Utilizing GEOPHIRES-X Beyond Electricity

Koenraad F. Beckers[1,*], Malcolm I. Ross[2]

[1] National Renewable Energy Laboratory, Golden, CO, USA

[2] Rothwell Group, Rice University, and the University of Texas Bureau of Economic Geology, Houston, TX, USA

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ABSTRACT

The GEOPHIRES tool is a techno-economic simulator for evaluating the thermal performance and cost-competitiveness of geothermal plants for electricity, heating, and/or cooling. The tool combines reservoir, wellbore, and surface plant cost and performance models to estimate overall techno-economic metrics such as net present value or levelized cost of electricity, heating, or cooling. We recently upgraded the tool to an object-oriented Python framework, presented in an accompanying paper. As part of the upgrade, we enhanced the capability to simulate the performance of geothermal plants for heating and cooling, which is the topic of this paper. Specifically, we (1) integrated absorption chillers to investigate the performance of utilizing geothermal heat for cooling, (2) integrated a heat pump module to boost the geothermal temperature and thermal output, (3) integrated a district heating module to estimate heating demand for a district based on local weather data, and simulated heat supply with geothermal energy and peaking boilers, and (4) integrated GEOPHIRES as an engine in the dGeo simulator to perform a geospatial analysis of geothermal district heating feasibility across a large region (e.g., a state or the entire United States) utilizing resource and thermal demand maps. This paper presents background information and case studies for several of these heating and cooling end-use options in GEOPHIRES.

1. Introduction

The GEOPHIRES simulation tool is a techno-economic Python-based model used to evaluate thermal and economic performance of a geothermal plant. The tool combines subsurface and wellbore models, surface plant models and cost correlations to calculate plant output (e.g., electricity, heating, cooling), estimate capital and operation and maintenance (O&M) costs, and evaluate techno-economic metrics such as levelized cost of electricity, levelized cost of heating (LCOH), and net present value. The tool can simulate various end uses for geothermal heat, including electricity production with a flash or organic Rankine cycle, direct-use heating and cooling, and co-generation. This paper presents an overview, background information, and case studies for several of the heating and cooling applications, including direct-use heating, heating combined with a heat pump, district heating with peaking boilers, and cooling with an absorption chiller.

The GEOPHIRES (“GEOthermal energy for Production of Heat and electricity (“IR”) Economically Simulated) tool was originally developed by Beckers et al. (2013; 2014) to investigate the feasibility of enhanced geothermal systems (EGS) for electricity generation and direct-use heating. It was upgraded by Beckers and McCabe in 2019 to Version 2 by converting the code from FORTRAN to Python, coupling with the TOUGH2 reservoir simulator, and upgrading the cost correlations. Recently, Ross and Beckers (2023) implemented several upgrades to GEOPHIRES, including converting the code to an object-oriented framework, including inline conversions of units and currencies, supporting several designs of closed-loop systems, integrating a new economic incentive and taxation program, and incorporating several new end uses. The latest iteration is launched as Version X (X for “extensible”), referring to the object-oriented structure which allows for easily integrating new modules and applications in the tool.

The objective of GEOPHIRES is to perform a high-level feasibility screening of a geothermal system during the early stages of a project. It has similarities to the GETEM tool (Mines, 2016; U.S. DOE, 2019), which was recently integrated into the System Advisor Model (SAM). Both tools have built-in models for simulating the subsurface reservoir, surface plant, and costs. However, GETEM’s focus is on power production, while GEOPHIRES allows simulating various end uses beyond electricity generation. Utilizing geothermal energy for heating and cooling applications instead of electricity generation has recently gained increased awareness and interest in the United States, especially in regions with lower-grade geothermal resources such as the eastern United States (U.S. DOE, 2019; Tester et al., 2021). This paper includes several case studies to demonstrate GEOPHIRES’ capabilities as well as to highlight various potential end uses of geothermal energy.

2. GEOPHIRES End Uses Beyond Electricity and Case Studies

Five different applications are discussed in this section: (1) direct-use heating, (2) direct-use heating with a centralized heat pump, (3) district heating with a peaking boiler, (4) cooling with an absorption chiller, and (5) GEOPHIRES coupling with the distributed market demand model dGen for geospatial analysis. For each application, background information and a case study are provided. The case study in the first three applications is a geothermal system at Cornell University, where earth-source heat for providing heating to the campus has been studied for several years, and a deep exploration well has recently been drilled (Tester et al., 2020; 2023).

2.1 Direct-Use Heating (Cornell University Case Study #1)

The simplest geothermal end use is utilizing the heat directly in a residential, commercial, industrial, or agricultural application. The surface equipment is less complex than a power plant, and relatively low heat-to-power conversion efficiencies are avoided. In the direct-use end-use option in GEOPHIRES, only a cost correlation and simple efficiency factor for a surface heat exchanger are considered as default (Beckers and McCabe, 2019); however, the user can manually adjust the costs and efficiency depending on the application considered.

This end-use option is applied to the Cornell University campus in Ithaca, New York. A recent deep exploration well (called Cornell University Borehole Observatory [CUBO]) was drilled to almost 3,000 m. Key CUBO results include that no or limited in-situ permeability was encountered, and therefore a potential geothermal reservoir may be an EGS-type reservoir with multiple fractures, created through multi-stage hydraulic stimulation. The calculated steady-state temperature based on temperature measurements after drilling is 81°C at 2,960 m depth, corresponding to a geothermal gradient of about 24°C/km. The stress field is transitional between reverse faulting and strike/slip faulting. A sketch of the envisioned fractured EGS reservoir is shown in Figure 1. A full list of simulation parameters used in the GEOPHIRES simulations for this case study (and the case studies in Sections 2.2 and 2.3) is provided in Table 1.

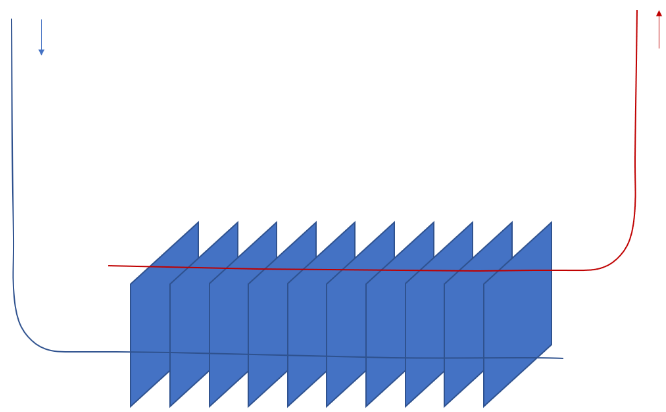

Figure 1: Simplified EGS reservoir considered in the Cornell University case studies (Sections 2.1, 2.2, and 2.3). The Gringarten et al. (1975) multiple parallel fractures model is selected to simulate the production temperature.

In an earlier phase of this project, we found that FALCON fracture thermal simulations are in good agreement with the Gringarten model (Gringarten et al., 1975), assuming uniform reservoir properties. Because we did not obtain data that characterizes 3D heterogeneity, we assumed uniform properties, and we selected the Gringarten model for reservoir simulations in GEOPHIRES. We assumed that a multi-stage hydraulic fracture job is conducted to create 32 fracture zones, with each fracture rectangularly shaped and measuring 300 m by 200 m. 32 fractures with 60,000 m^2 heat transfer area each resulted in a thermal decline of 10°C after 20 years (when operating at 50 kg/s), which we deemed tolerable. Given the rapid advancements in industry (e.g., by Fervo Energy) and FORGE, developing such discrete fracture networks may be possible today or in the near future.

Table 1: GEOPHIRES input parameters for the Cornell University case studies in Section 2.1 (Direct-Use Heating), Section 2.2 (Heating with Heat Pump) and Section 2.3 (District Heating with Peaking Boiler).

Parameter	Value		
	Direct-Use Heating (Section 2.1)	**Direct-Use Heating with Heat Pump (Section 2.2)**	**District Heating with Peaking Boiler (Section 2.3)**
Configuration	Doublet	Doublet with heat pump	Two doublets with peaking boiler
Reservoir depth	2,960 m (CUBO true vertical depth [TVD])		3,500 m
Reservoir initial temperature	81°C (CUBO calculated equilibrium bottom hole temperature [BHT])		94°C (extrapolated from CUBO)

Number of fractures	32		64 (32 for each doublet)
Fracture separation	50 m		
Fracture length (i.e., spacing between injection and production lateral)	300 m		
Fracture width	200 m		
Fracture geometry	Rectangular parallel fractures		
Reservoir model	Gringarten et al. (1975)		
Uniform rock thermal conductivity	2.83 W/m/K (best estimate based on earlier phase in Earth-Source Heat (ESH) project)		
Uniform rock specific heat capacity	825 J/kg/K (best estimate based on earlier phase in ESH project)		
Uniform rock density	2,730 kg/m^3 (best estimate based on earlier phase in ESH project)		
Wellbore model	Ramey		
Heat transfer fluid	Pure water		
Injection temperature	40°C	30°C	40°C
Flow rate per producer	50 kg/s		
Discount rate	7%		
Project lifetime	20 years		
Cost correlations	GEOPHIRES built-in		

In Case Study 1, we simulate a geothermal doublet to provide heating to the district heating system without a centralized heat pump. A doublet can operate at a large utilization factor (i.e., percentage of time the system is in operation at its nominal output) because at least 10 MW_{th} of heating is required year-round by the university (see Section 2.3). For surface equipment, only a heat exchanger is considered to transfer the geothermal heat to the district heating system circulating water. We assumed a utilization factor of 90% to allow for 10% downtime, e.g., for maintenance. Other key input parameters are listed in Table 1. For these conditions, the simulation results are provided in Table 2. The *GeoVision* drilling cost correlation for deviated small diameter open hole wells is considered (U.S. DOE, 2019), resulting in a cost of about $10M per well. Case Study 1 has a competitive LCOH of $15.2/MMBtu.

Table 2: GEOPHIRES simulation results for Case Study 1: Direct-Use Heating at Cornell University.

Parameter	Value
Average heat production	6.72 MW_{th}
Average annual heat delivery	53 GWh/year
Average production temperature	76°C
Doublet drilling and completion costs	20.4 MUSD
Stimulation costs	1.5 MUSD
Field gathering system cost	1.1 MUSD
Surface plant costs	2.6 MUSD
Total system capital cost	25.6 MUSD
Total system O&M cost	580 kUSD/year
LCOH	$15.2/MMBtu

2.2 Direct-Use Heating with Centralized Heat Pump (Cornell University Case Study #2)

A second end-use option is utilizing the geothermal heat coupled with an industrial-sized centralized heat pump to boost heat output and temperature. Different coupling configurations are possible, but GEOPHIRES considers the simplest configuration where the geofluid heat directly feeds the heat pump. A coefficient of performance (COP) is provided by the user or calculated with a built-in correlation based on the production temperature. The user can also provide the heat pump capital cost or utilize the built-in cost value (\$150/kW_{th} unloaded cost).

For a case study, we apply this end-use option in GEOPHIRES to the Cornell University example. Again, we consider one doublet but now a heat pump is utilized at the surface to extract additional heat from the geofluid. We manually set the heat pump COP to 4. The heat pump allowed us to lower the geofluid reinjection temperature. We selected a reinjection temperature of 30°C. The heat pump requires electricity to operate, and the overall O&M cost significantly depends on the electricity rate. We assumed an electricity rate of 7 cents/kWh. The utilization factor was lowered to 85% as the total heat production is larger than the minimum heat production required in summer. Other key parameter values are listed in Table 1. The results of this case study are provided in Table 3. In comparison with Scenario 1, the heat production almost doubled to over 11 MW_{th}; however, the system consumes on average 23.3 GWh of electricity per year.

Table 3: GEOPHIRES simulation results for Case Study 2: Direct-Use Heating with Centralized Heat Pump at Cornell University.

Parameter	Value
Average heat production	11.24 MW_{th}
Average annual heat delivery	84 GWh/year
Average geofluid production temperature	75°C
Doublet drilling and completion costs	20.4 MUSD
Stimulation costs	1.5 MUSD
Field gathering system cost	1.1 MUSD
Surface plant costs	5.7 MUSD
of which heat pump cost	2.4 MUSD
Total system capital cost	28.7 MUSD
Annual heat pump electricity demand	23.3 GWh/year
Annual heat pump electricity cost	1.6 MUSD/year
Total system O&M cost	2.3 MUSD/year
LCOH	\$16.4/MMBtu

2.3 Geothermal District Heating with Peaking Boilers (Cornell University Case Study #3)

Simulating geothermal energy coupled with peaking boilers to provide heating to a district is a new end-use option recently added into GEOPHIRES. The foundational work was developed by Walton (2022) in GEOPHIRES v2; A summary of Walton's (2022) model assumptions and capabilities follows. The district heating end-use model either utilizes a user-provided heat demand profile (with a CSV file) or estimates the district heat demand using built-in correlations. When relying on the built-in correlations, GEOPHIRES requires number of households in the community (or total community population), a typical meteorological year (TMY) weather file, and the U.S. census division where the community is located. Using the TMY dataset, GEOPHIRES calculates the heating degree days and coupled with EIA-provided space heating values (in kWh per household per heating degree day for each U.S. census division), calculates a heating demand profile. EIA-provided water heating demand data (in kWh per household for each U.S. census division) is added to the space heating profile to estimate total district heating demand profile throughout the year. Cost correlations based on district road length or district area and population density are built-in to estimate district network capital cost. Capital costs for peaking boilers are included, and a user-provided natural gas rate allows calculation of annual natural gas peaking fuel costs. District pumping costs are estimated as 2% of the annual heat demand multiplied with an electricity rate, based on a correlation by Molar-Cruz et al. (2022).

We apply this end-use option to the Cornell University campus. The reservoir field consists of two doublets, and reservoir depth was increased to 3.5 km to boost production temperature and increase total geothermal heat production. The bottom hole temperature in this scenario is 94°C, allowing heat to directly feed into the district heating system without requiring heat pumps. On days of high heat demand, heat from natural gas as peaking fuel is assumed to cover the difference. The natural gas rate for the peaking boilers was set to $8/MMBtu. A full list of key parameters is provided in Table 1. Campus heating demand is provided as input to GEOPHHIRES and is based on actual heat supply in 2016 and 2017. GEOPHIRES calculates for each day the geothermal and natural gas heat supply to cover the campus heating demand for that day (Figure 4). The GEOPHIRES simulation results are provided in Table 4. With two doublets, the annual geothermal heat supply is about 56% of the campus heating demand, and about 44% is covered by natural gas. This scenario allows the wells to operate at a utilization factor of about 88%. Additional well pairs can be considered, but this results in diminishing returns and a decrease in overall utilization factor. The LCOH of $12/MMBtu is relatively low, partially a result of a low natural gas price and 44% of the heat supplied by natural gas in this scenario.

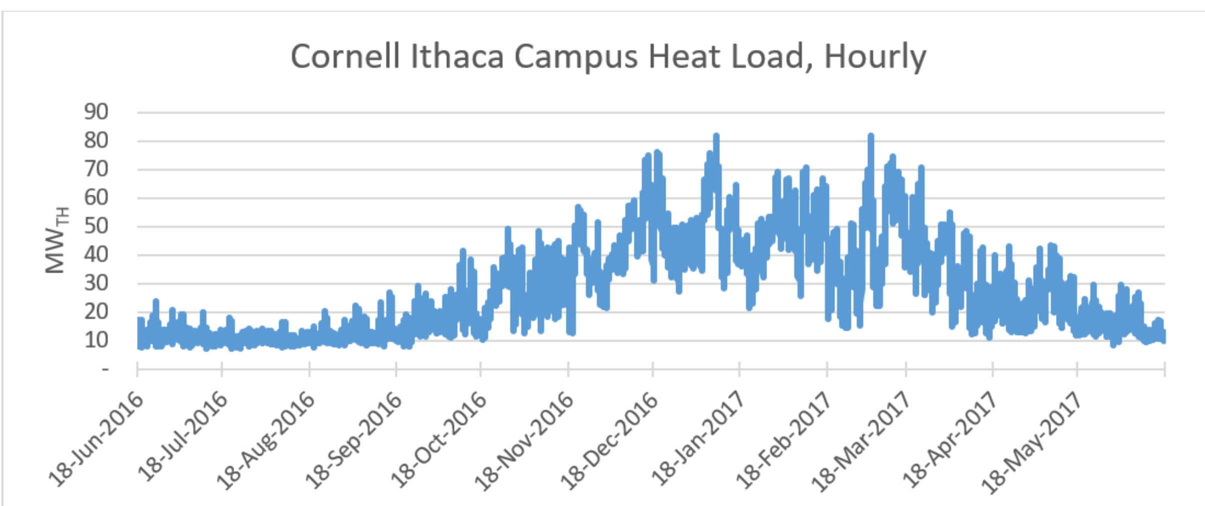

Figure 3: Cornell University hourly campus heating demand (in MW_{th}) provided as input to GEOPHIRES.

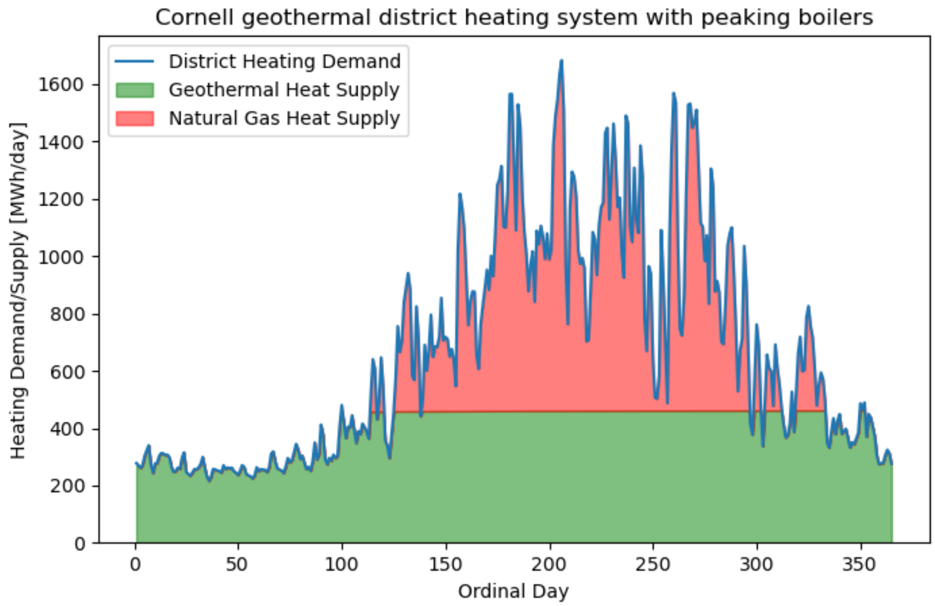

Figure 4: GEOPHIRES simulation result showing campus heat supply throughout the year of geothermal heat and peaking boiler heat (from natural gas).

Table 4: GEOPHIRES simulation results for Case Study 3: District Heating with Peaking Boiler at Cornell University

Parameter	Value
Annual district heating demand	243 GWh/year
Average annual geothermal delivered heat	137 GWh/year
Average annual peaking fuel delivered heat	106 GWh/year
Average geofluid production temperature	87°C
Wellfield drilling and completion costs	48.8 MUSD
Stimulation costs	3.0 MUSD
Field gathering system cost	2.1 MUSD
Surface plant costs	11.3 MUSD
of which peaking boiler cost	4.4 MUSD
Total system capital cost	65.2 MUSD
Average annual peaking fuel cost	3.4 MUSD/year
Total system O&M cost	4.8 MUSD/year
LCOH	12.0 $/MMBtu

The DOE-funded Wells of Opportunity Oklahoma project is another case study where this GEOPHIRES end-use model is applied to estimate feasibility of geothermal district heating in Tuttle City, Oklahoma, using 4 abandoned oil wells (Akar et al., 2023).

2.4 Cooling with Absorption Chiller

Recently, an absorption chiller module was built-in to GEOPHIRES to simulate chiller water production from geothermal heat and evaluate cooling output, investment cost, and levelized cost of cooling (Beckers et al., 2021). An absorption chiller utilizes a heat source to drive a refrigeration cycle and relies on a binary solution of refrigerant and absorbent. Two common solutions are water (refrigerant) and lithium bromide (absorbent), and ammonia (refrigerant) and water (absorbent). In the cooling cycle, the geothermal heat provides the thermal energy to boil the refrigerant out of the solution in the generator. After condensing, the refrigerant evaporates, which provides the useful cooling. Performance of the absorption chiller can be expressed with a COP, defined as the useful cooling divided by the thermal energy input. Different types of absorption chillers exist, including single-effect and double-effect absorption chillers. Single-effect chillers operate with a COP of around 0.75 for a heat supply of around 100°C, whereas double-effect chillers are best suited for higher heat supply temperatures and can reach COPs above 1 (Henning et al., 2006).

The absorption chiller module in GEOPHIRES requires as input a capital cost, an O&M cost, and a COP. The user can manually provide these values or rely on built-in correlations. The built-in default capital cost is $2,500/ton (unloaded), the built-in default annual O&M cost is 2% of the investment cost, and the built-in COP correlation is a correlation for a single-effect absorption chiller with COP ranging from about 0.6 to 0.78 for temperatures in the range 75°C to 150°C, and quickly dropping to 0 for temperature below 75°C (Henning et al., 2006).

The absorption chiller module was recently applied to a geothermal deep-direct-use case study investigating the feasibility of geothermal heat providing cooling for turbine inlet air at a chemical plant in Longview, Texas (Turchi et al., 2020; Beckers et al., 2021). Key parameters for this case study are listed in Table 5. Wellbore heat losses for the production well were calculated with Ramey's wellbore model. We considered the *GeoVision* "Intermediate 1" drilling cost correlation to estimate drilling costs, assuming technology improvements resulting in cost reductions. Using its built-in correlation, the GEOPHIRES simulation estimated the absorption chiller COP at about 0.74, the average cooling at 11 MW_{th}, and a levelized cost of cooling of roughly $20/MWh.

Table 4: GEOPHIRES input parameters for deep-direct-use absorption chiller case study.

Parameter	Value
Drilling Depth	2.7 km
Reservoir Temperature	120°C
Number of Wells	1 injector + 1 producer
Total Flow Rate	125 kg/s
Injectivity and Productivity Indices	5.5 kg/s/bar
Reservoir Thermal Drawdown	0.1% per year
Injection Temperature	88°C
Utilization Factor	90%
Plant Lifetime	30 years
Discount Rate	5%

2.5 dGeo – Distributed Geothermal Market Demand Model

A final example to illustrate GEOPHIRES' capability to be used as an engine in another simulator is the recent coupling we performed between dGeo and GEOPHIRES v3. The dGeo model—or Distributed Geothermal Market Demand Model—is a Python-based tool used to simulate nationwide (or regional) potential and adoption of geothermal energy (both shallow geothermal with heat pumps and deep direct use) for heating and cooling applications (McCabe et al., 2019). It is part of the National Renewable Energy Laboratory's (NREL's) dGen suite of tools (such as dSolar and dWind) and was developed in 2019 for the *GeoVision* study (U.S. DOE, 2019). dGeo has access to several geospatial datasets such as resource maps, thermal demand data, road lengths, current HVAC equipment, and energy costs, and can evaluate regional and nationwide geothermal feasibility for individual homeowners (using geothermal heat pumps) and district thermal networks (currently only with deep geothermal) at the county or census tract level. We recently integrated GEOPHIRES into dGeo to enhance dGeo's geothermal simulation capability, allowing for simulating various end uses (such as those discussed in Section 2.1 through 2.4) within dGeo. Beckers (2023) recently presented the updated tool and preliminary simulation results. New upgrades are currently being implemented into dGeo (including simulating ambient loop systems) and will be presented in a forthcoming publication.

3 Conclusions

The GEOPHIRES techno-economic simulation tool is a Python-based, open-source model for evaluating technical performance and cost-competitiveness of geothermal systems. It was recently upgraded to Version 3 by converting the code structure to an object-oriented framework and incorporating several new features, including inline conversion of units and currencies, support for several closed-loop geothermal designs, integration of a new economic incentive and taxation program, integration of a generic "add-on" module to easily account for addition of devices (for example direct air capture powered by geothermal), a heat-in-place resource assessment and statistical analysis module, and several new end uses including geothermal district heating combined with peaking boilers, geothermal coupled with heat pumps, and geothermal coupled with absorption chillers to provide cooling. These upgrades are documented in an accompanying paper (Ross and Beckers, 2023).

This paper focused on illustrating various non-electric end uses in GEOPHIRES to demonstrate its modeling capabilities and highlight the wide diversity of geothermal applications. Using the Cornell University case study—where deep geothermal resources are being explored to provide heating to the campus in Ithaca, New York—we investigated feasibility of using the geothermal heat directly (Case Study 1), coupled with a centralized heat pump (Case Study 2), and coupled with natural gas peaking boilers (Case Study 3). Based on CUBO well data, we estimate for Case Study 1 that a 3-km deep doublet with an EGS reservoir provides a thermal output on the order of 6 MW_{th} with an LCOH of about $15/MMBtu (considering only a surface heat exchanger for equipment to transfer the geothermal heat to the existing district heating network). When utilizing a centralized heat pump (Case Study 2), the thermal output can be increased to over 10 MW_{th}; however, that scenario required over 23 GWh of annual electricity consumption for the heat pump and resulted in a slightly higher LCOH. In Case Study 3, the campus thermal demand is provided as input to GEOPHIRES and the tool calculates throughout the year the amount of geothermal heat provided and the amount natural gas required for the peaking boilers. In the scenario with two 3.5-

km deep doublets, about 56% of the heat can be supplied by geothermal while still achieving a high well utilization factor of 88%. The LCOH for the total system (geothermal + peaking boilers) is relatively low ($12/MMBtu) in part due to the low natural gas price ($8/MMBtu) and significant amount of natural gas consumption in this scenario (44%). Drilling additional wells can lower the natural gas consumption but will decrease the geothermal well field utilization factor (as all the heating demand in the summer is already covered with two doublets) and increases the LCOH. A fourth case study illustrated simulating cooling with an absorption chiller in GEOPHIRES for a chemical plant in Texas. In this example, GEOPHIRES found that a doublet operating at 125 kg/s with production temperature of 120°C provides about 11 MW_{th} of cooling with an absorption chiller operating at a COP of 0.74. The corresponding levelized cost of cooling was about $20/MWh. Finally, in a fifth case study we discussed how GEOPHIRES was coupled as engine in the geospatial simulator dGeo, to evaluate feasibility and potential of shallow and deep geothermal for heating and cooling nationwide.

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REFERENCES

Akar, S., Oh, H., Beckers, K., Vivas, C., and Salehi, S. "Techno-Economic Analysis for a Potential Geothermal District Heating System in Tuttle City, Oklahoma" GRC Transactions, Vol. 47. 2023.

Beckers, K.F., Lukawski, M.Z, Reber, T.J., Anderson, B.J., Moore, M.C., and Tester, J.W. "Introducing GEOPHIRES v1.0: Software package for estimating levelized cost of electricity and/or heat from enhanced geothermal systems." In Proceedings, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (Vol. 11). 2013

Beckers, K.F., Lukawski, M.Z., Anderson, B.J., Moore, M.C. and Tester, J.W. "Levelized costs of electricity and direct-use heat from Enhanced Geothermal Systems." Journal of Renewable and Sustainable Energy, 6(1). 2014.

Beckers, K.F. and McCabe, K. "GEOPHIRES v2.0: updated geothermal techno-economic simulation tool." Geothermal Energy, 7(1), pp.1-28. 2019.

Beckers, K.F., Kolker, A., Pauling, H., McTigue, J.D. and Kesseli, D. "Evaluating the feasibility of geothermal deep direct-use in the United States." Energy conversion and management, 243, p.114335. 2021.

Beckers, K.F. "Introducing dGeo 2.0: updated distributed geothermal supply, demand and adoption model for evaluating potential of geothermal district heating and cooling systems" International District Energy Annual Meeting, June 5-8, Chicago, Illinois, USA. 2023.

Gringarten, A.C., Witherspoon, P.A., and Ohnishi. Y., 1975. "Theory of heat extraction from fractured hot dry rock." J Geophys Res. 1975;80(8):1120–4.

Henning, H., Häberle, A., Lodi, A. and Motta, M., "Solar cooling and refrigeration with high temperature lifts–thermodynamic background and technical solution." In Proc. Of 61st National ATI Congress, ATI-IIR International Session 'Solar Heating and Cooling', 14th September, 2006.

McCabe, K., Beckers, K.J., Young, K.R. and Blair, N.J., 2019. GeoVision Analysis Supporting Task Force Report: Thermal Applications. Quantifying Technical, Economic, and Market Potential of Geothermal District Heating Systems in the United States (No. NREL/TP-6A20-71715). National Renewable Energy Lab. (NREL), Golden, CO (United States).

Mines, G.L. "GETEM User Manual." Idaho National Laboratory, Idaho Falls, ID, USA, available from https://workingincaes.inl.gov/SiteAssets/CAES%20Files/FORGE/inl_ext-16-38751%20GETEM%20User%20Manual%20Final.pdf. 2016.

Molar-Cruz, A., Keim, M.F., Schifflechner, C., Loewer, M., Zosseder, K., Drews, M., Wieland, C., and Hamacher, T., "Techno- economic optimization of large-scale deep geothermal district heating systems with long-distance heat transport," J. Energy Conversion and Management 267, 2022.

Ross, M. and Beckers, K. "GEOPHIRES-X: An object-oriented update to GEOPHIRES2.0", GRC Transactions, Vol. 40, 2023.

Tester, J.W., Beyers, S., Gustafson, J.O., Jordan, T.E., Smith, J.D., Aswad, J.A., Beckers, K.F., Allmendinger, R., Brown, L., Horowitz, F. and May, D., 2020. District geothermal heating using EGS technology to meet carbon neutrality goals: a case study of earth source heat for the Cornell University campus. In Proceedings of the World Geothermal Congress (Vol. 1, No. 2020, p. 1).

Tester, J.W., Beckers, K.F., Hawkins, A.J. and Lukawski, M.Z., 2021. The evolving role of geothermal energy for decarbonizing the United States. Energy & Environmental Science, 14(12), pp.6211-6241.

Tester, J., Gustafson, J.O., Fulton, P., Jordan, T., Beckers, K. and Beyers, S., 2023. Geothermal direct use for decarbonization—progress towards demonstrating Earth Source Heat at Cornell. In Proceedings, 41st Workshop on Geothermal Reservoir Engineering: Stanford, California, Stanford University.

Turchi, C.S., McTigue, J.D.P., Akar, S., Beckers, K.J., Richards, M., Chickering, C., Batir, J., Schumann, H., Tillman, T. and Slivensky, D., 2020. Geothermal Deep Direct Use for Turbine Inlet Cooling in East Texas (No. NREL/TP-5500-74990). National Renewable Energy Lab. (NREL), Golden, CO (United States).

U.S. DOE – United States Department of Energy. "GeoVision Full Report." 2019. Available from: https://www.energy.gov/eere/geothermal/geovision.

Walton, C. "Techno-Economic Simulations of Geothermal District Heating Systems with GEOPHIRES", Office of Science, Science Undergraduate Laboratory Internship Program, Final Report. 2022.