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Socio-Techno-Economic Feasibility of Deep Geothermal With EGS for Residential District Heating in the Northeastern United States

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ABSTRACT

In this paper, we present socio-techno-economic simulation results for enhanced geothermal system (EGS) district heating systems in the northeastern United States. We applied the geospatial Distributed Geothermal Market Demand (dGeo) tool coupled with GEOPHIRES to evaluate the feasibility of geothermal deep direct-use, utilizing EGS reservoirs for providing residential heating with district heating systems. The results were combined with JEDI results to assess social impacts. Simulation results assuming doublet EGS reservoirs with target production temperature of 80°C and newly constructed district heating systems indicate a wide range in system levelized cost of heat (LCOH) values ranging from ~$15/MMBtu to over $1,000/MMBtu, with most the attractive regions urban areas with high total thermal demand and high thermal demand density. We estimate about 60 GW_{th} in potential installed capacity with LCOH values under $50/MMBtu and 100 GW_{th} in potential capacity with LCOH values under $100/MMBtu, respectively.

1. INTRODUCTION

Recently, there has been increased interest in the United States in utilizing geothermal energy for low-temperature district heating and cooling applications. Various types of geothermal district energy systems exist, depending on factors like geothermal resource type, distribution and supply temperatures, wellbore depth, system size, and whether heat pump equipment is used (Robins et al., 2021). One category of systems exploits deeper (e.g., multiple kilometers depth) geothermal resources to produce relatively high-temperature geothermal energy (e.g., ~80°C) serving district heating systems. Examples include the Boise district heating system in operation now over 100 years (Tester et al., 2016) and the Cornell Earth Source heat project, developing a 3-km-deep enhanced geothermal system (EGS) reservoir for heating the university's main campus in upstate New York (Fulton et al., 2024). Another category of systems utilizes a shallow (e.g., 100-m depth) geothermal borehole field to provide a thermal source/sink at stable temperature for providing heating and cooling to a district with heat pumps. Older generation systems (e.g., the Ball State University geothermal system (Oh and Beckers, 2023)) utilize both supply and return lines and have the geothermal field as main or sole thermal mass. Latest-generation systems, such as thermal energy networks or ambient temperature loops, utilize only a single distribution loop that operates at near-ambient temperature, target mixing various heating/cooling loads and sources, and have the geothermal field balancing the circulating fluid temperature. In this study, given the recent successes and advances in EGS technologies and cost reductions in deep drilling, we focused on more traditional, deep, and high-temperature geothermal district heating systems with the geothermal heat extracted using EGS reservoirs.

The goal of this study is to conduct a high-level socio-techno-economic feasibility assessment of geothermal deep direct use combined with EGS in the northeastern United States. We focused on this region due to its high thermal demand, high population density, relatively high energy prices, and its identification in the DOE (2019) GeoVision study as having significant potential for geothermal district energy. Our analysis expands on the GeoVision study by using the Distributed Geothermal Market Demand (dGeo) tool and incorporating its recent integration with GEOPHIRES, which enables EGS simulations using the Gringarten et al. (1975) model. Additionally, several updates were made to the dGeo datasets, such as incorporating latest vintages of energy demand data, energy prices, geothermal resource data, and road length information (Beckers et al., 2024). Our simulations also included the latest drilling cost estimates and were performed at the census-tract level, rather than the county level, to better reflect the typical scale of geothermal district heating systems.

Methodology of this study is provided in Section 2, including a discussion on the dGeo-GEOPHIRES tool, geospatial datasets utilized, EGS reservoir model considered, and our approach to sizing the distribution network and hybridizing the system with peaking boilers. A list of technical, economic, and financial modeling assumptions is provided in Section 3. Simulation results are presented and discussed in Section 4. The results are presented with a map of levelized cost of heat (LCOH) by census tract, a geothermal district heating supply curve, and a table listing statewide GW_{th} potential numbers. Finally, overall conclusions are presented in Section 5.

2. METHODS

We leveraged NREL's dGeo tool with its coupling to GEOPHIRES to evaluate the socio-techno-economic potential of geothermal deep direct-use for district heating at the census-tract level in northeastern United States. We considered an EGS type reservoir hybridized with a natural gas-fired peaking boiler providing heating with a distribution network to residential homes. Geothermal resource maps were utilized to estimate local geothermal gradient and required drilling depths. Road lengths were used as proxies to size distribution network length. Thermal demand datasets were utilized to estimate local demand for space heating. The different components of our simulation workflow and corresponding data source are discussed in more detail in the following sections.

2.1 dGeo Model

The dGeo tool is an agent-based modeling tool to evaluate nationwide potential of shallow geothermal heat pump systems and deep direct-use systems for providing heating and cooling to individual buildings and districts in the residential and commercial sector. The dGeo tool (Gleason et al., 2017) is part of NREL's distributed generation market demand models (dGen), which includes dSolar and dWind. The dGeo tool was originally developed for the GeoVision study (DOE, 2019), evaluating the potential for geothermal heat pumps in individual buildings (Liu et al., 2019) and deep direct use for residential district heating systems (McCabe et al., 2019).

Several upgrades were recently implemented to dGeo, including: (1) incorporating an ambient temperature loop module; (2) coupling with GEOPHIRES to allow simulating more advanced deep geothermal systems; (3) updating to the 2020 census tract framework; and (4) updating to the latest vintages of the U.S. Energy Information Administration energy demand datasets and Annual Energy Outlook energy price projections. In this project, we leveraged the dGeo-GEOPHIRES coupling to utilize dGeo's census tract-based geospatial datasets (subsurface temperature, thermal demand, road lengths, etc.) combined with GEOPHIRES EGS district heating simulation capability (i.e., utilizing the Gringarten subsurface model and the district heating surface model) to perform a high-level feasibility assessment for the Northeast.

2.2 Region of Study and Geospatial Granularity

Our region of study is the northeastern United States, comprising nine states: Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont (Figure 1). We focused on the Northeast due to its combination of high population density, colder climates, high heat demand, and relatively high energy prices, all favoring techno-economic performance of geothermal district heating systems, as identified in the GeoVision study (Figure 4–7; DOE, 2019).

The granularity of our study is the census-tract level (Figure 1) as most datasets incorporated into dGeo are at the census-tract level. In addition, the typical population of a census tract falls in the range 1,200 to 8,000, corresponding to a medium-sized district heating system with heating capacity on the order of a few MW_{th}, in line with typical heat output of a geothermal production well (Robins et al., 2021).

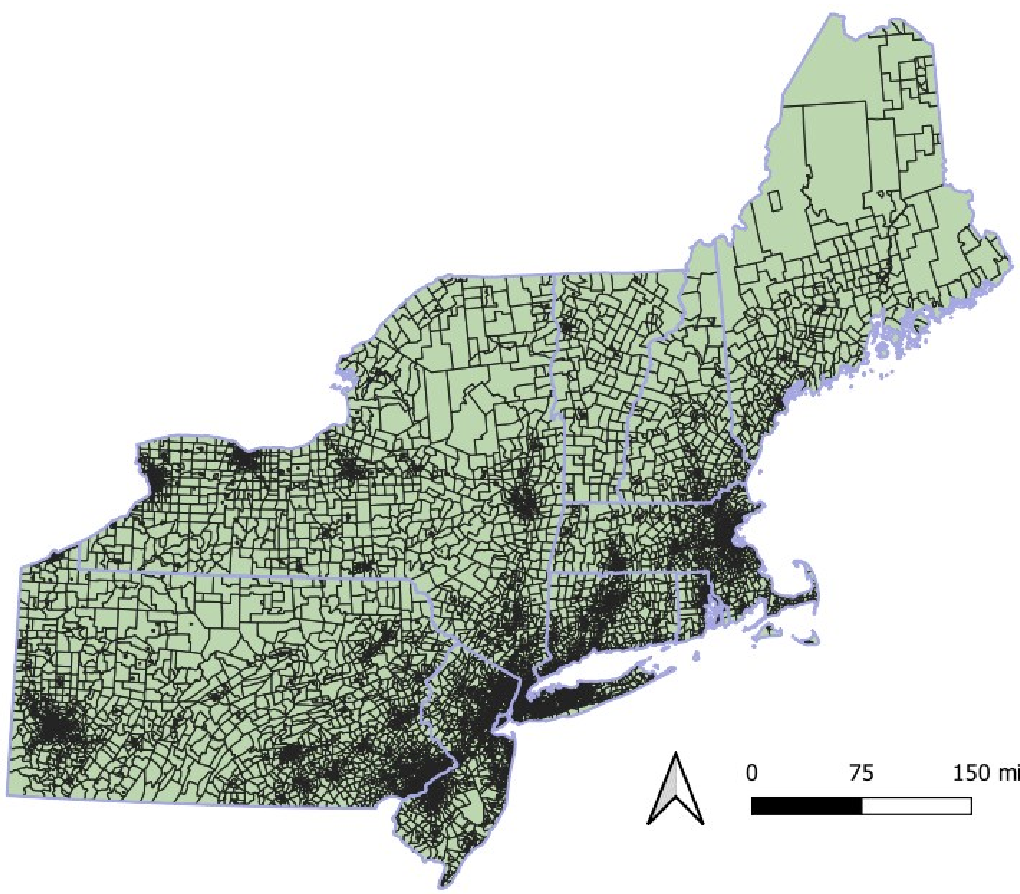


Figure 1: Northeastern states considered in this study (outlined in purple) with census tracts shown.

2.3 Subsurface Model

For each census tract, we sized an EGS reservoir to provide baseload heating to the residential sector in that census tract. The EGS reservoirs considered assume a doublet-style configuration with long horizontal laterals and vertical fractures (Figure 2), comparable to the designs developed by FORGE (Xing et al., 2024) and Fervo (Norbeck et al., 2024). We applied the Gringarten et al. (1975) multiple parallel fractures model incorporated in GEOPHIRES to size the EGS reservoir in each census tract. Assuming a fracture cluster spacing of 20 m, we sized the required number of fracture clusters and total lateral length to limit the decline in heat production to approximately 20% after 20 years of operation. The flow rate was set to 40 kg/s, a conservative value in comparison to the much higher flow rate obtained by Fervo at Project Cape. In this study, we did not consider the local stress field, which may be a reverse stress regime, hindering development of vertical fractures and likely requiring a different EGS design. We also did not consider water loss rate, assuming 100% of the injected water is recovered in the production well. Initial EGS circulation tests by FORGE and Fervo indicate recovery rates less than 100%; however, over time, the recovery rate increases and different EGS designs have been considered (e.g., a well field of alternating injection and production wells) to further increase recovery rates.

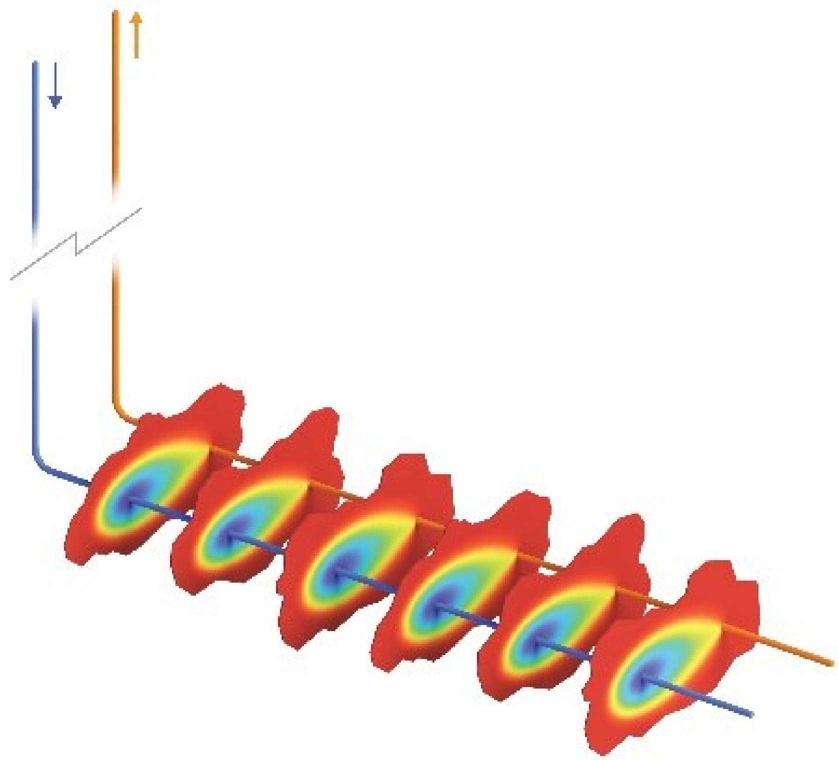


Figure 2: Doublet EGS designs considered for each district heating system at each census tract. Source: NREL

Various EGS district heating configurations are possible. In this study, we targeted reservoir depths to obtain EGS production temperatures on the order of 80°C for direct utilization of the heat (i.e., without use of heat pumps) at the surface. We leveraged the Stanford Temperature Model developed by Aljubran and Horne (2024) to estimate required drilling depths. For example, at 3.5 km depth (Figure 3), expected subsurface temperatures are on the order of 80°C for most of the Northeast, with colder temperatures in the northern regions and several “hot spots” with higher temperatures in Connecticut, Pennsylvania, New Jersey, Vermont, and Long Island. The reinjection temperature assumed is 40°C (the lowest temperature reasonably achievable when providing heat for residential heating without using a heat pump). Section 2.5 discusses how the subsurface system is coupled with peaking boilers at the surface to supply the census tract heat demand.

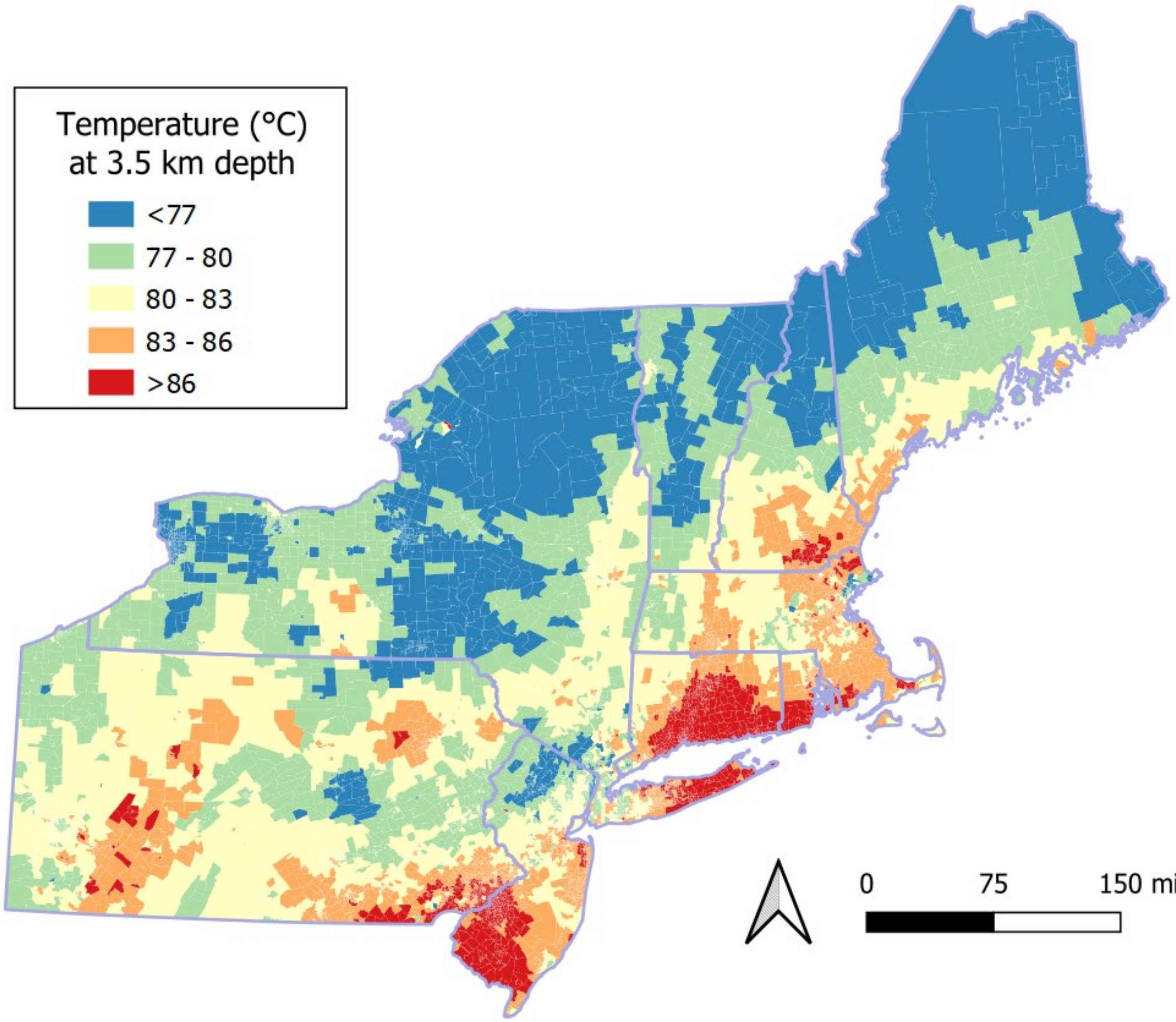
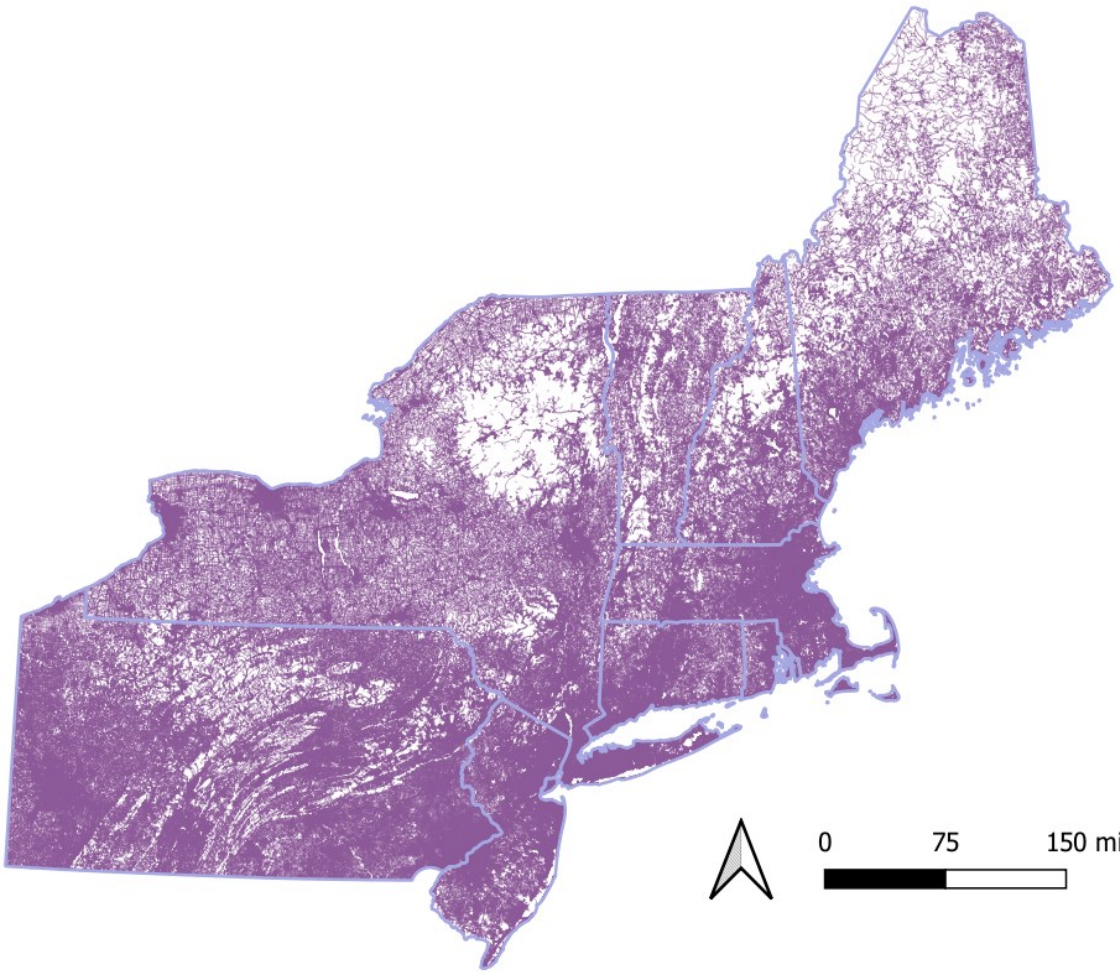


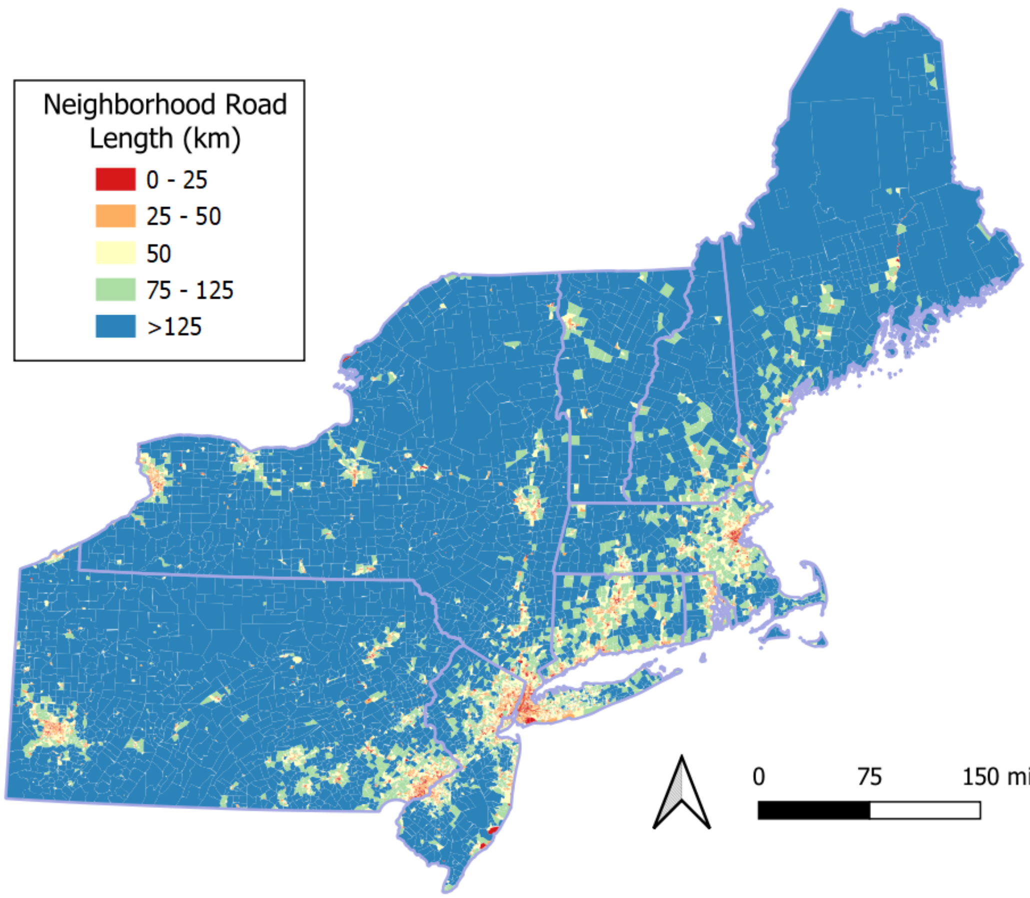
Figure 3: Subsurface temperature (°C) at 3.5 km depth as estimated by Stanford Temperature Model (Aljubran and Horne, 2024).

2.4 Distribution Piping Network

District heating systems have significant costs associated with the piping distribution network. As a proxy, the distribution network cost is a function of the distribution piping length, which scales with the road length of the community served. In this study, we estimated the road lengths in each census tract based on the S1400 road category of the U.S. census TIGER dataset (Figure 4). The S1400 roads are defined as "Local Neighborhood Road, Rural Road, City Street" (Census, 2023). This excludes S1100 roads, which are "primary roads" or limited-access highways, and S1200 roads, which are secondary roads, also representing main arteries. We followed Reber's (2013) approach in sizing the distribution network based on 75% of the road length. In addition, the maximum allowable distribution piping length was set to 7.5 km for each square kilometer of land in the census tract. Individual components of the distribution network (e.g., circulation pumps, heat exchangers, etc.) are not simulated. Instead, the district heating module in GEOPHIRES (Beckers and Malcolm, 2024) applied in this analysis assumes high level capital cost and operating & maintenance costs for installing and running the distribution piping network.



(a)



(b)

Figure 4: (a) Neighborhood roads and (b) neighborhood road length by census tract. Neighborhood roads represent S1400 roads from the U.S. Census TIGER dataset (Census, 2022).

2.5 Hybridization With Natural Gas-Fired Boilers

We applied GEOPHIRES' district heating module within dGeo to simulate a district heating system hybridized with natural gas-fired peaking boilers. During agent generation in dGeo, annual heating demand is estimated for each census tract based on state total heating demand from the U.S. Energy Information Agency Residential Energy Consumption Survey datasets (EIA, 2020) combined with the number of housing units in each census tract. The annual heating demand is converted to daily heating demand based on normalized heat demand profiles generated by Typical Meteorological Year 3 weather data. The daily heating demand is provided as input to GEOPHIRES and used for calculating heat supply from geothermal and heat supply from natural gas with peaking boilers (Figure 5). The maximum amount of heat geothermal can supply is based on a user-provided well flow rate and the production temperature.

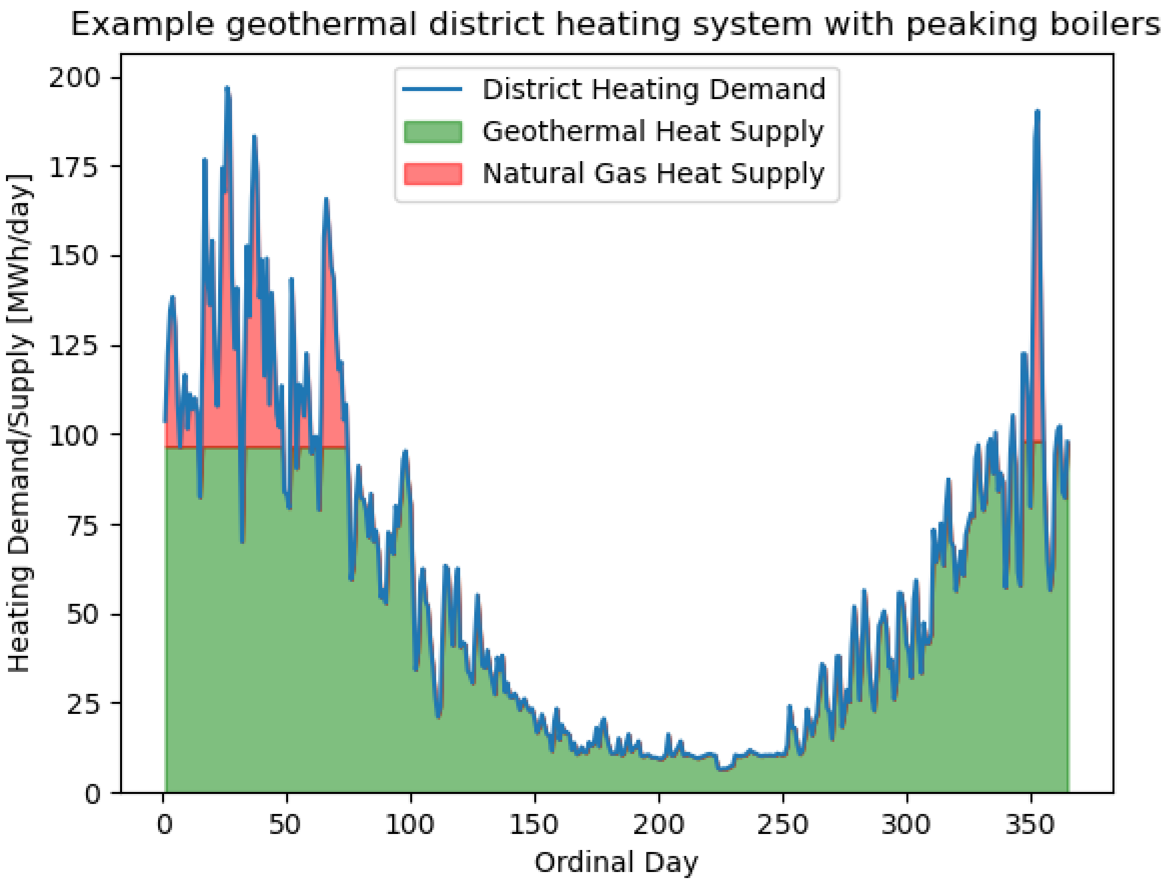


Figure 5: Example heat demand and supply profile for district heating system with peaking boilers. Geothermal supplies baseload heating while natural gas-fired boilers supply peak heating.

3. DGEO-GEOPHIRES SIMULATION ASSUMPTIONS

Within dGeo, the GEOPHIRES tool was applied to each census tract to simulate a hybrid geothermal district heating system supplying heating to the residential buildings within the census tract. The simulation assumptions are listed in Table 1. We considered a doublet EGS reservoir with horizontal laterals with one doublet per 50 GWh of tract annual heat demand. Census tracts with annual heat demand of less than 5 GWh were excluded. Future analysis could consider combining small, neighboring census tracts to be served by a single district heating system. The Gringarten model was applied to simulate the temperature profile over a 20-year lifetime for an EGS reservoir. The number of vertical fractures was set to 120 and corresponding lateral length to 2.4 km, which yields a reduction in heat output of 20% after 20 years when considering a fracture spacing of 20 m, total flow rate of 40 kg/s, injection temperature of 40°C, and effective heat transfer area per fracture of 25,600 m^2. For every simulation, we estimated the vertical depth to obtain a bottom hole temperature of 80°C. Wellbore heat losses in the production well were estimated with Ramey's wellbore heat transmission model. Total pressure drop and pumping power were estimated assuming a uniform 8-inch internal diameter for both injection and production well, and reservoir impedance of 0.005 GPa/(m^3/s). Drilling costs were estimated based on $1,000/m which corresponds to Fervo Energy's recent drilling costs (El-Sadi et al., 2024). As described in Section 2.4, the distribution network length scales with the census tract total neighborhood road length, with the distribution piping costs estimated at $1,200/m (Beckers et al., 2024). Reservoir stimulation costs were estimated at $5 million/doublet, and exploration costs were omitted. The LCOH was estimated assuming a 20-year lifetime and 7% discount rate. We did not consider any financial incentives such as tax credits or grants.

Table 1: List of GEOPHIRES assumptions for each census tract district heating simulation.

Parameter	Value
Well configuration	Doublet with horizontal laterals
Number of doublets	1 doublet per 50 GWh of census tract annual heat demand
Well vertical depth	Depth where bottom-hole temperature is 80°C
Lateral length	2.4 km
Bottom-hole temperature	80°C
Production well flow rate	40 kg/s
Effective heat transfer area per fracture	25,600 m^2 per fracture (160 m by 160 m)
Number of fractures	120

Fracture spacing	20 m
Rock thermal conductivity	2.8 W/m/K
Rock density	2,700 kg/m^3
Rock specific heat capacity	800 J/kg/K
Reservoir impedance	0.005 GPa/(m^3/s)
Injection well diameter	8 inches (assumed uniform along wellbore)
Production well diameter	8 inches (assumed uniform along wellbore)
Production wellbore heat transmission model	Ramey wellbore heat transmission model
Circulation pump efficiency	80%
Peaking boiler efficiency	85%
End-use efficiency	90%
Reinjection temperature	40°C
Distribution network length	Based on census tract neighborhood road lengths (see Section 2.4)
Drilling costs	$1,000/m (based on recent Fervo drilling costs)
Reservoir stimulation cost	$5 million per doublet
Distribution network costs	$1,200/m
Exploration cost	$0
Peaking boiler cost	\$65/kW$_{th}$ (based on peaking boiler peak heat supply)
Surface plant cost	\$322/kW$_{th}$ (based on peak total heat supply)
Electricity rate	Based on Annual Energy Outlook 2023 Reference Scenario
Natural gas rate	Based on Annual Energy Outlook 2023 Reference Scenario
Discount rate	7%
Lifetime	20 years

4. DGEO-GEOPHIRES SIMULATION RESULTS AND DISCUSSION

Figure 6 shows the dGeo-GEOPHIRES simulation results for the LCOH for each census tract geothermal district heating system. The map is color-coded, with warmer colors representing lower LCOH values and colder colors higher LCOH values, respectively. Census tracts shown in gray indicate they were excluded from the simulation run, in most cases due to their annual thermal demand not meeting the lower limit of 5 GWh per year. The LCOH calculation includes the capital cost of the distribution network, in most cases the biggest cost item in the life cycle cost calculation. For areas with an existing district heating system, the LCOH calculation is likely an overestimate in case the existing system can readily be converted to geothermal. Systems with lower LCOH values tend to correspond to more urban areas, including near major cities such as New York City, Pittsburgh, Philadelphia, and Buffalo, as urban areas have higher thermal demand density and need a relatively smaller size for the distribution network than rural areas.

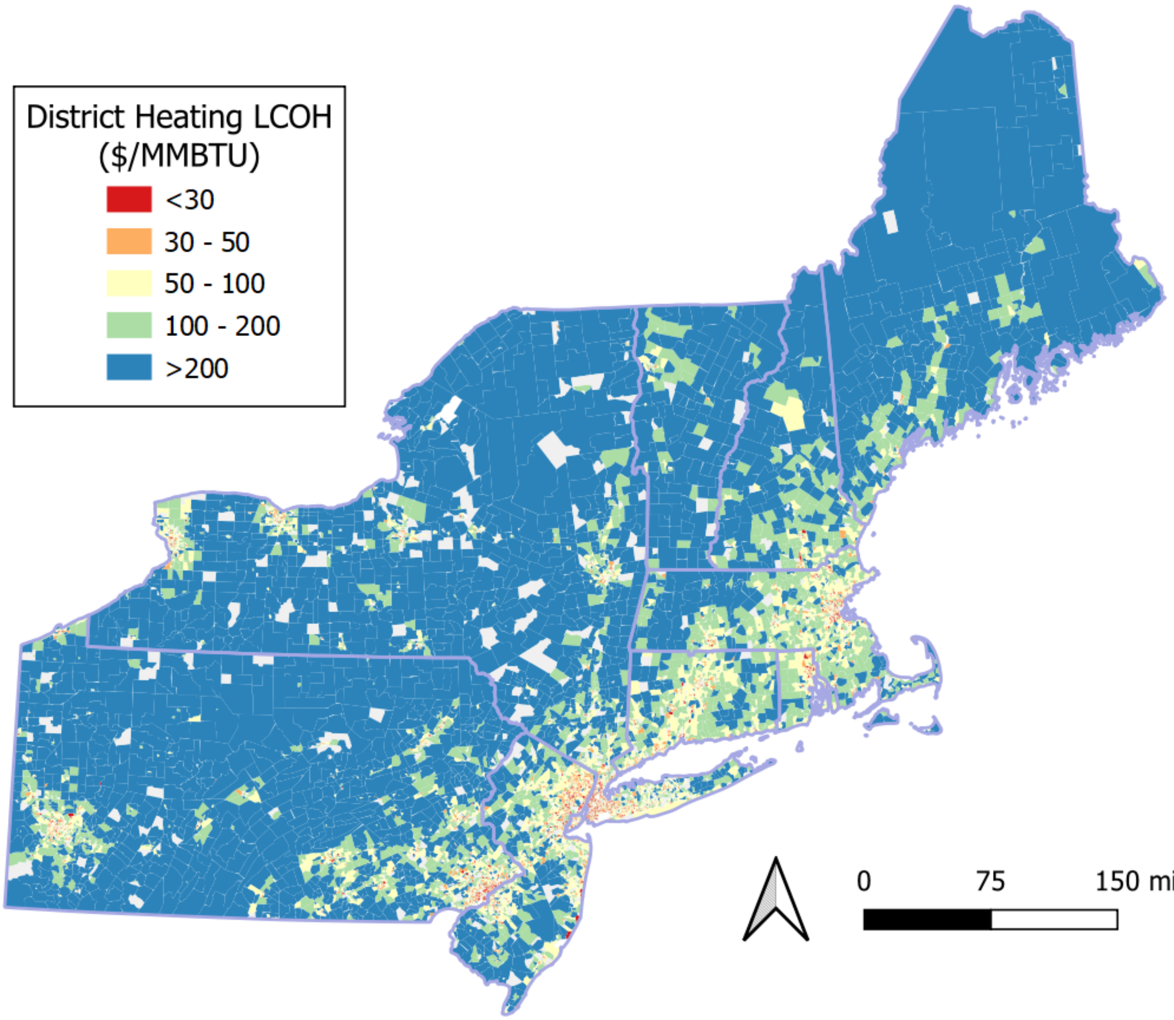


Figure 6: LCOH in $/MMBTU for EGS-based geothermal district heating systems by census tract.

Figure 7 shows a supply curve for all geothermal district heating systems in the Northeast, ranking the systems by LCOH, with capacity representing the total capacity of the systems (geothermal plus peaking boiler). The supply curve indicates roughly 60 GW_{th} in district heating capacity can be developed with an LCOH less than $50/MMBtu, and roughly 100 GW_{th} with an LCOH less than $100/MMBtu. Table 2 lists the total capacity by state with LCOH values under $50/MMBtu and $100/MMBtu.

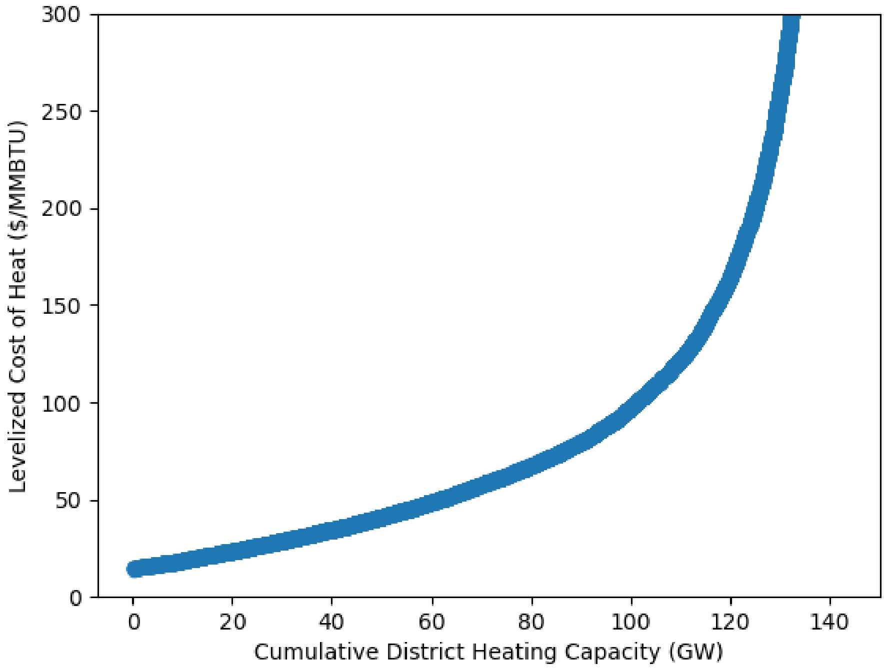


Figure 7: Supply curve for geothermal district heating systems in the Northeast.

Table 2: Total geothermal district heating capacity by state with LCOH values less than $50/MMBtu and $100/MMBtu.

State	**Total Capacity (GW_{th}) With LCOH Under $50/MMBtu**	**Total Capacity (GW_{th}) With LCOH Under $100/MMBtu**
Connecticut	2.6	6.5
Massachusetts	6.1	11.9
Maine	0.3	0.7
New Hampshire	0.5	1.2
New Jersey	14.5	23.8
New York	25.7	35.4
Pennsylvania	10.5	19.0
Rhode Island	1.2	2.3
Vermont	0.2	0.4

We applied the findings by the GeoVision Task Force Report on Impacts (Millstein et al., 2019) to evaluate the impact of deep geothermal district heating systems on local construction jobs and capital expenditures. Millstein et al. (2019) utilized the JEDI tool and estimated job creation during construction is on average about 7.5 jobs per MWth installed capacity, and estimated capital expenditures are in the range $1,000 to $1,500 per kW_{th} installed capacity. We applied these numbers to the capacities by state with LCOH values under $50/MMBtu (Table 2). The results are presented in Table 3, indicating that roughly 60 GWth in capacity corresponds to tens of thousands of local construction jobs and tens of billions of dollars in capital expenditures, mostly for constructing the district heating systems and well drilling.

Table 3: Construction jobs and capital expenditures corresponding to geothermal district heating capacities by state with LCOH values under $50/MMBtu (see Table 2). Impact estimated based on findings Millstein et al. (2019) for the GeoVision Study.

State	**Construction Jobs**	**Capital Expenditures**
Connecticut	19,500	$3.3 billion
Massachusetts	45,800	$7.6 billion
Maine	2,300	$0.4 billion
New Hampshire	3,800	$0.6 billion
New Jersey	108,800	$18.1 billion
New York	192,800	$32.1 billion
Pennsylvania	78,800	$13.1 billion
Rhode Island	9,000	$1.5 billion
Vermont	1,500	$0.3 billion

5. CONCLUSIONS

In this study, we applied NREL's dGeo-GEOPHIRES simulation tool to assess technical performance and economic competitiveness of EGS-based geothermal district heating systems providing direct-use heating to the residential sector in the northeastern United States. We leveraged Gringarten's multiple parallel fractures model for simulating the thermal performance of EGS doublets. We targeted 80°C bottom-hole temperatures, and sized the reservoir to limit thermal decline by 20% over 20 years. Our analysis was based at the census-tract level: for each census tract, we sized an EGS reservoir (hybridized with natural gas peaking boilers) to provide heating with a newly constructed district heating network to the residential buildings in the census tract. U.S. Energy Information Administration data were leveraged for estimating heating demand, and local neighborhood road lengths from the Census TIGER dataset were utilized to estimate required distribution network length.

Simulation results indicate a wide range in system LCOH values ranging from ~$15/MMBtu to over $1,000/MMBtu, with most attractive regions urban areas with high total thermal demand and high thermal demand density. We estimated about 60 GW_{th} in potential installed capacity with LCOH values under $50/MMBtu and 100 GW_{th} in potential capacity with LCOH values under $100/MMBtu. Potential future work can include expanding the analysis to the commercial sector, allowing EGS reservoirs to serve larger regions by combining census tracts, considering alternative EGS reservoir designs (e.g., one injection well plus two production wells), and comparing techno-economic performance with other types of heating and district energy systems.

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