National Modeling of Geothermal District Energy Systems with Ambient-Temperature Loops Using dGeo

Preprint

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National Modeling of Geothermal District Energy Systems with Ambient-Temperature Loops Using dGeo

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Keywords

Ambient-temperature loop, thermal energy network, district energy system, heating and cooling, geothermal boreholes, spatial modeling, dGeo

ABSTRACT

Geothermal district energy systems (DES) with ambient-temperature loops, also known as thermal energy networks, are one option for decarbonizing space heating and cooling loads. Geothermal fifth-generation DES include an “ambient” temperature thermal loop that connects heat pumps at each building with thermal balancing sources such as geothermal borehole fields. Heating and cooling are provided via a water-source heat pump at each end-user.

This project seeks to analyze the nationwide potential for ambient-temperature loop districts by creating a new module within the Distributed Geothermal Market Demand Model (dGeo). dGeo is an agent-based modeling tool for distributed geothermal resources; it can investigate potential on a nationwide or statewide scale using geospatial data for all 50 states and thermal demands for existing buildings. This process allows for high-level estimates of technical and economic potential for ambient-temperature loop districts across the United States.

A lookup table was created using GHEDesigner to size borehole fields for different thermal loads and ground conditions experienced across the country. A cost and financing structure, along with incentives, were applied. Cost estimates include costs for the distribution network, borehole field installation and operation, and circulation pump operation, while savings are calculated based on energy bills for building owners (agents). This newly developed module can be used for assessing which areas of the country have the highest potential for agent benefits from ambient-temperature loop installation and assess the impact of future cost and price scenarios.

Initial results for statewide analysis (for Vermont) and nationwide (for United States) are provided. Future work includes expanding the module to consider mixed residential and commercial districts as well as evaluating multiple cost scenarios.

1. Introduction

Decarbonizing heating and cooling is a critical step to achieve carbon reduction goals, as traditional heating has significant on-site carbon emissions (often from burning natural gas or fuel oil). Even traditional district heating and cooling systems which utilize steam or chilled water often use fossil-fuel-based systems in the central plant. In 2020, commercial and residential building energy consumption accounted for 40% of the United States' primary energy consumption (U.S. Energy Information Administration 2020). In the European Union, heating and cooling of buildings accounted for more than half of the energy consumption in 2020 (International Energy Agency (IEA) 2023). It is critical to decarbonize heating and cooling loads in ways that are economical, equitable, and compatible with a renewable electric grid.

District energy systems connect buildings in a community with a thermal network (generally one or several pipes running under the street) to provide heating and cooling. Ambient-temperature loops (ATL) are a specific subset of district systems which provide water at near-ambient temperatures (generally in the range 10°C to 25°C) to localized water-source heat pumps located in each building to meet heating and cooling loads. The water in the loop may exchange heat with multiple buildings and other energy sources (such as boreholes, waste heat from refrigeration, or heat from a sewer heat exchange system). One common way of moderating the loop's temperature is to run the fluid in the loop through geothermal boreholes in a borehole field. This allows the ground to act as a heat exchanger and transfer heat to or from the loop. These shallow closed loop geothermal systems, also known as geo-exchange, can be used to provide consistent low-temperature energy streams.

District systems enable a thermal resource with a relatively high capital cost (such as a geothermal borehole system) to be shared among a large number of users and amortized over a long period of time (30 or more years). Distributing costs in this manner may increase equitable access to decarbonization and reduce energy bills.

A recent study by Liu et al. (2023) found that converting existing HVAC systems to individual geothermal heat pumps reduced loads, energy prices, transmission requirements, and emissions. Ambient-temperature districts are thought to have equal or greater potential to reduce load on the electrical grid compared to individual geothermal heat pumps, resulting in significant grid cost savings.

A diagram for an ambient-temperature loop system is shown in Figure 1. The main thermal loop carries water (or a glycol-water mixture) between loads in the community and exchanges heat with the ground via the geothermal borehole field. These systems have various names in the literature including thermal energy networks and fifth generation district energy systems.

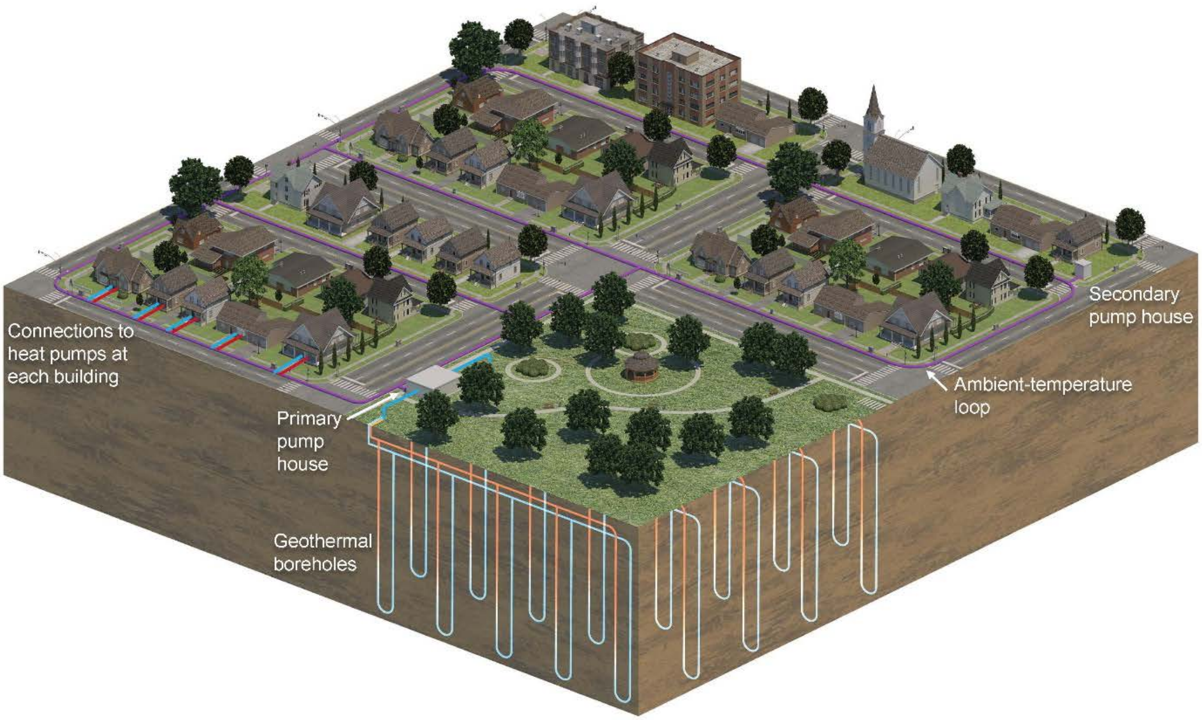

Figure 1. Example ambient-temperature loop district system with a single pipe thermal loop (purple line). This loop connects with heat pumps at each building to meet heating and cooling loads and exchanges heat with the ground via geothermal boreholes, under a park. ***Graphic by Besiki Kazaishvili, NREL.***

The major components covered in this project, shown in Figure 1, include buildings with heat pumps, a single-pipe thermal loop, a geothermal borehole field, and a pump house. The pump house contains the pumps for the borehole field, the circulation pumps for the main thermal loop, any auxiliary heating or cooling, and the control system.

These systems have been deployed on campuses and in communities with promising results. Examples include Colorado Mesa University (Woodruff 2022; Schulman 2020; Oh and Beckers 2023; Electric Power Research Institute, n.d.), Minewater (Brummer and Bongers 2019; Verhoeven et al. 2014; Boesten et al. 2019), and Whisper Valley (Marin 2022; Wolfson and Mapel 2020; "Whisper Valley," n.d.). Unlike most previous examples, the Eversource DES in Framingham, Massachusetts is retrofitting an existing community in the United States through a utility-led installation (Eversource, n.d.; HEET 2022), which provides a clear example for how district systems can be installed in existing communities.

The National Renewable Energy Laboratory developed the Distributed Geothermal model (dGeo) as part of its Distributed Generation Market Demand Model (dGen) to explore the technical, economical, market, and adoption potential for geothermal heating and cooling technologies in the United States (Liu et al. 2019; McCabe et al. 2019; Beckers and Young 2017; Gleason et al. 2017). dGeo is an agent-based modeling framework that uses geospatial-based data on geothermal resources, thermal demand, building characteristics, and energy prices to evaluate technical performance, cost-competitiveness, and potential adoption of geothermal heating and cooling systems. While dGeo does not model each building in the United States, it simulates "a *synthetic* *population* of commercial and residential buildings that is statistically representative of the true population" (McCabe et al. 2019).

Given the potential benefits to the electrical grid, decarbonization, and energy justice, this study investigated the potential of ambient-temperature districts for national deployment. The initial focus of dGeo was geothermal heat pumps and geothermal direct use for district heating. In this project, a new capability was added to dGeo for modeling ambient-temperature loop district energy systems using geothermal boreholes. This module investigates high-level techno-economic performance of ambient-temperature loops across the United States.

2. dGeo Ambient-Temperature Loop Methodology

The new ambient-temperature loop module uses the same dGeo agent-based modeling framework as previously documented (Liu et al. 2019; McCabe et al. 2019; Beckers and Young 2017; Gleason et al. 2017). Geospatial data layers for dGeo modeling include:

- Building type count for the residential (such as single-family detached and single-family attached) and commercial (such as restaurant, hotel, and office) sectors at the census block level based on the Federal Emergency Management Agency's HAZUS 6.1 dataset (FEMA 2023).
- County heating and cooling load in the residential and commercial sectors based on statewide and regional data and county level building counts from the U.S. Energy Information Administration's Residential Energy Consumption Survey and Commercial Buildings Energy Consumption Survey.
- Residential Energy Consumption Survey /Commercial Buildings Energy Consumption Survey microdata by climate zone to allow sampling of current building HVAC system types, HVAC lifetimes, and housing square footages.
- National and state incentives (such as rebates or tax credits) for geothermal technologies.
- Shallow ground thermal conductivity ranges by climate zone.
- Current and projected future regional energy prices for electricity, propane, natural gas, and distillate fuel oil, collected from the U.S. Energy Information Administration's Annual Energy Outlook datasets.
- Neighborhood road lengths by census tract.

Non-geospatial inputs include:

- Current and future costs for well drilling, heat pump and baseline HVAC systems.
- Project financing inputs.
- Current and future HVAC system performance.

2.1 Creating Borehole Field Look-up Tables

While ambient-temperature loops can be designed to use a variety of thermal sources and sinks, this study only considered the use of geothermal borehole fields. Sizing a borehole field for every potential district across the United States would have prohibitively high computational costs.

Instead, a look-up table was created to represent the different thermal loads and ground conditions across the country. This table was then used to size borehole fields.

For each set of inputs in the look-up table, GHEDesigner (a ground heat exchanger design tool) was used to size the number of boreholes and length needed to meet the thermal load (Jeffery Spitler et al., n.d.; Jeffrey Spitler, West, and Liu 2022; Mitchell et al. 2023). The recorded metric was the total borehole length required per gross building load (sum of absolute value of annual heating and cooling loads in the district). Thus, the output can be used to scale the size of the borehole field based on the total load in each district.

A multi-dimensional look-up table of 540 scenarios (= 15 × 3 × 3 × 4) was developed by independently varying climate zone, ground thermal conductivity, number of buildings and ratio of annual heating to cooling load (see Table 1).

Table 1. Lookup table inputs

Variable	Inputs
Climate zone*	1A, 2A, 2B, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B, 6A, 6B, 7A, 7AK
Ground thermal conductivity quartile	25^{th}, 50^{th}, 75^{th}
Number of buildings	3 options (between 25-300, range varied by climate zone)
Ratio of annual heating to cooling loads	4 options (from 0.002 – 12, range varied by climate zone)

**ResStock building loads were not available for climate zones 7B or 8A. Those loads were thus excluded from this analysis.*

Within the United States, there are eight climate zones and three moisture regimes (A, B, C), using the categories designated by the Internation Energy Conservation Code (IECC). For each climate zone, a representative city was selected and ResStock (National Renewable Energy Laboratory, n.d.) timeseries building data was retrieved. Building data from actual meteorological year 2012 was used to be compatible with ReEDS for future grid impact analysis. For each climate zone, the average ground temperature (Xing 2014) and each of the three quartiles for ground thermal conductivity (Liu, Warner, and Adams 2016) were used as inputs for the geothermal borehole modeling.

The number of buildings and ratio of heating to cooling loads specified as inputs for the look-up table (as described in Table 1) were determined based on analyzing loads across each climate zone. The goal was to create three different district sizes by specifying a number of buildings, while maintaining district borehole field size between 200 and 1000 total boreholes. Climate zones with more balanced loads can hold more buildings in each district within these bounds, while climate zones with highly unbalanced heating and cooling loads use fewer buildings. Additionally, the ratio of heating to cooling was varied to capture differences between different building types and load profiles. While the heating and cooling loads may be scaled up or down to capture a specific ratio, the hourly variations are still present. This allowed the lookup table to capture a wide variety of potential district building compositions.

Once the buildings were selected for a given climate zone and the loads scaled to match a given ratio, the building loads were summed for each hour of the year across all the buildings in the district and then converted into ground loads via the heating and cooling coefficient of performance (COP). The resulting timeseries ground load values were then input into GHEDesigner to size the appropriate borehole field.

The general model settings for GHEDesigner were:

- 30-year design period
- Minimum entering temperature of 0°C and maximum entering temperature of 35°C for the heat pump
- Initial COP values of 4 for heating and 6.5 for cooling (Liu et al. 2023), then iterated to find new COP values based on fluid temperature leaving borehole field during simulation and a residential heat pump COP curve
- Maximum borehole depth of 175 m
- Borehole spacing of 6.1 m
- 20% glycol mixture
- 1.25-inch single U-tube pipe

2.2 Other Pre-processing and Inputs

Before running dGeo, the distribution network (the length of thermal loop piping to be installed) was sized for each census tract based on road lengths and land area. First, the distribution system was sized to be 75% of the road lengths in each census tract, excluding major roads (based on (Reber 2013)). Then, upper and lower limits were applied to cap distribution network sizing based on a study of European district energy systems (Sánchez-García et al. 2023).

Additionally, the census tract was flagged for potential space constraints if the land area required for the borehole field is greater than 5% of the tract's total land area. These census tracts may require a more in-depth assessment of land availability and heat exchange options. Borehole locations underneath roads or deeper concentric boreholes may increase the chances of installing borehole fields in dense urban areas.

The HEATNETS model (Simpson and Zhu 2024) was used to estimate operational energy and cost. Given load cancelling, loop thermal inertia, and heat exchange between the thermal loop and the surrounding soil, borehole field heat exchange may not be required at all times, with the working fluid instead circulating only in the thermal loop. The borehole fields may operate less in the shoulder seasons, which reduces pumping power needed to operate the system. HEATNETS was used to choose reasonable parameters for the dGeo system estimates, including a borehole capacity factor of 50%. Thus, for operational energy, the borehole field pumps are only considered to run 50% of the year.

2.3 District Costs

Estimating the capital and operational cost for these district energy systems is critical to determining their economic feasibility. In addition to costs, the potential incentives and financing structures must be considered.

Because district geothermal system adoption is limited in the United States, the financing structures are still to be determined. The study team assumed that the district-level components—including the borehole field installation, control system, distribution piping, and operation costs—are all covered by a commercial entity. Those costs are then passed on to agents through monthly bill payments based on each building's annual heating and cooling load. Agents are then responsible for heat pumps and building retrofits, as well as a portion of the district cost.

The potential economic benefits are quantified by the net present value for the agent. This value is based on the annual energy savings from the new system compared to baseline HVAC energy consumption, the agent's annual costs for the upgrades, and the agent's portion of the district cost.

Cost assumptions are highly uncertain due to the technology's early development stage. Cost estimates were gathered from the literature and publicly available financial data on utility installations. However, a range of values will be assessed to look at the impact of different values on economic potential.

The structure for building the cost estimate is as follows:

- District cost (assumed by commercial entity):
    - Borehole field:
        - Drilling cost per foot of depth (per borehole).
    - Distribution system:
        - Horizontal thermal loop pipe installation under community streets, cost per meter.
        - Central pump house or plant with controls, piping, and auxiliary systems, cost per kW of pumping power (to scale with system size).
        - Pump cost (for circulation of thermal loop and operation of borehole fields), cost per kW or HP.
    - Engineering, procurement, and construction, as a percent of installed cost before incentives.
    - Operations and maintenance, as a percentage of total installed cost before incentives.
- Agent cost (assumed by building owner):
    - Heat pump cost per ton.
    - Hook-up cost per building to connect to distribution network.
    - Retrofit cost per ton (only applied if the current HVAC system is not ducted).
- Incentives:
    - Federal investment tax credit (ITC) applied to district costs.
    - Federal tax incentive and state and local incentives (if available) applied to agent costs.

- Additional assumptions:
    - Pump operation costs assume borehole fields are run 50% of the time, with commercial electric rates applied.

2.4 Simulation Steps

An ambient-temperature loop simulation in dGeo begins with the same initial process documented previously (Gleason et al. 2017; McCabe et al. 2019; Liu et al. 2019), including referencing spatial databases and creating agents. Agents are assigned heating and cooling loads and HVAC system types, ages, and costs. After this general set-up, the ambient-temperature loop module in dGeo performs the following tasks:

1. Performs district sizing calculations for district energy systems within each census tract:
    - Ground thermal conductivity is randomly assigned as either 25^{th}, 50^{th}, or 75^{th} percentile of thermal conductivity for that climate zone.
    - Imports ground heat exchanger (borehole field) sizing lookup table, discussed in Section 2.1.
    - Sums the agent thermal heating and cooling loads in the census tract and scales to a reasonable size for a single district.
    - From the look-up table, assigns to the census tract a ratio of total length of borehole heat exchanger needed to gross heating and cooling load (m/kWh) based on the total thermal load, ratio of heating to cooling load, climate zone, and ground thermal conductivity of the district.
    - Assigns the distribution length needed to connect all agents in the census tract into districts based on pre-processed data (discussed in Section 2.2).
2. Sizes the heat pumps and calculates energy savings based on the geothermal heat pump module (Liu et al. 2019).
    - Compares current baseline capital and energy costs to proposed heat pump costs.
3. Calculates district sizing and costs for each census tract:
    - Sizes the borehole field based on the total gross load within the census tract (representing a total borehole field size that would likely be distributed amongst multiple borehole fields supporting multiple districts).
    - Estimates district system cost by applying the cost structure defined in Section 2.3, and then applies commercial financing and incentives.
    - Applies district costs to agents in each census tract based on $/kWh of total demanded thermal load.
4. Calculates agent financials:
    - Applies residential incentives and financing.

- Converts agent costs and energy savings into cashflows and then calculates net present value.
- Marks agents with positive net present value as economic potential.

5. Repeats every 2 years.

Note that district sizing and cost calculations are done at a census tract scale. Most census tracts will need to include multiple districts. The study team assumed that each district in a given census tract has the same mix of buildings and the required costs are scaled up to the census tract level.

In the dGeo geothermal heat pump module, the market potential and adoption over time are calculated using adoption data and Bass diffusion curves. However, there is limited data available on district systems in general and no clear adoption data available at this time. Therefore, the ambient-temperature loop analysis will only go as far as economic potential and will not calculate market potential or adoption rates as was done previously for geothermal heat pump (Liu et al. 2019).

3. Initial Results and Discussion

Many geospatial data layers are used as inputs for dGeo. Figure 2 provides examples for the road lengths and thermal demand density spatial data for Vermont (chosen arbitrarily).

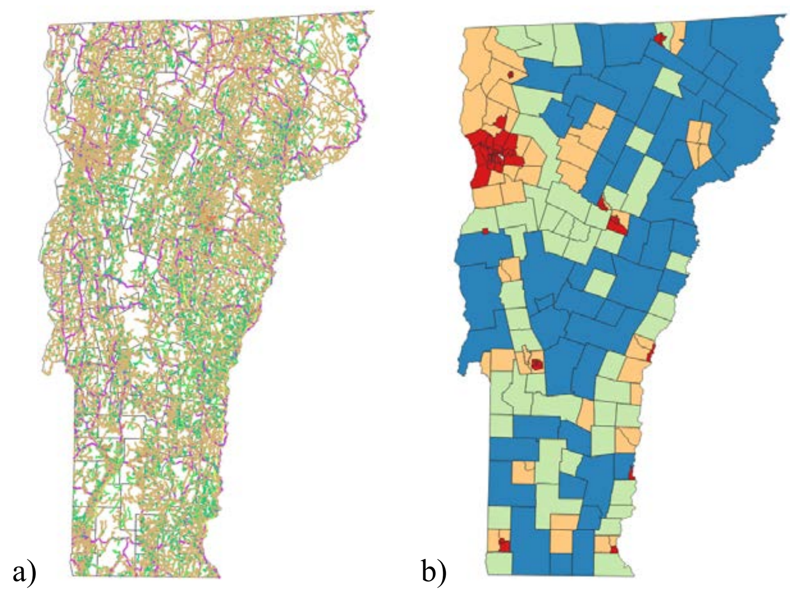

Figure 2: a) Roads (different colors represent different road types), and b) thermal demand density (warmer colors represent higher thermal demand density) in Vermont.

To demonstrate dGeo's potential, a state-wide run was completed for Vermont, followed by a nationwide run for the entire United States, with results for 2032 shown in Figures 3 and 4. An advanced costing scenario was used, with cost values for well drilling, distribution system, etc. at the lower end of current estimates. The median relative favorability of ATL for each census tract is shown, with darker colors representing a more economically favorable median agent net present value and lighter colors representing a less economically favorable median.

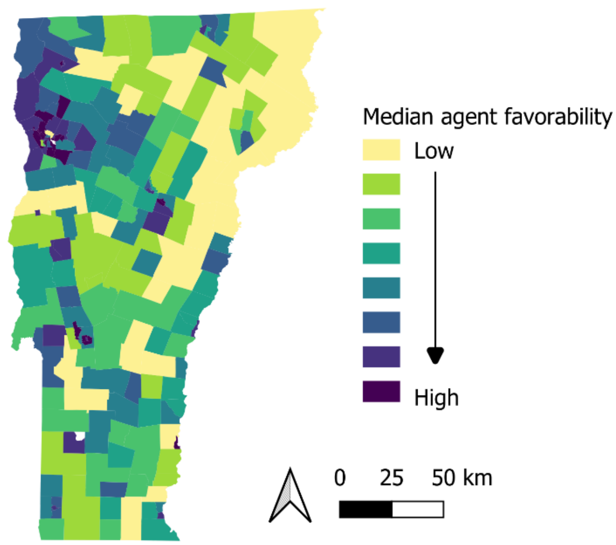

Figure 3: Vermont census tract median agent economic favorability in 2032.

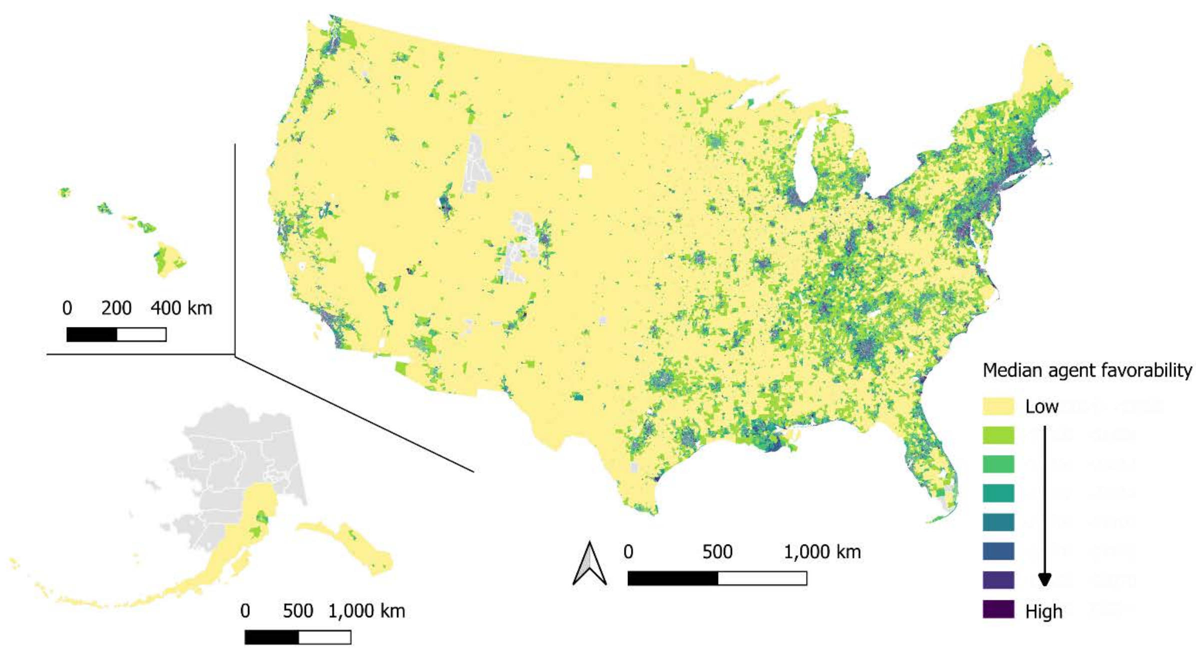

Figure 4: United States census tract median agent economic favorability in 2032. (Representative building models were not available for regions shaded in grey.)

To create the maps in Figures 3 and 4, the net present value for each agent was calculated for 2032. These net present values account for the additional capital costs of the heat pump installation, shared ambient-temperature loop capital costs, and each agent's potential energy savings from switching from an original HVAC system to a geothermal heat pump. The year 2032 was used because the federal investment tax credit is still in place at this time, significantly decreasing capital costs. As expected, cities in each state tend to have higher favorability. More urban settings are likely to have reduced transmission costs per load, which can be a significant factor in the total capital costs. There are also differences in favorability seen among tracts in individual cities.

Figure 5 shows the ATL economic potential (given an advanced costing scenario) for Vermont, defined as the sum of the HVAC system size for all agents with a positive net present value when switching from their baseline HVAC to an ATL system. Every two years, dGeo adds new agents, updates HVAC costs and ages, adjusts energy costs, and generates new results. The number of agents with positive net present value generally increases over time until the federal investment tax credit expires at the end of 2034, after which the economic potential decreases significantly.

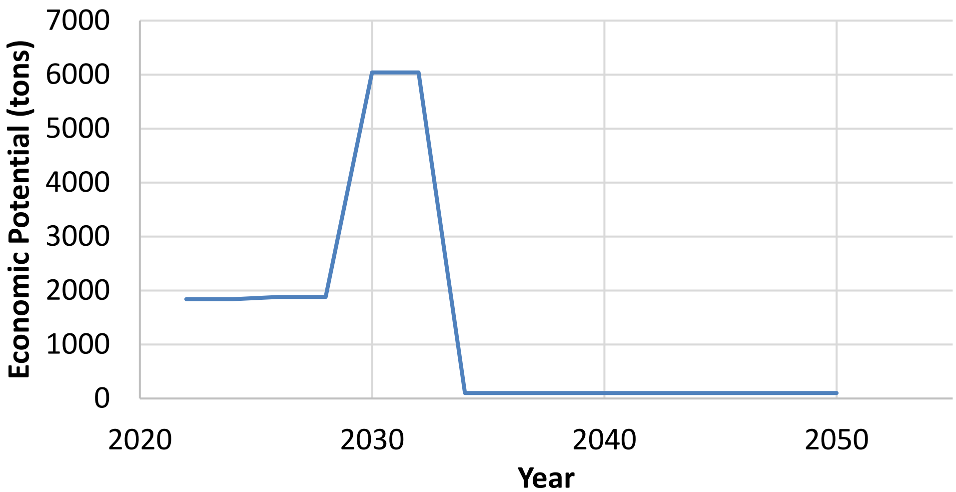

Figure 5: Vermont economical potential for agents with positive net present value over time.

The preliminary economic potential shown in Figure 5 accounts for most current incentives and rebates, but it does not account for any additional value to the electric grid or benefits for retiring natural gas infrastructure. These benefits to utilities are expected to be significant and may influence future adoption of ambient-temperature loop systems. Additionally, these initial results only consider residential buildings, and it is expected that performance would be improved when residential and commercial buildings are considered on the same loop.

These results are based on the economic potential for each individual agent. For district systems to work effectively, a critical mass of agents would need to agree to join a network. The study did not consider this aspect of district adoption, instead focusing on determining which agents would find district systems economically viable if district systems were an option in their community.

4. Conclusions and Future Work

In this project, dGeo was expanded with a new module to consider economic potential for ambient-temperature loop systems in the residential sector. A methodology was created for building a look-up table to size borehole fields for ambient-temperature loop districts across the United States. Cost correlations and financial structure assumptions were added to the module. The developed methodology compares the costs and benefits of ambient-temperature loop systems against baseline HVAC systems for agents in each census tract in the United States.

This new module can be used for assessing which areas of the country have the highest economic potential for ambient loop installations and what the impact is of different futures cost and price scenarios.

This research is ongoing, with additional improvements planned for the dGeo code. National simulations are still being processed, and the cost models continue to be updated as additional information becomes available. Future work includes expanding the module to consider mixed residential and commercial districts and considering multiple cost scenarios.

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