation
Wang, Jing, Matt Mitchell, Tanushree Charan, Brian Ball, Nathan Moore, and Shadi Abdel Haleem. 2024. *Development of a Sizing and Modeling Platform for District Energy Systems with Geothermal Heat Pumps: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-88178. https://www.nrel.gov/docs/fy24osti/87975.pdf.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5500-88178
May 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Geothermal Technologies Office.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

IGSHPA Research Conference
Montréal, May 28-30, 2024

Development of a Sizing and Modeling Platform for District Energy Systems with Geothermal Heat Pumps

Jing Wang **Matt Mitchell** **Tanushree Charan**
Brian Ball **Nathan Moore** **Shadi Abdel Haleem**

ABSTRACT

Existing tools for community or urban scale energy system modeling and simulation are often limited in their capabilities and require expert-level modeling proficiency to develop system models. To help fill this gap, we are proposing an integrated sizing and modeling platform for district energy systems with geothermal heat pumps. The proposed platform uses geometric and non-geometric user inputs related to the buildings, borefield, and district energy loop. The platform sizes the geothermal heat exchanger, generates a corresponding district energy system model, and runs an annual simulation automatically. The borefield component model on our platform was validated against EnergyPlus to ensure a reliable simulation performance. A case study is provided in this paper to demonstrate the workflow and simulation result plausibility of the proposed platform.

INTRODUCTION

Buildings account for about 35% of the total carbon dioxide emissions in the United States (EIA 2022) and roughly 40% of all energy use (EIA 2023). Electrification of building loads with clean sources of electricity is vitally important to achieve a decarbonized, clean energy future. District energy systems coupled with geothermal heat pump (GHP) systems are a promising solution for community and urban scale energy decarbonization. Such systems typically have the advantage of a reduced network peak load as the buildings connected to the same loop may offset each other's heating/cooling demand due to asynchronous load profiles (e.g., one building is heating while another one is cooling). The near-ambient temperature fluid loop also reduces distribution heat losses to the environment. Finally, water source heat pumps will have a higher coefficient of performance (COP) when compared to air-source heat pumps and on average in the U.S. will reduce carbon emissions compared to traditional fossil fueled heating equipment. The carbon benefit will increase as electricity generation becomes cleaner.

Several research works have concentrated on modeling and simulating district energy systems incorporating ambient temperature loops with distributed geothermal heat pumps. Abugabbara et al. (2022) developed a simulation model for the first existing Swedish district system with simultaneous heating and cooling demands and bidirectional energy flows using the Modelica language (Modelica Association 2024). The results unveiled a 69% reduction in energy consumption compared to a traditional four-pipe district system. Gautier et al. (2022) delved into the resilience potential of geothermal-coupled district energy systems in providing free cooling during heat waves. Their findings indicated that, by relying solely on waterside economizer cooling, indoor thermal comfort could be maintained within a tolerable range for most building zones, with half the cooling energy compared to standard chiller operation.

Jing Wang (jing.wang5@nrel.gov), Matt Mitchell (matt.mitchell@nrel.gov), and all other co-authors are researchers at the National Renewable Energy Laboratory, United States.

Additionally, Sommer et al. (2020) conducted a comparative analysis between a single-pipe reservoir network and a double-pipe network based on Modelica simulations. They concluded that the design and control of the single-pipe network play a pivotal role in achieving high energy efficiency.

Existing tools for community or urban scale energy system modeling and simulation are often limited in their capabilities or require expert-level modeling proficiency to couple tools of various domains. Many of them are focused on building energy modeling and do not provide district energy system modeling capabilities. EnergyPlus (Crawley et al. 2001) is an example of a building energy simulation platform focused on simulating the energy performance of a single building. Other tools, such as the Modelica Buildings Library (Wetter et al. 2014) and TRNSYS (TESS 2023) are component-based frameworks that let users connect disparate component models to create larger system models. However, the standalone building energy models and component-based model frameworks often require complex coupling by the users among different domain-specific tools to conduct a comprehensive system-level design and operational analysis. District energy simulation tools also typically lack geothermal heat exchanger (GHE) sizing capability, making it more difficult to be integrated into the district energy analysis. Therefore, the necessity exists to build an integrated platform for an efficient and holistic workflow to support the analysis of GHP integrated district energy systems.

To address the above-mentioned challenges, this work presents the development of a new holistic design and modeling capability to support the analysis of district-scale GHP systems. We base our workflow on URBANopt (NREL 2023; Polly et al. 2016; El Kontar et al. 2020), which is an open-source platform that integrates multiple physics-based building energy modeling platforms (EnergyPlus, OpenStudio, Spawn of EnergyPlus) and includes capabilities to analyze district-scale energy solutions. More specifically, the proposed new workflow allows users to input geometric and non-geometric information about the buildings and the borehole field. Then, utilizing the annual building energy simulation results, it automatically sizes the GHEs for the ground loop through a newly developed python package named “ThermalNetwork” (Mitchell et al. 2023), which uses the GHEDesigner python package (Spitler et al. 2022; Mitchell et al. 2023). Based on the design specifications of the GHEs, the new workflows then programmatically generate the district energy system model with the designed GHEs and building systems using the object-oriented modeling language, Modelica. That model can then be used to conduct various analyses. A case study will be presented in this paper to showcase the usage of this proposed modeling and simulation workflow.

PLATFORM ARCHITECTURE

This section describes the overall software architecture for sizing and modeling GHEs in a ground loop using URBANopt. The workflow for GHP analysis, shown in Figure 1 can be run using the URBANopt command line interface (CLI) that connects several underlying URBANopt modules to perform different analyses. An initial GeoJSON Feature File can be created using an open-source web tool and then used as an input in the analysis. It contains geometric information such as GHE and building footprints and pipe locations. Based on the initial file, additional properties for buildings then can be added such as building type, construction, HVAC system type, number of floors, etc. Based on these building inputs, and by leveraging intelligent defaults based on OpenStudio libraries, the URBANopt CLI generates timeseries building loads.

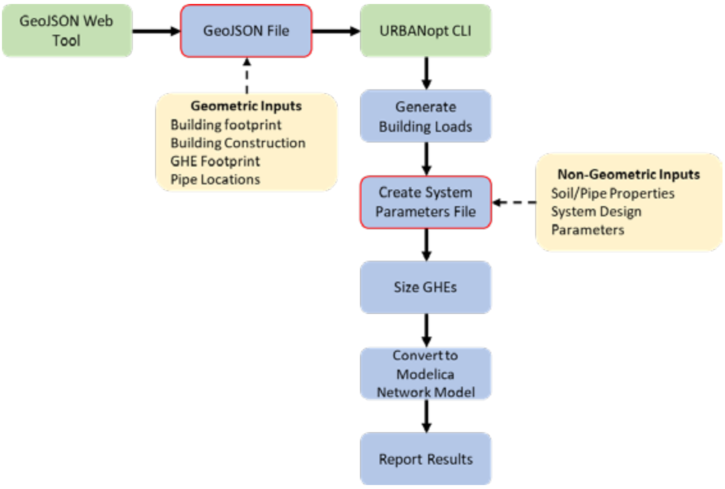

Figure 1 Schematic diagram of the platform architecture and data exchange flow.

The URBANopt CLI is then used to call the GeoJSON to Modelica Translator (GMT) repository (Long et al. 2021) to create a system parameters file. This file contains several non-geometric inputs that are used in the GHE sizing analysis. These include pipe, fluid, soil, and borehole properties. The system parameters file is populated with default values for all these properties that can be overwritten by users if site specific information is available. The file also contains GHE specific properties such as the dimensions of the GHE that are derived from the GeoJSON feature file. Currently only rectangular GHEs are supported. The building loads and system parameters file are passed on as inputs to the ThermalNetwork code that performs sizing calculations for the GHE distributed around the one-pipe network. The outputs from this analysis include the number and length of boreholes for each GHE. These values are written back to the updated system parameters file. G-function files for each sized GHE are also generated, which give the temperature response of the GHEs to the past and current heat rejection or extraction to or from the ground.

The URBANopt CLI then calls the GMT again to create a Modelica network model based on these sizing results. The GMT can programmatically generate a model of a district thermal energy system based on the GeoJSON input file and the system parameters file (Figure 2). With these two input files, Modelica template files are used to generate a complete Modelica package with the user's custom configuration. The new capability proposed in this paper introduces new GHE templates, system parameters, and capabilities that use the building loads and GHE sizing results to construct a complete package. The generated Modelica model can then be simulated using the URBANopt CLI, and results can be reported.

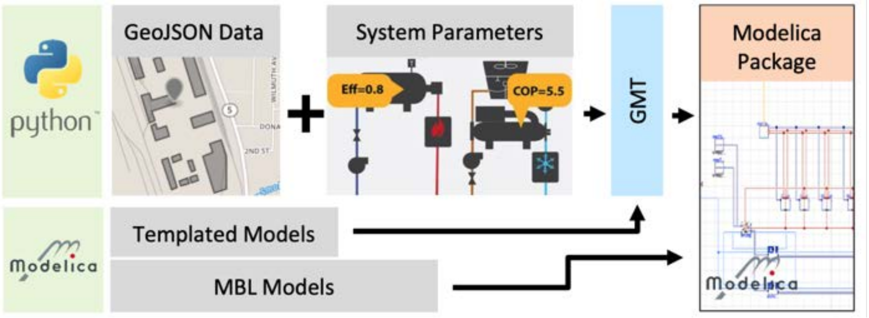

Figure 2 Diagram to demonstrate the GMT workflow.

SIZING NETWORKED GROUND HEAT EXCHANGERS

To size GHEs distributed around a single-pipe loop, a new software package was created named "ThermalNetwork."

The tool applies a heat pump model to convert the building's heating and cooling space loads to the heat pump's source-side network loads, aggregates the network loads for each building, distributes the network loads to each GHE on the network, sizes each GHE based on the distributed loads, and updates the system parameters file so the URBANopt CLI and GMT can generate a Modelica network model.

Through the URBANopt CLI, an OpenStudio measure is applied to process each building's sensible heating and cooling loads into an output file which can be processed by the ThermalNetwork code. Each building's annual hourly heating and cooling loads are assumed to be occurring simultaneously within each building, and thus the net heating and cooling space loads are used as the building's space load. Once the simultaneous space loads are determined, a constant-COP heat pump model is applied to convert the space loads to the network loads on the source side of the heat pump. A fixed COP of 3.5 is used for cooling, and a fixed COP of 2.5 is used for heating. Currently, the code used for GHE sizing (GHEDesigner) is not able to apply heat pump models which compute performance as a function of entering fluid temperature, however, we expect that this feature may be added in the future.

After the network loads for each building have been determined, the network loads for all buildings are aggregated together. Currently, the ThermalNetwork code can distribute loads using one of two approaches: "area proportional" and "upstream." The area proportional approach aggregates the annual hourly heating and cooling loads for all buildings connected to the one-pipe network. Once the total simultaneous heating and cooling loads for all buildings have been computed, the loads are distributed to each GHE proportional to its footprint area as a fraction of the total GHE footprint area connected to the network. This method has the advantage that it is simple to process, however, it may not be robust enough to properly size GHEs so that the loop fluid temperature entering each building remains within reasonable temperature limits.

The "upstream" load aggregation approach collects network loads from buildings which are immediately upstream of each GHE. Thus, network loads from buildings which are upstream of each GHE are expected to be fully served by the downstream GHE. This approach is expected to be more favorable for properly sizing GHEs based on the load from buildings which are near each GHE in the loop. However, the approach is more complicated and could require iteration, for example, if a downstream GHE does not have sufficient capacity to meet the upstream network loads. GHEDesigner and ThermalNetwork will need to be enhanced with improved error handling abilities to accommodate this situation. We have experimented with these approaches, but no conclusions have yet been made as to which yield sufficient performance, or if other methods or approaches should be developed.

After the network loads for each GHE have been determined and distributed, GHEDesigner is used to size each GHE. The system parameters file is then updated with the data from the sized GHE, including depth, number of boreholes, and G-functions. The Modelica network model is then generated dynamically based on the input data and is ready for simulation and analysis.

MODEL VALIDATION

To evaluate the performance of the workflow and the accuracy of the borefield model, a comparative testing validation case was built between the URBANopt GHP platform and EnergyPlus. We consider a two-by-two borefield hydronic loop with a constant annual cooling load of 10 kW. The same borefield configuration and input parameters were used in both EnergyPlus and the URBANopt workflows, and annual simulations were conducted with both tools. Table 1 lists the detailed configuration and inputs of the borefield validation simulation.

Table 1. Borefield Configuration and Input Parameters of the Validation Case

Parameter	Value	Unit
Borehole diameter	0.15	m
Borehole length	100	m
Borehole top depth	1	m
Design flow rate per borehole	0.001	m^3/s
Grout thermal conductivity	1	W/m-K
Grout thermal heat capacity	3.9E6	J/m^3-K
Pipe thermal conductivity	0.4	W/m-K
Pipe thermal heat capacity	1.77E6	J/m^3-K
Pipe outer diameter	0.03341	m
Pipe thickness	0.002984	m
U-tube distance	0.04913	m
Borehole type	Single u-tube	N/A
Soil thermal conductivity	2.5	W/m-K
Soil thermal heat capacity	2.5E6	J/m^3-K

The weather file used in the simulations is the Typical Meteorological Year 3 (TMY3) weather data for Chicago, Illinois. The G-function calculation method in EnergyPlus is UHFcalc (i.e., uniform heat flux boundary conditions). For the URBANopt GHP platform, the same external G-function file used by EnergyPlus is processed and then used by GMT in the generated GHE models. It should be noted that EnergyPlus uses the Kusuda-Achenbach model (Kusuda and Achenbach 1965) to calculate the undisturbed soil temperature. Whereas in the current form of our proposed workflow, the undisturbed soil temperature is set to a constant input by the user. We plan to integrate soil temperature prediction models in the URBANopt GHP workflow soon. Following are some validation result plots.

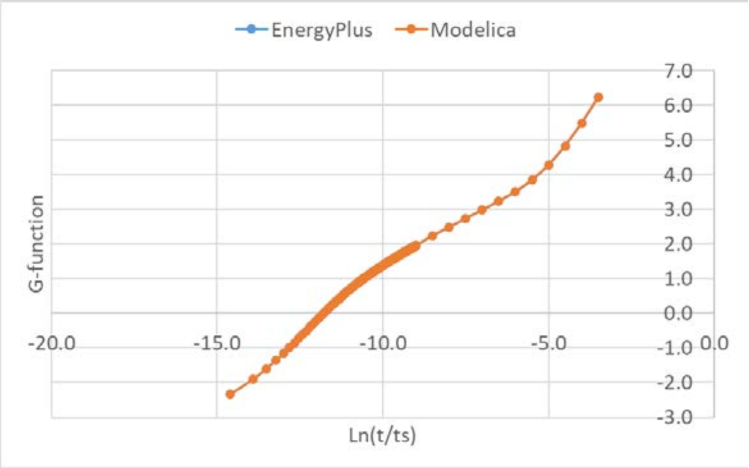

Figure 3 G-function comparison between EnergyPlus and Modelica.

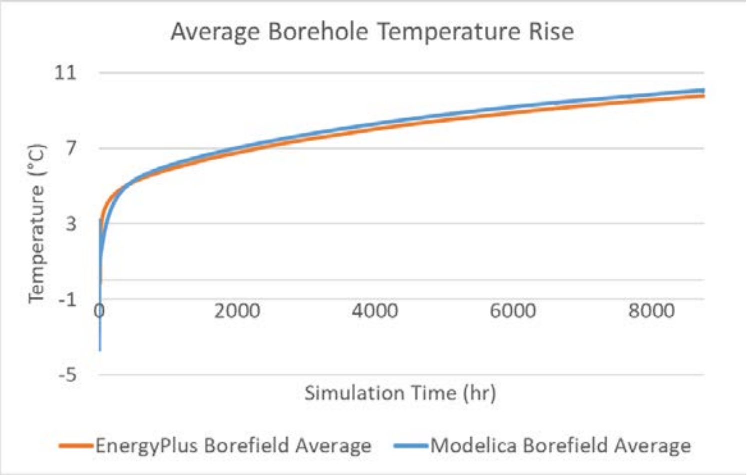

Figure 4 Borefield average borehole temperature rise comparison between EnergyPlus and Modelica.

Figure 3 shows a comparison between the G-function values used by EnergyPlus and the Modelica models generated through the proposed workflow. As mentioned before, the Modelica model G-function was converted from the same G-function file that EnergyPlus uses. In this figure, the Modelica G-function values are generated by reverse-converting the actually used G-function in the Modelica simulations. This leads to the two G-function curves aligning perfectly with each other, which is expected. This step makes sure the processing of the external G-function file is correct in the GMT workflow. Since the undisturbed soil temperatures in the two models are different, Figure 4 compares the average borehole temperature rises across the two tools, which is obtained by subtracting the corresponding undisturbed soil temperatures from the average borefield temperatures. For reference, the EnergyPlus soil temperature obtained from the Kusuda-Achenbach model lies between 15 to 16°C while Modelica uses a constant soil temperature of 18.3°C. The good alignment between the two temperature curves validates the accuracy of our GHE model against EnergyPlus.

CASE STUDY

This section presents a case study for a district energy system with one GHE and two buildings. The whole workflow of the proposed platform will be demonstrated, starting from the user inputs to the simulation outputs. Figure 5 depicts the GeoJSON file of a hypothetical community in Buffalo, NY, USA. We have two ten-story hospital buildings connected to a district geothermal heating and cooling loop. Building 1 has a footprint of 3,746 m^2 and is an outpatient health care facility. Building 2 has a footprint of 8,887 m^2 and is an inpatient health care facility, leading to different heating and cooling profiles between the two buildings. The designed area for the borefield is rectangular (232.5m×158.0m) with a total area of 3,413 m^2. Based on the footprints and other specific inputs about the buildings, URBANopt then creates OpenStudio models for each building based on DOE prototypical building models (DOE, 2023) and runs annual simulations. Here, the prototypical building models refer to a set of DOE developed standardized commercial and residential building models to represent typical new constructions in compliance with evolving building codes in different climate zones. Then the annual heating and cooling loads of each building can be used by the ThermalNetwork code to size the GHE.

Figure 5 GeoJSON file of the case study district visualized by geojson.io.

In addition to the geometric user inputs mentioned above, the non-geometric user inputs used in this case study are similar to those used in the model validation. Their detailed values are listed in Table 2 below. Based on the geometric and non-geometric inputs, the ThermalNetwork tool then sizes the GHE. Depending on the search algorithm used, the GHE sizing tool, GHEDesigner, uses a univariate or bi-variate bisection search algorithm to determine the number of boreholes required to meet the design temperature conditions. After selecting a GHE configuration which has sufficient boreholes to meet the design, but which is slightly oversized, the sizing tool then adjusts the borehole depth until the design conditions are met. The user configures the design parameters that constrain the search algorithms, such as by specifying the boundary size, max/min borehole depth, borehole to borehole spacing, etc., which the tool then uses as previously described to meet the design conditions. In this case, the borehole-to-borehole space should lie between 3 to 10 meters and the borehole length between 60 and 135 meters. Further, it is assumed that the heat pump entering fluid temperature is between 5°C and 35°C during the GHE sizing. The undisturbed soil temperature is constant at 18.3°C as discussed above. In this case study, based on 240 months of simulation, the GHE for the two hospital buildings is sized to have 50 boreholes, each of which has a length of 99.6 m.

Table 2. Borefield Configuration and Input Parameters of the Case Study

Parameter	Value	Unit
Borehole diameter	0.14	m
Borehole top depth	2	m
Design flow rate per borehole	0.0005	m^3/s
Grout thermal conductivity	1	W/m-K
Grout thermal heat capacity	3.901E6	J/m^3-K
Pipe thermal conductivity	0.4	W/m-K
Pipe thermal heat capacity	1.542E6	J/m^3-K
Pipe outer diameter	0.0400	m
Pipe inner diameter	0.0354	m
Shank spacing	0.0200	m
Borehole type	Single u-tube	N/A
Soil thermal conductivity	2	W/m-K
Soil thermal heat capacity	2.343E6	J/m^3-K

After the GHE has been sized, the information about the district loop, the borefield, and the building thermal loads are then adopted by GMT to generate the Modelica district energy system model. Figure 6 shows the diagram of the closed-loop district energy system model generated by Modelica for this case study. The GHE is placed upstream of the two buildings. A distribution pump circulates the water in the district loop. The variable-speed pump is controlled by the pump controller to maintain the loop water temperature within a certain range. Two temperature sensors measure the inlet and outlet temperatures of the borefield, assuming no heat is added to the loop by the pump. The loop nominal water mass flow rate is 25 kg/s. An annual simulation was run for the case study with the TMY3 weather data for Buffalo, NY.

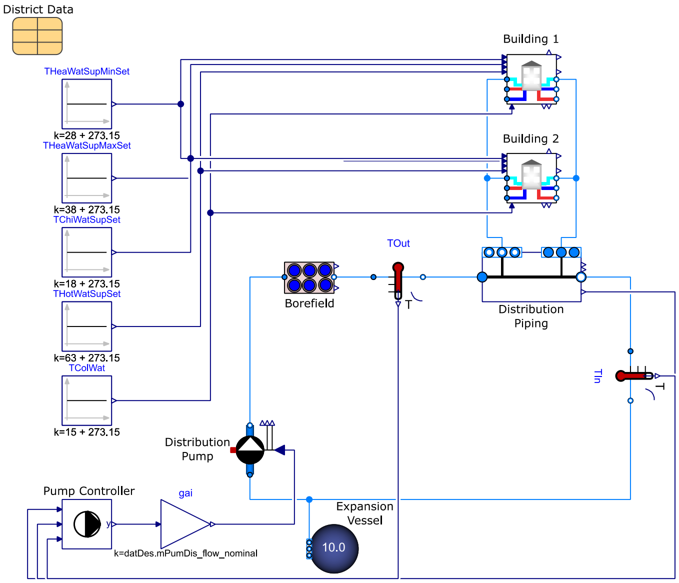

Figure 6 Modelica diagram of the generated district energy system model with one GHE and two buildings.

Figure 7 plots the simulated annual thermal loads for buildings 1 and 2 and the total heat flow from the soil. From the figure, we see that Building 1 is cooling dominant while Building 2 is heating dominant. This asynchronization of thermal loads leads to a smaller total loop load on the borefield as the building loads offset each other (i.e., one building removes heat from the loop while the other adds heat to the loop). Therefore, we see that during winter, the heat flow from the soil fluctuates with the total loop load varying between heating and cooling dominant.

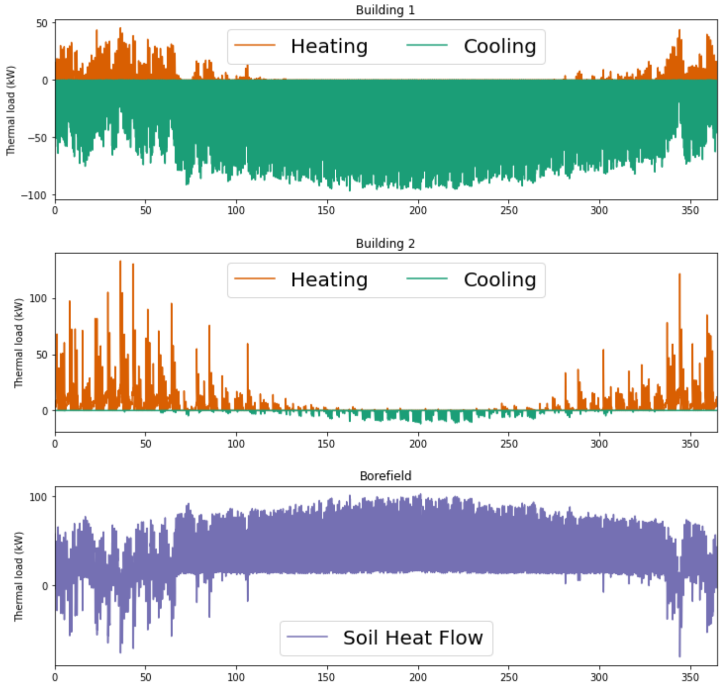

Figure 7 Annual plot for building thermal loads and borefield heat exchange flow with the soil.

Figure 8 shows the simulated annual borefield inlet, outlet, and average borehole wall temperatures. As indicated by the figure, the borefield inlet temperature is the highest among the three temperature trends and has the largest oscillations. The borefield average temperature lies within the 18°C to 21°C range with small variations annually. This helps to stabilize the borefield outlet temperature, which then feeds back to the buildings.

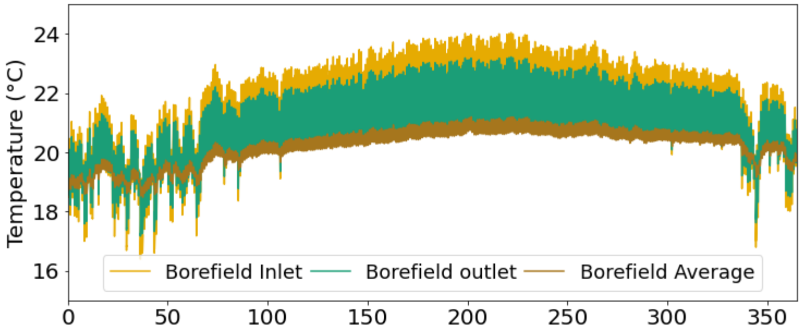

Figure 8 Annual plot for borefield inlet, outlet, and average borehole wall temperatures.

CONCLUSION

In this paper, we proposed a modeling and simulation platform for district energy systems with geothermal heat pumps. This platform is based on the URBANopt DES workflow and integrates a GHE sizing and data exchange tool - ThermalNetwork. In the proposed workflow, the users can specify geometric and non-geometric inputs related to the buildings, GHE, and district energy loop. Our platform sizes the GHE, generates a corresponding district energy system model, and runs an annual simulation automatically. We validated the borefield simulation performance in the proposed platform against EnergyPlus. In addition, a case study has been provided to showcase the proposed workflow. The simulation results discussed in the case study are plausible. This tool can be used by researchers and practitioners to facilitate their design and study of district energy systems with GHPs.

ACKNOWLEDGMENTS

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Geothermal Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NOMENCLATURE

CLI = Command Line Interface
COP = Coefficient of Performance
DOE = Department of Energy
GHE = Geothermal Heat Exchanger
GHP = Geothermal Heat Pump
GMT = GeoJSON to Modelica Translator
TMY3 = Typical Meteorological Year 3

REFERENCES

Abugabbara, Marwan, Saqib Javed, and Dennis Johansson. "A simulation model for the design and analysis of district systems with simultaneous heating and cooling demands." Energy 261 (2022): 125245.

Crawley, Drury B., Linda K. Lawrie, Frederick C. Winkelmann, Walter F. Buhl, Y. Joe Huang, Curtis O. Pedersen, Richard K. Strand et al. "EnergyPlus: creating a new-generation building energy simulation program." Energy and buildings 33, no. 4 (2001): 319-331.

Department of Energy (DOE). 2023. “Prototype Building Models.” https://www.energycodes.gov/prototype-building-models.

EIA. 2022. “U.S. Energy-Related Carbon Dioxide Emissions, 2021.”

EIA. 2023. “U.S. Energy Consumption by Source and Sector, 2022.”

El Kontar, Rawad, Benjamin Polly, Tanushree Charan, Katherine Fleming, Nathan Moore, Nicholas Long, and David Goldwasser. URBANopt: An open-source software development kit for community and urban district energy modeling. No. NREL/CP-5500-76781. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.

Gautier, Antoine, Michael Wetter, and Matthias Sulzer. "Resilient cooling through geothermal district energy system." Applied Energy 325 (2022): 119880.

Kusuda, Tamami, and Paul R. Achenbach. 1965. Earth Temperature and Thermal Diffusivity at Selected Stations in the United States. Vol. 71. National Bureau of Standards Gaithersburg, MD, USA.

Long, Nicholas, Antoine Gautier, Hagar Elarga, Amy Allen, Ted Summer, Lauren Klun, Nathan Moore, and Michael Wetter. Modeling district heating and cooling systems with URBANopt, GeoJSON to Modelica Translator, and the Modelica Buildings Library. Vol. 17. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2021.

Mitchell, Matt, Lee, Edwin, Spitler, Jeffrey, Borshon, Ishraque, Cook, Jonathan, Liu, Xiaobing, and West, Timothy. GHEDesigner [SWR-23-33]. Computer Software. https://github.com/BETSRG/GHEDesigner. USDOE Office of Energy Efficiency and Renewable Energy (EERE), Renewable Power Office. Geothermal Technologies Office. 28 Mar. 2023. Web. doi:10.11578/dc.20230406.4.

Mitchell, Matt, Ball, Brian, and Moore, Nathan. ThermalNetwork [SWR-23-101]. Computer Software. https://github.com/nrel/thermalNetwork. USDOE Office of Energy Efficiency and Renewable Energy (EERE), Renewable Power Office. Geothermal Technologies Office. 14 Nov. 2023. Web. doi:10.11578/dc.20231114.3.

Modelica Association. 2024. https://modelica.org/.

National Renewable Energy Laboratory (NREL). 2023. “URBANopt Advanced Analytics Platform.” https://www.nrel.gov/buildings/urbanopt.html.

Polly, Ben, Chuck Kutscher, Dan Macumber, Marjorie Schott, Shanti Pless, Bill Livingood, and Otto Van Geet. "From zero energy buildings to zero energy districts." Proceedings of the 2016 American council for an energy efficient economy summer study on energy efficiency in buildings, Pacific Grove, CA, USA (2016): 21-26.

Sommer, Tobias, Matthias Sulzer, Michael Wetter, Artem Sotnikov, Stefan Mennel, and Christoph Stettler. "The reservoir network: A new network topology for district heating and cooling." Energy 199 (2020): 117418.

Spitler, J.D., T.N. West and X. Liu. 2022. Ground Heat Exchanger Design Tool with RowWise Placement of Boreholes. IGSHPA Research Conference Proceedings. Pp. 53-60. Las Vegas. Dec. 6-8. https://doi.org/10.22488/okstate.22.000016

TESS. 2023. "Transient System Simulation Tool." Thermal Energy System Specialists. https://www.trnsys.com/

Wetter, Michael., Wangda Zuo, Thierry S. Nouidui, and Xiufeng Pang. 2014. “Modelica Buildings Library” Journal of Building Performance Simulation. 7(4): 253-270. https://doi.org/10.1080/19401493.2013.765506