GeoVision Analysis Supporting Task Force Report: Thermal Applications

Quantifying Technical, Economic, and Market Potential of Geothermal District Heating Systems in the United States

Kevin McCabe, Koenraad Beckers, Katherine R. Young, and Nate Blair

National Renewable Energy Laboratory

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Foreword

This report describes research and analysis performed in support of the U.S. Department of Energy Geothermal Technologies Office for its Geothermal Vision Study. A summary of the study is captured in DOE's report, *GeoVision: Harnessing the Heat Beneath Our Feet* (DOE 2019) and included ground-breaking, detailed research on geothermal technologies. The study projects and quantifies the future electric and nonelectric deployment potentials of these geothermal technologies within a range of scenarios in addition to their impacts on U.S. jobs, the economy, and environment. Coordinated by the U.S. Department of Energy Geothermal Technologies Office, the Geothermal Vision Study development relied on collecting, modeling, and analyzing robust data sets through seven national laboratory partners that were organized into eight technical task force groups. These task forces and their respective principal leading national laboratory are listed in Table F-1. The table also provides a guide to the final research documents produced by each *GeoVision* task force. In most cases, these were prepared as laboratory reports, and they are referenced accordingly. Consult these external reports for detailed discussions of the topics contained within, which form the basis of the *GeoVision* analysis.

Table F-1. Guide to Technical Research Documents Providing the Basis of the *GeoVision* Analysis

***GeoVision* Task Force**	**Lead National Laboratory**	**Reference/Citation**
Exploration and Confirmation	Lawrence Berkeley National Laboratory	LBNL-2001120 (Doughty et al. 2018)
Potential to Penetration	National Renewable Energy Laboratory	NREL/TP-6A20-71833 (Augustine et al. 2019)
Thermal Applications: Direct Use (this report)	National Renewable Energy Laboratory	NREL/TP-6A20-71715 (McCabe et al. 2019)
Thermal Applications: Geothermal Heat Pumps	Oak Ridge National Laboratory	ORNL/TM-2019/502 (Liu et al. 2019)
Reservoir Maintenance and Development	Sandia National Laboratories	SAND2017-9977 (Lowry et al. 2017)
Hybrid Systems	Idaho National Laboratory	INL/EXT-17-42891 (Wendt et al. 2018)
Institutional Market Barriers	National Renewable Energy Laboratory	NREL/PR-6A20-71641 (Young et al. 2019)
Social and Environmental Impacts	Lawrence Berkeley National Laboratory	NREL/TP-6A20-71933 (Millstein et al. 2019)

Acknowledgments

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List of Acronyms

BAU	Business as Usual
DER	distributed energy resource
dGeo	Distributed Geothermal Market Demand Model
DOE	U.S. Department of Energy
EGEC	European Geothermal Energy Council
EGS	enhanced geothermal system
EIA	U.S. Energy Information Administration
GDH	geothermal district heating
GDU	geothermal direct use
IEA	International Energy Agency
LCOH	levelized cost of heat
OECD	Organisation for Economic Co-operation and Development
TI	Technology Improvement

Executive Summary

The Distributed Geothermal Market Demand Model (dGeo) has been developed to explore the potential role of geothermal district heating (GDH) systems in meeting current and future energy demands in the contiguous United States. The dGeo model simulates the technical, economic, and market potential for deployment of GDH systems in the residential and commercial sectors through 2050. Two scenarios are considered: a Business as Usual (BAU) scenario assuming status quo, and a Technology Improvement (TI) scenario assuming significant technology advancements resulting in lower drilling and exploration costs, lower discount rates, and higher well flow rates. For known hydrothermal resources, dGeo estimates a technical, economic, and market potential of 27 GW_{th}, 2.8 GW_{th}, and 1.0 GW_{th} in the BAU scenario and 27 GW_{th}, 4.6 GW_{th}, and 1.6 GW_{th} in the TI scenario. For EGS resources, the corresponding values are up to two orders of magnitude higher. The simulation results are compared with current GDH systems in the United States and Europe.

Table of Contents

List of Figures

List of Tables

1 Introduction

The current and future role of renewable distributed energy resources (DERs) in the United States has garnered significant attention in recent years. Most research in this area has focused on electric generation DERs—notably, solar photovoltaics (Gagnon et al. 2016; Labistida and Gauntlett 2016) and, to a lesser degree, wind (McCabe et al. 2018; Orrell and Foster 2016; Distributed Wind Energy Association 2015) and energy storage (Eller and Dehamna 2016). By comparison, distributed applications of thermal technologies have drawn less research and systematic consideration, with a few notable exceptions (Batocletti and Glassley 2013; Liu 2010; Schoonover and Lawrence 2013). The comparative scarcity of research on thermal DERs is incongruent with the large role that thermal demand plays in the United States. The aggregate end-use thermal demands (space heating, space cooling, water heating) of residential and commercial buildings compose approximately 20% to 25% of the total energy consumed in the United States (EIA 2013; EIA 2016b; EIA 2016c). Meeting those demands with renewable DERs instead of conventional generation such as electricity could significantly reduce fuel demand and influence the evolution of the electric power sector.

The National Renewable Energy Laboratory (NREL) developed the Distributed Geothermal Market Demand Model (dGeo) as a tool to explore the potential role of geothermal DERs in meeting current and future thermal energy demands in the United States. The dGeo model simulates the potential for deployment of geothermal DERs in the residential and commercial sectors of the contiguous United States with a focus on two specific technologies: (1) geothermal heat pumps and (2) geothermal direct use (GDU) for district heating. The model is described further in Section 4.

This technical report provides the results of the research activities conducted by the *GeoVision* GDU thermal task force and the dGeo teams, covering dGeo input parameters, simulation approach, and output results. These teams investigated the potential for geothermal district heating (GDH) penetration in the United States up to the year 2050 as part of the DOE Geothermal Technologies Office *GeoVision* study. To support this effort, dGeo was developed to simulate the deployment of GDH in the United States under two scenarios: (1) Business as Usual (BAU) and (2) Technology Improvement (TI), as described in Section 3.2. The model results are used to investigate the role GDH systems could play in meeting current and future thermal demands in the residential and commercial sectors in the United States (Gleason et al. 2016). The results of the geothermal heat pump analysis are provided separately by Oak Ridge National Laboratory (Liu et al. 2019).

1.1 Current Status of GDU and GDH

1.1.1 GDU and GDH Installations in the United States

A review of GDU installations in the United States by Snyder, Beckers, and Young (2017) found that there are currently 407 GDU installations in operation, of which 21 are GDH, and 107 GDU systems have been closed during the past century, of which 2 were GDH. The total GDU capacity in operation is estimated to be 501 MW_{th}, of which approximately 100 MW_{th} is GDH. Historical development curves show that resorts and pools are the earliest GDU application (since the 18^{th} century), and they continue to be the dominant application over time by number of installations. In terms of historical cumulative installed capacity (see Figure 1), a major increase in installation occurred in the 1970s and 1980s, as seen in the development of district heating, aquaculture, and greenhouse systems, but it has declined since the 2000s because of recent closures of facilities (mainly aquaculture and greenhouses). The spike in installations in the 1970s and 1980s correlates with the significant increase in fossil fuel prices around that time (see Figure 2 for crude oil prices during the last 150 years). This price increase rendered GDH more attractive because it became relatively less expensive. This difference in prices also led to increased deployment rates of GDH systems in Europe (see Figures 29 and 30). The effect of an increase in fossil fuel prices on GDH deployment is investigated with dGeo, and the results are presented in Section 5.3.2.

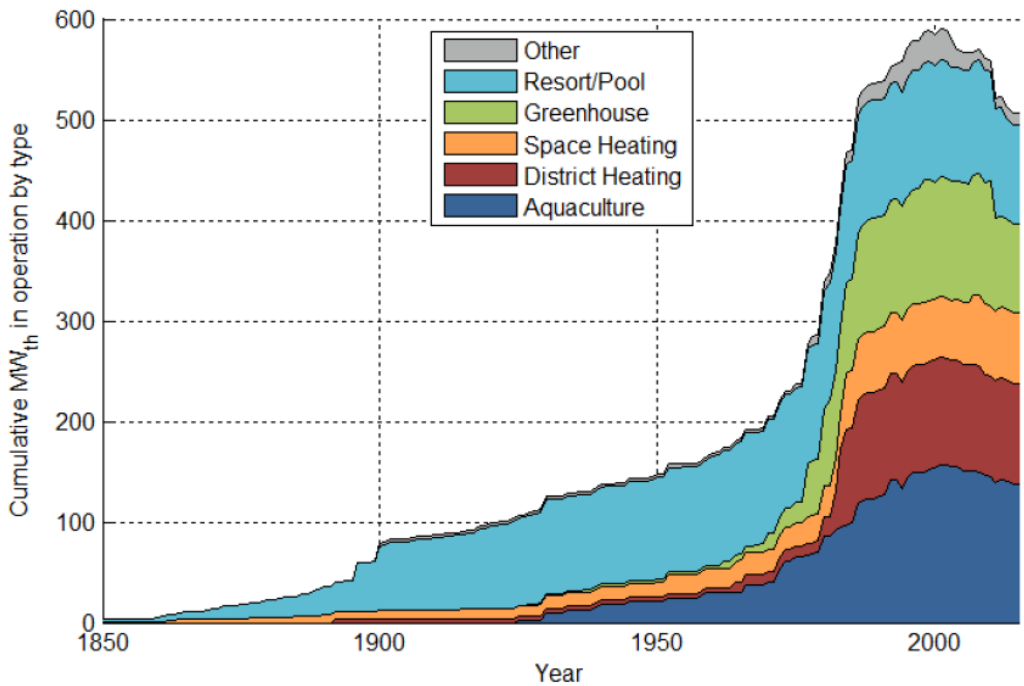

Figure 1. Cumulative installed capacity of GDU in operation (MW_{th}). GDU system construction spiked in the 1970s and 1980s, explained by the increase in fossil fuel prices in the 1970s (Figure 2), after which it leveled off and decreased as a result of installation closures. GDH currently accounts for about 100 MW_{th} (20%) out of 500 MW_{th} of total installed GDU capacity.

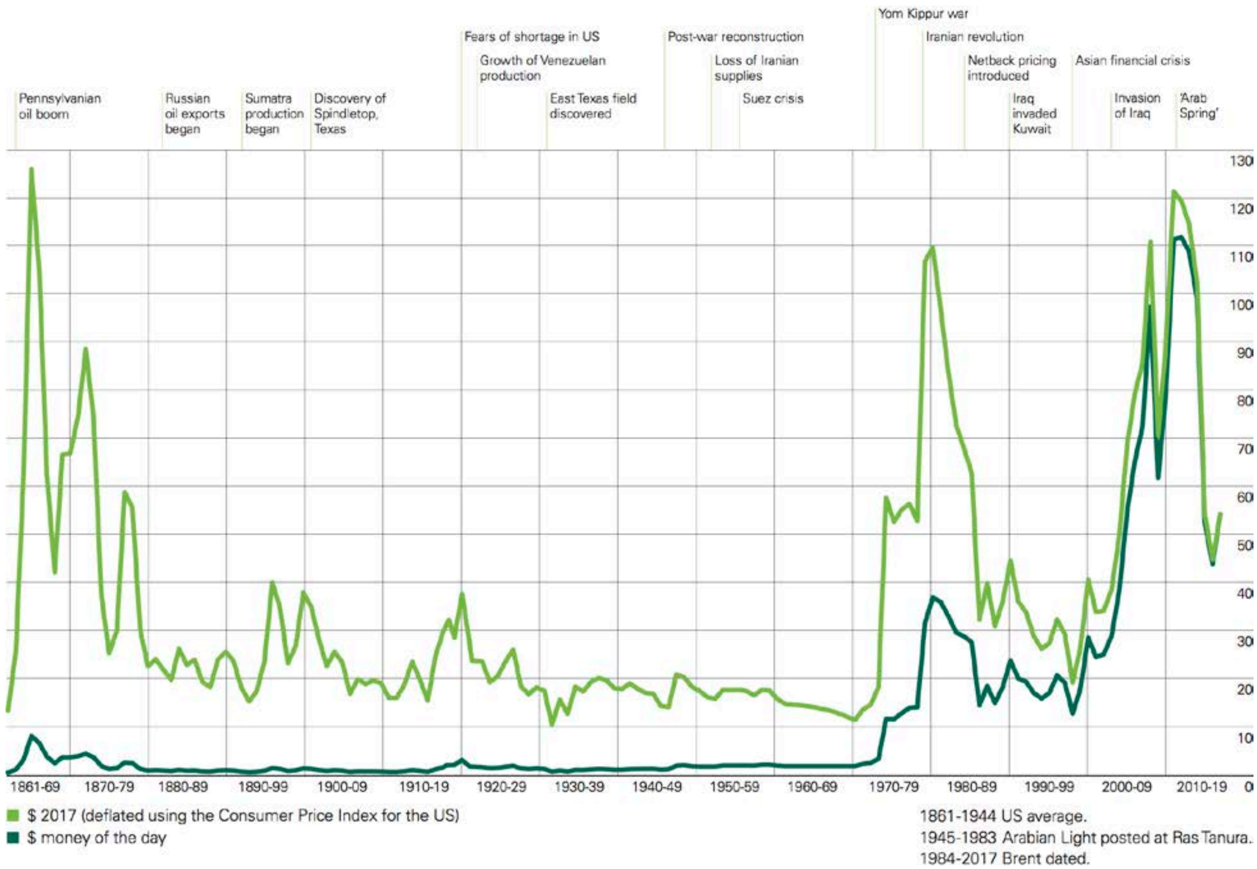

Figure 2. Crude oil prices from 1861 to 2017 in $/barrel. The prices are expressed in dollar amounts of the day (dark green line) and in 2017 U.S. dollars after adjusting for inflation (light green line). The large crude oil price spike in the 1970s triggered significant GDU development in the United States (Figure 1).

Source: BP (2018)

1.1.2 District Heating Systems in the United States

The 21 GDH systems are a small subset of the total number of district heating systems in the United States considering all heating sources (i.e., heat from natural gas or other fossil fuels, waste heat, solar thermal energy, and geothermal energy). The exact number of total district heating systems is uncertain because reported numbers vary widely: 837 (OECD/IEA 2014), 2,500 (Treddinick 2013), 3,400 (DOE 1992), and 5,800 (Ulloa 2007). Average system sizes reportedly range between 60 MW_{th} (DOE 1992) and 90 MW_{th} (OECD/IEA 2014). The majority of the systems have between 10 and 50 buildings connected to the distribution network (DOE 1992). The dominant customers are college campuses, hospitals, and city downtowns. The history of district heating systems in the United States dates to 1853, with the first district heating system built at the U.S. Naval Academy in Annapolis, Maryland (*Sun & Wind Energy* 2010). Major development occurred in the 1970s (Treddinick 2013) because of an increase in fossil fuel prices (see Figure 2). A recent renaissance has been reported in the development of GDH systems (*Sun & Wind Energy* 2010), with 20 to 40 million ft^2 of buildings space added to a district energy network each year since 2000 (OECD/IEA 2014). The most recent GDH system built was in 2005 in Lakeview, Oregon (Snyder, Beckers, and Young 2017).

1.1.3 Comparison with Europe

Although GDH systems currently have limited penetration in the United States, other countries have much more deployment. As of 2015, 257 GDH systems were in operation in Europe, with an installed capacity of 4,702 MW_{th} (EGEC 2016), or 49% of the total global 9,600 MW_{th} of GDU installed capacity (Antics, Bertani, and Sanner 2016). The European countries with the largest amount of GDU installed capacity, as estimated by Antics, Bertani, and Sanner (2016), are:

1. Turkey: 3,300 MW_{th}, of which 30% is district heating
2. Iceland: 2,100 MW_{th}, of which 90% is district heating
3. Italy: 1,400 MW_{th}, of which 10% is district heating.

The level of penetration of GDU in several European countries as a percentage of total thermal demand (up to 90% for Iceland) is currently orders-of-magnitude higher than in the United States (only approximately 0.01%).

1.2 Paper Structure

This report consists of the following nine sections:

1. Section 1: introduction and background
2. Section 2: background information on the dGeo model including the model framework and output metrics
3. Section 3: review of the research efforts compiling input data for dGeo for the BAU and IT scenarios
4. Section 4: discussion of parameters with high impact on the levelized cost of heat (LCOH) of GDH systems
5. Section 5: dGeo GDH technical, economic, and market potential results
6. Section 6: dGeo estimated spatial trends in GDU district heating system viability
7. Section 7: comparison of results
8. Section 8: barriers to deployment of geothermal direct use
9. Section 9: discussion of results.

2 Methodology

2.1 The dGeo Model

To quantify the potential deployment opportunity for GDH, dGeo leverages a highly resolved geospatial database and robust, bottom-up, agent-based modeling framework. This design is consistent with other models in the dGen family of market demand models, including dSolar and dWind (Sigrin et al. 2016). dSolar has been used extensively in previous analyses, and dWind was used recently in analyses of distributed wind potential (McCabe et al. 2018; Lantz et al. 2016). For in-depth discussion of the dGeo model, see Gleason et al. (2017).

2.1.1 dGeo Agent Generation

The first component of the dGeo model is the process of agent generation, which occurs at the outset of each model run. Each agent in dGeo represents a commercial or residential building type, complete with several attributes describing the specific characteristics of that building type that might affect the economics of or suitability for GDU adoption. No single agent within the model should be interpreted as a real building that has a one-to-one correspondence to an actual building in reality; instead, each agent has a replication weight, indicating the number of buildings that it is meant to represent. Altogether, the complete collection of agents in the model is meant to capture the statistical variation of key attributes for the real population of buildings across the United States. In other words, the overall collection of agents in dGeo comprises a "synthetic population" of commercial and residential buildings that is statistically representative of the true population to which it corresponds. The agent generation component of dGeo is the process by which the model constructs the synthetic population of buildings for each model run.

For the GDU module, agents are generated at a county-level resolution, where a fixed number of agents are sampled to represent the population of commercial and residential buildings within a given county. These agents are then populated with attributes of statistically representative buildings as surveyed by the U.S. Energy Information Administration (EIA) (EIA 2014; EIA 2016a). As the model steps through time, many of the core attributes of the building remain the same, such as the building type, energy consumption, and space heating/water heating equipment and fuel types. Other attributes evolve as the model progresses, such as the equipment ages, energy costs, and the building's annual heat demand profile.

2.1.2 dGeo Modeling Process

The agent generation and mutation processes represent two of four major steps in the GDU module procedure. The following steps illustrate the full model process at a high level:

1. **Agent generation:** During agent generation, which occurs at model initialization, dGeo creates a synthetic population of agents within each region, where each agent represents a type of commercial or residential building, complete with several key attributes.
2. **Agent mutation:** At each time step, agents are updated to inherit new time-dependent attributes (or change existing ones) that might affect their evaluation of the opportunity for technology adoption.
3. **Assessment of technical potential:** Based on the current status of agents at each time step, dGeo assesses the quantity of the GDU resource that is technically feasible, given proximity to end-use thermal demand and any siting constraints.

4. **Assessment of economic potential:** At each time step, dGeo evaluates the economics of an investment in GDU technology for each agent using discounted cash-flow analysis. This analysis produces financial metrics that can be used to assess how economically attractive each technology is to each agent as well as the overall number of agents for which technology adoption would be economically rational.
5. **Assessment of market potential:** Based on empirical data that relate financial metrics (e.g., payback period, net present value) to the number of customers who would be willing to adopt a technology, dGeo translates economic potential into market potential at each time step.

2.2 Output Metrics of the dGeo Geothermal Direct Use Module

As discussed in Section 3.2, a number of cost, technology, and financing inputs are also ingested into the model that combine with the core agent attributes to determine the economic viability of a geothermal district heating system that serves the agents' space and water heating loads. The following section details the calculation of the technical and economic potential for GDU that is calculated in dGeo.

2.2.1 Technical Potential

As the dGeo GDU module progresses through the model time steps, it calculates three key metrics to quantify the potential opportunity for the GDU district heating technology: technical potential, economic potential, and market potential. The first of these metrics, technical potential, represents the quantity of energy generation potential of these resources that is technically feasible without regard to whether that potential is economically viable or likely to be deployed. For utility-scale renewable resources, the basis for assessing technical viability includes the "resource availability and quality, technical system performance, topographic limitations, and environmental and land-use constraints" (Lopez et al. 2012). In comparison, distributed renewable resources such as GDU require additional considerations for technical potential because of their very site-specific nature and their need to be sited on or proximal to an end use.

For the dGeo GDU module, we define technical potential as the developable capacity of GDU available at a given model time step based on the resource availability and quality, technical system performance, and proximity to a suitable thermal end use. Although many definitions of technical potential do not consider it to be demand constrained, the dGeo GDU module caps the technically available resource at a given location. This is primarily because of the inclusion of the immense amount of enhanced geothermal system (EGS)[1] resource potential as calculated in Mullane et al. (2016). Although the magnitude of shallow EGS resources far exceeds the thermal demand of the United States, EGS as a technology has not yet been proven at commercial scale. Thus, the technical potential as reported in the dGeo GDU module is constrained spatially by the local (county) thermal demand for both hydrothermal and EGS resources for all model run years.

Using the Mullane et al. (2016) resource assessment, dGeo is able to quantify the total number of potentially developable GDU wells associated with each county and the quantity of resource that

[1] EGS, also sometimes called engineered geothermal systems, are human-made reservoirs created where there is hot rock but insufficient or little natural permeability or fluid saturation. These systems differ from traditional hydrothermal systems, which are naturally occurring and are defined by three key elements already in place: heat, fluid, and permeability at depth (DOE 2012).

can be extracted from each. These metrics enable dGeo to calculate the technical potential for GDU in each county. To do so, the model first sums the extractable resource associated with each developable well in each county, determining the total extractable resource for the county. Next, dGeo estimates the quantity of the extractable resource in the county (c) that can actually be used (H_c) (i.e., the beneficial heat), according to Equation 1:

$$H_c = R_c * e \quad \text{(Eq. 1)}$$

Where R_c is the extractable resource, and e is a user-specified end-use efficiency factor that accounts for heat losses during distribution and thermal losses through the heat exchanger at each end-use location. dGeo excludes resources in counties for which there is no heat or hot water demand (as determined by site energy demands of the residential and commercial agents in the county). The resulting aggregate quantity of beneficial heat represents the GDU technical potential, as estimated by dGeo at each model time step.

As mentioned in the introduction to this section, technical potential is a measure that is agnostic to economic factors. Therefore, the technical potential for GDU calculated by dGeo includes both hydrothermal and EGS resources even though the development of the latter class of resources might be unrealistic under the BAU scenario. To account for this dissonance, dGeo summarizes the technical potential for GDU collectively as well as separately for hydrothermal and EGS resources.

2.2.2 Economic Potential

The economic potential of a renewable resource is defined broadly as the portion of technical potential that is "economically viable" (Brown et al. 2015). Various formulas can be used to assess economic viability; however, in generic terms, economic viability is defined as projects for which revenues from a renewable resource exceed the costs of development, producing a positive return on investment.

The dGeo model uses separate methods to assess the economic potential and viability of the two modeled technologies: geothermal heat pumps and GDU. These differences in methodologies are driven primarily by our focus on representing the most critical and driving real-world economic and market dynamics for each technology. For GDH systems (unlike geothermal heat pump systems), technology deployment is generally not feasible on an individual building basis; rather, several individuals must collectively choose to subscribe to the district system to enable the system developer or operator to recoup investment costs and make a positive return on investment. Further, the economics of GDU systems are highly resource dependent. Therefore, in the case of GDU, dGeo places more focus on capturing the dynamics of collective decision-making and resource availability and less focus (relative to geothermal heat pumps) on individual-level factors such as financing terms. dGeo's estimation of the economic potential for GDU is calculated by simulating the local demand and supply for GDU for each county, then determining the portion of supply with sufficiently low price to meet the demand. Figure 3 illustrates the dynamics of this process in more detail.

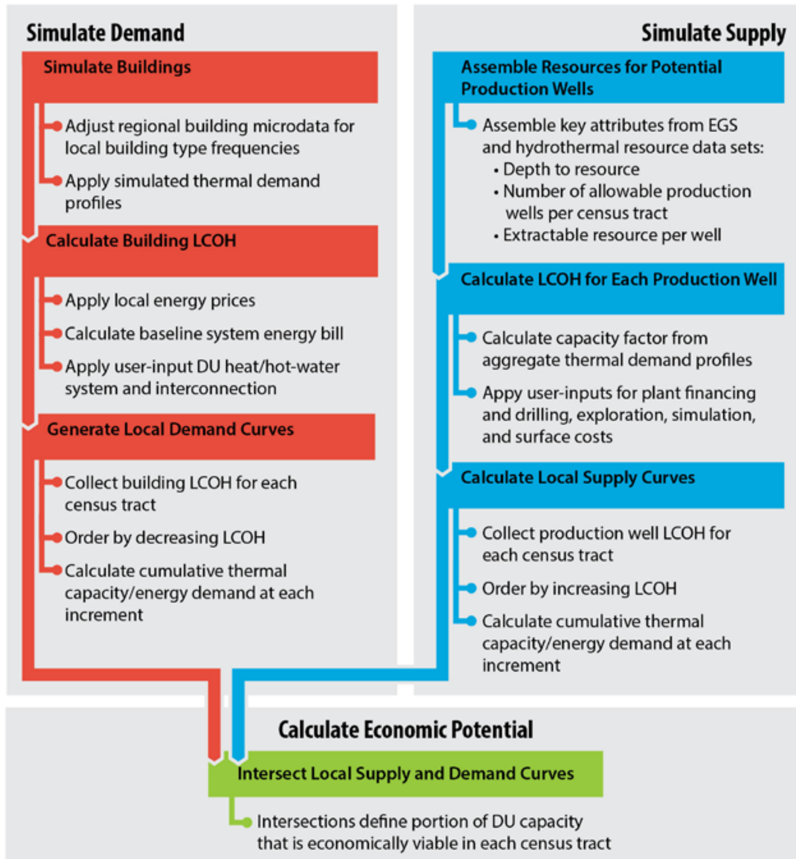

Figure 3. Framework used to calculate the economic potential of GDU district heating systems

Using the agent attributes in combination with several user-defined inputs (e.g., district heating interconnection costs, fixed operation-and-maintenance costs, and annual space/water heating fuel costs), an LCOH is created for each agent. Given the amount of heat demanded by each agent and the associated LCOH for each agent, a demand curve (e.g., the red curve shown in Figure 4) is constructed that quantifies the cumulative thermal capacity within the county associated with *decreasing* values of LCOH. Similarly, on the supply side, an LCOH is calculated for every resource located within (beneath) each county. The cost and financing inputs that describe the LCOH calculation are numerous and described in Section 3.2, but they include drilling costs, plant installation costs, and annual operation-and-maintenance costs. dGeo then constructs a supply curve (e.g., the blue curve shown in Figure 4), quantifying the cumulative thermal capacity within the county associated with *increasing* values of LCOH.

Finally, dGeo combines the supply and demand curves to determine the economic potential within each county. To do so, the model intersects the supply and demand curves to identify the equilibrium price and quantity (Figure 4). This point of intersection represents the local market conditions in which the supply and demand are at equilibrium. The *equilibrium price* is defined as the lowest price the supply side would be willing to sell the product (geothermal heat) and the highest price the demand side would be willing to purchase the product. Although the equilibrium price represents an LCOH value (more accurately, two intersecting LCOH values), it is considered distinct from the sets of agent LCOH values and GDU LCOH values, which can take on different values based on the building or resource type. The cumulative capacity associated with this intersection defines the economically viable GDU capacity within the county and, therefore, its economic potential. The sum of all economically viable GDU capacities among all counties determines the national economic potential for GDU at each model time step.

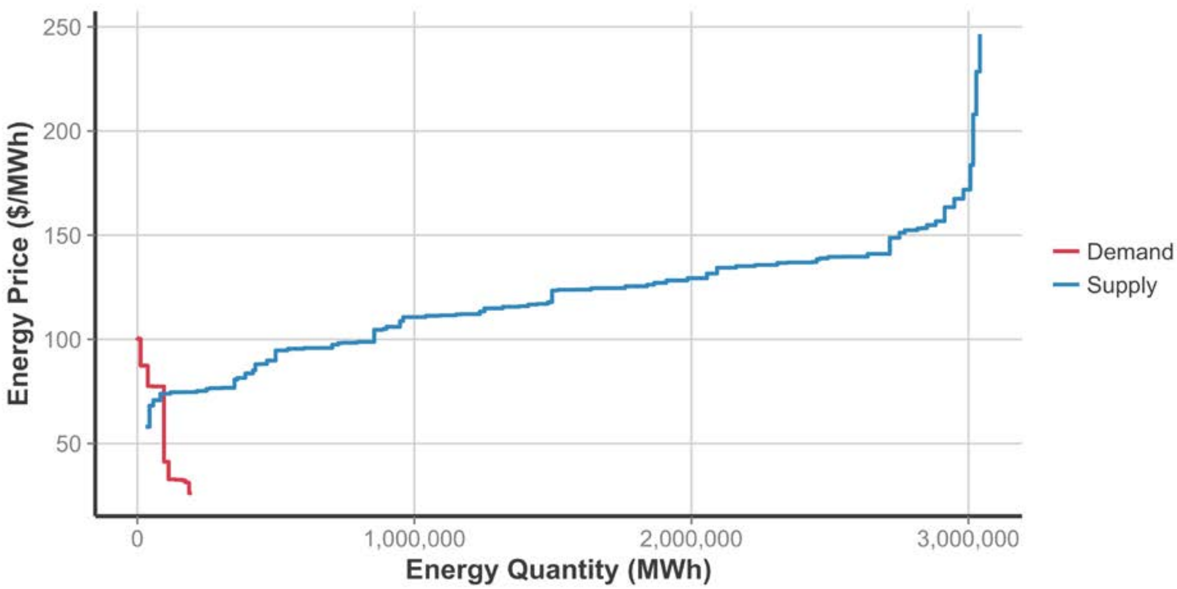

Figure 4. Example of the overlay of demand and supply curves for a single county showing the equilibrium price and quantity for heat. Demand and supply curves like this are developed for each county in the United States for each dGeo run.

2.2.3 Market Potential

Whereas economic potential considers the portion of renewable resources that is economically viable, market potential considers the portion that is likely to be deployed given the reaction of consumers in the market to economic factors. To quantify the market potential for GDH, dGeo employs the same methodology used by other models in the dGen family (Sigrin et al. 2016). This approach determines the maximum market share for each agent, which is defined as the portion of the potential market that would eventually adopt the technology given its level of economic attractiveness.

To quantify the maximum market share, dGeo relies on a series of empirically derived curves that relate the economic attractiveness of technology adoption and maximum market share. Several studies have estimated this relationship based on the payback period of specific technologies, including Sigrin and Drury (2014), Paidipati et al. (2008), EIA (2004), R.W. Beck, Inc. (2009), and Kastovich et al. (1982). For the GDU module, however, the community-scale nature of a district heating project means that the quantification of a payback period is nonintuitive. Instead, the relationship between economic attractiveness and maximum market share is quantified in terms of the percentage monthly bill savings as received by an adopter of or subscriber to a district heating system; Sigrin and Drury (2014) provided such a relationship, as shown in Figure 5.

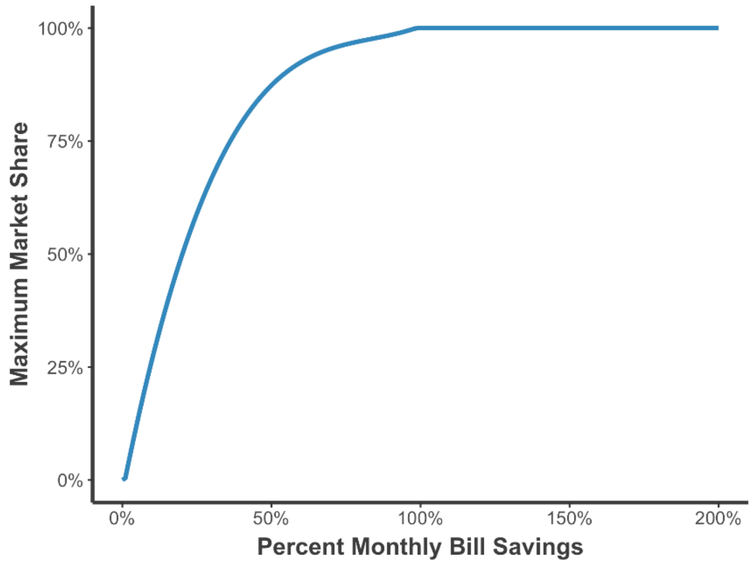

Figure 5. Generalized maximum market share curve as a function of percentage of monthly bill savings (based on Sigrin and Drury [2014])

From the GDU economic analysis, dGeo is able to estimate the percentage monthly bill savings for each potential agent. This percentage monthly bill savings is calculated based on the surplus between each agent's demand LCOH and the equilibrium price for GDU heat (determined by the supply-demand intersection point), divided by the agent's demand LCOH. When there is no surplus (i.e., the equilibrium price exceeds the agent's LCOH), the percentage monthly bill savings is set to zero. Then, using the maximum market share curve for percentage monthly bill savings (Figure 5), dGeo calculates the maximum market share for each agent.

The economic potential estimate is based on the assumption that all buildings with a cost surplus (i.e., the agent LCOH exceeds the equilibrium price) will subscribe to the GDU district heat facility. This assumption does not hold true under the market potential paradigm, where the maximum market share curve suggests that only a portion of buildings with cost surplus will adopt. According to the maximum market share curve, the portion of buildings that would be willing to adopt GDU decreases as the cost surplus decreases. These changes result in a steepening of the demand curve for market potential. This change causes feedback on the equilibrium price and quantity for GDU energy, driving down both equilibrium price and quantity.

To account for this feedback process, dGeo estimates the market potential for each county through an iterative process, repeatedly intersecting the supply and demand curves, determining the maximum market share for each agent, and creating a new demand curve before proceeding to the next iteration. At each iteration, the steepening of the demand curve because of the application of the maximum market share curve results in a reduced equilibrium price, which in turn results in an increased max market share because the agents receive more bill savings. dGeo repeats this process until the equilibrium price and quantity begin to converge, where convergence is defined as a change of less than 10% in the equilibrium price from the previous iteration. Once the results have converged, dGeo uses the resulting quantity of energy and the associated amount of heat capacity as the market potential for GDU for each county.

2.3 Additional Methodological Notes and Possible Related Limitations

As noted in Section 2.1.1, dGeo only considers buildings in the residential and commercial sectors. While certain categories of industry, including subsectors such as agriculture, manufacturing, and mining, is considered a promising use of geothermal heating, the industrial sector as a whole is not modeled by dGeo because of a lack of sufficient data. The existing publicly available data for the industrial sector—most notably, data describing facility structure and energy consumption characteristics—are insufficiently detailed and resolved to capture the key attributes that would drive the technical, economic, and market potential for GDU. As a result, only geothermal district heating as a technological application is modeled for this analysis—other applications of geothermal direct use (e.g., industrial process heat, greenhouse applications, pools/spas) are not considered. Furthermore, district *heating* alone is modeled in this analysis—while geothermal heat could theoretically be used for cooling applications (e.g., in conjunction with absorption chillers), this technology is considered highly niched in nature and is not considered.

With respect to the calculations of the potential metrics outlined in Sections 2.2.1-2.2.3, it should be noted that the step from economic potential to market potential includes an inherent, increased level of uncertainty because of the difficulty in modeling consumer behavior. The maximum market share curve (Figure 5) is not calibrated specifically for adopters of GDH systems and does not include any consideration of the infrastructural requirements of a large-scale system. Nonetheless, the curve captures a sense of acceptance for distributed technologies and can provide what could be considered an upper bound of GDU capacity that is economically viable and consumer accepted.

Beyond the calculation of the market potential, one further step is often included in analyses that use other models in the dGen suite of tools—the adoption of the distributed technology (e.g., rooftop photovoltaics, geothermal heat pumps). In these analyses, the diffusion of innovations framework (Bass 1969) dictates the rate of technology uptake for different agent types as well as the maximum market size. This adoption pattern is characterized by a logistic "S-curve" (Figure 6), itself a function of two key parameters which represent the influence of innovation (p-value) and imitation (q-value) on technology adoption. Traditionally, these parameters are calibrated using historical data that describes the amount and rate of technology adoption over time. The scarcity of installation data for GDH systems in the United States precludes the ability to model adoption with any level of fidelity—this is in contrast with the Thermal Applications Task Force report that details the geothermal heat pump analysis (Liu et al. 2019), which co-opts diffusion parameters from other DERs. Instead, only market potential values are reported for the GDU analysis.

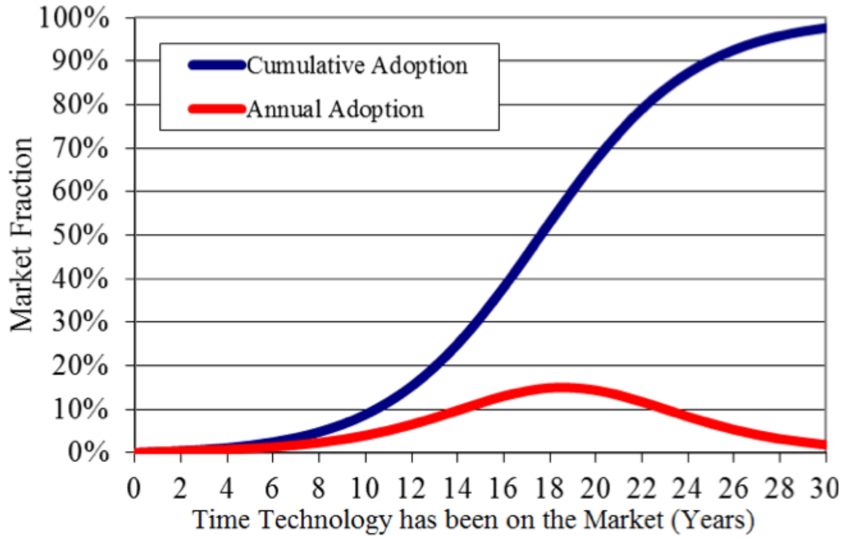

Figure 6. Annual and cumulative adoption rates simulated using the diffusion of innovations framework.

2.3.1 Further Model Development

As noted above in Section 2.3, there is no representation of the industrial sector in the dGeo model because of a lack of sufficiently detailed data. Additional detailed information—in particular, the requisite variation in building-level or facility-level characteristics, such as the efficiency, expected lifetimes, and replacement costs of the equipment at such facilities—is needed to model the industrial sector with greater fidelity. Further, this data is needed at a comprehensive level in order to integrate fully into the dGeo model, which is capable of simulating GDH adoption for the contiguous United States.

Finally, the dGeo model could be further enhanced by gaining a better understanding of the residential and commercial heating market, specifically for GDH technologies. This could be accomplished by developing a maximum market share curve (see Figure 5) that is specific to adoption of GDH systems in both the residential and commercial sectors, and preferably at a geospatial resolution that is fine enough to capture intra-regional tendencies and trends in aspects such as consumption patterns, predominant heating fuels, and general attitudes towards GDH technology. In addition, finding data and/or developing novel calibration methods would improve the adoption modeling by providing the necessary diffusion parameters to understand when and where GDH might be implemented.

3 dGeo Input Parameters

To perform a simulation of GDH deployment over time, the dGeo model relies on dozens of input parameters, including GDH cost, performance, and financing; cost of heating alternatives; and regional geothermal resource potential and thermal demand. This section provides a summary of the research efforts of compiling the necessary dGeo input data.

3.1 Regional Data

The resource potential in dGeo is based on a previous NREL study by Mullane et al. (2016) investigating the location, temperature, and amount of stored heat of low-temperature (<150℃) and relatively shallow (<3,000 m) hydrothermal and EGS resources in the United States. Another NREL study by McCabe et al. (2016) on low-temperature thermal demand in the United States provides the dGeo input data for regional demand for space and water heating in the residential and commercial sector. Regional cost of fuel comes from the EIA *Annual Energy Outlook* projections (EIA 2016d). The costs of alternative space heating systems (e.g., natural gas furnace) were based on data developed by Xiaobing Liu at Oak Ridge National Laboratory, a collaborator on the *GeoVision* study (Liu 2010; Liu, Warner, and Adams 2016). Fuel costs and alternative system costs were used in dGeo to estimate the heating bill savings.

3.2 GDH Cost, Performance, and Financial Data

A study by Beckers and Young (2017) on GDH cost, performance, and financial parameters provides the basis for the dGeo input data for the LCOH calculation of GDH systems. This study provided a review of more than 40 U.S. and international geothermal studies as well as the studies by the other *GeoVision* task forces to derive BAU and TI scenario values for 31 performance, cost, and financial parameters. Where applicable, the dGeo values use those derived by other *GeoVision* study task forces (e.g., exploration and drilling costs) for the *GeoVision* electricity sector analysis to provide consistency. Most of these parameters common to both the heat and electricity sector analyses are subsurface related and were assessed by the Exploration and Confirmation and Reservoir Maintenance and Development task forces (e.g., well capital, operation-and-maintenance cost, EGS well flow rate, and exploration costs) (Doughty et al. 2018; Lowry et al. 2017). Other parameters, though relevant and studied by the other task forces, are not directly transferable to GDH. For example, the discount rate used for calculating the cost of financing is assumed to be less for GDH systems than power plants because GDH systems are considered (in dGeo) to be financed with low-interest municipal bonds and run by municipalities. Finally, some parameters are unique to GDH and are based on a review of external studies (e.g., the heat distribution network and central plant capital and operation-and-maintenance costs, the GDH construction period, and typical peaking boiler sizing and efficiencies).

4 Potential Technology Improvements

4.1 GDH LCOH Sensitivity Analysis to Determine High-Impact Parameters

A literature review of techno-economic studies on GDH (and GDU in general) was conducted (Beckers and Young 2016) to identify parameters that have the biggest impact on GDH LCOH. The LCOH metric is considered to assess the techno-economic feasibility of a GDU installation because it captures both costs and technical performance aspects of GDU systems and allows for easy comparison with other space and water heating technologies.

The seven parameters that have the biggest impact on LCOH are geothermal gradient, drilling capital cost, well flow rate, discount rate, system lifetime, reinjection temperature, and surface capital cost (system lifetime shows up in two categories but refers to the same parameter), as shown in Figure 7, and they can be grouped into three categories:

1. **Geothermal reservoir system**: drilling costs, well flow rate, geothermal gradient, and system lifetime (i.e., reservoir lifetime).
2. **User application**: surface equipment capital costs, reinjection temperature, and system lifetime (i.e., equipment lifetime).
3. **Financing**: discount rate.

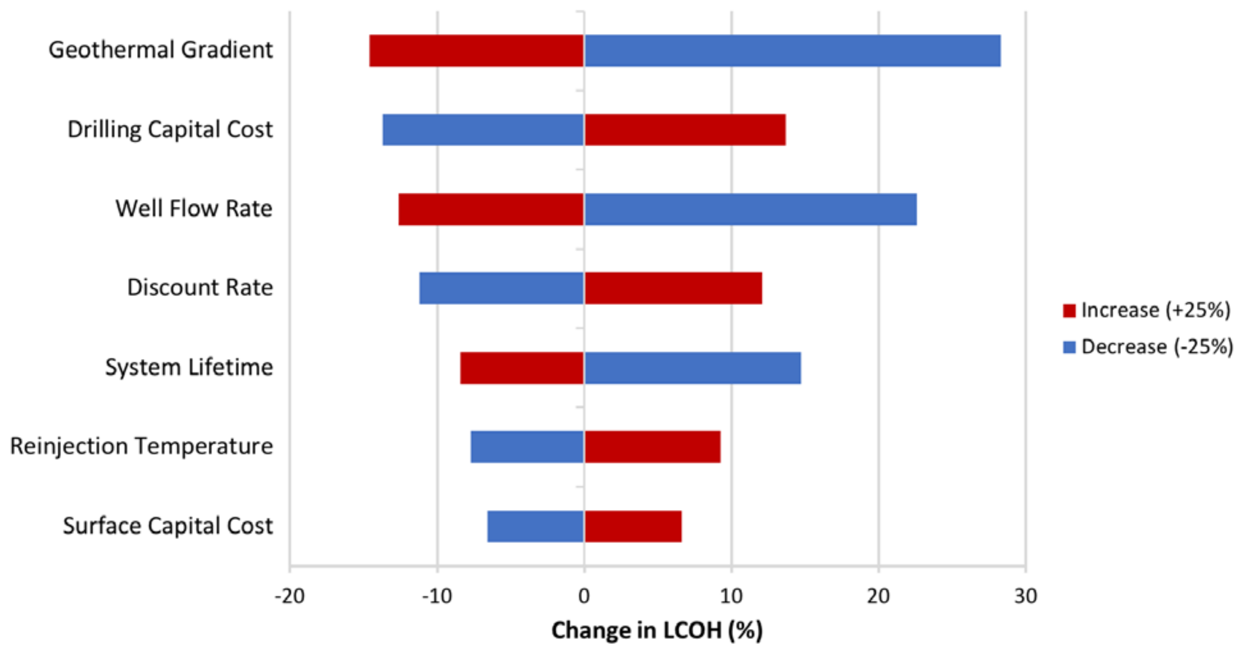

Figure 7. Tornado chart showing sensitivity of LCOH to seven parameters. The chart shows the impact on LCOH by increasing parameter value by 25% (red bars) and decreasing parameter value by 25 % (blue bars) with respect to its reference value. Parameters are ranked from most (top) to least (bottom) impact on decreasing LCOH. Data are based on a study by Reber (2013). This figure suggests that the geothermal gradient has the most impact on LCOH. Because the geothermal gradient is set by nature and cannot be modified through technological improvements, it is not discussed as a potential technology improvement. The next three parameters—drilling capital

cost, well flow rate, and discount rate—can be modified through technology improvements to reduce LCOH and are discussed in more detail in this section.

Of these seven parameters, three have more potential to decrease LCOH through technological improvements:

1. **Drilling capital cost:** Because of the high drilling cost per well (e.g. $2.5 million for a 2,000-m well in the BAU scenario), and because several wells are required for a GDH system, any decrease in drilling cost significantly reduces the overall LCOH. The drilling capital cost can be decreased, for example, by developing advanced drill bits with high lifetime (to reduce tripping time) and by developing advanced drilling techniques to better handle lost circulation zones (to decrease overall drill time). The BAU and TI scenario drilling costs assumed in dGeo are taken from the drilling cost study by the Reservoir Maintenance and Development Task Force (Foris 2016), which assumes an approximate 50% drop in drilling cost in the improved scenario.
2. **Well flow rate:** Because drilling wells is expensive, increasing the amount of thermal energy extracted per well (i.e., increasing the well flow rate assuming the same reservoir lifetime) significantly reduces the overall project LCOH. The well flow rate can be increased by proper reservoir design and management and stimulating the reservoir to increase well productivity and injectivity. The flow rate assumed for hydrothermal system wells was taken from the geothermal low-temperature resource assessment by Mullane et al. (2016) and stays constant in the TI scenario (31.5 L/s). For EGS wells, the flow rate comes from the Reservoir Maintenance and Development Task Force, and it significantly increases from the BAU to the TI scenario (from 40 to 110 L/s).
3. **Discount rate:** Reducing the discount rate significantly decreases the GDH LCOH. A reduced discount rate can be achieved for GDH by reducing the risk (e.g., through resource exploration) or shifting the project from a private entity to a government/community entity, as is usually the case for GDH projects (which results in reduced interest rates and increased time horizons). In dGeo, municipal GDH systems are assumed, and therefore the assumed BAU discount rates are already low. The discount rate is reduced in the TI scenario because of an increase in exploration success rates.

4.2 dGeo BAU and TI Scenarios

Two GDH scenarios were analyzed for the *GeoVision* study:

1. The BAU scenario*,* which incorporates current and anticipated technical, cost, and financial parameter values of GDH systems, assuming similar market conditions for the next 30 years or more and no investments made to improve technology or financing parameters.
2. The TI scenario, which assumes improvements to some GDH parameters, including technical, cost, and financial parameters. The improvements include: (1) a 50% reduction in drilling costs, (2) an increase in EGS well flow rate from 40 to 110 L/s, (3) an approximate 15% decrease in discount rate, and (4) an average 15% decrease in exploration-related costs. These improvements are modeled to occur gradually (linearly) from 2016 to 2030 and stay constant through 2050.

The supply curves for these two scenarios are provided in Figure 8, showing an average reduction in LCOH in the TI scenario of approximately 20%.

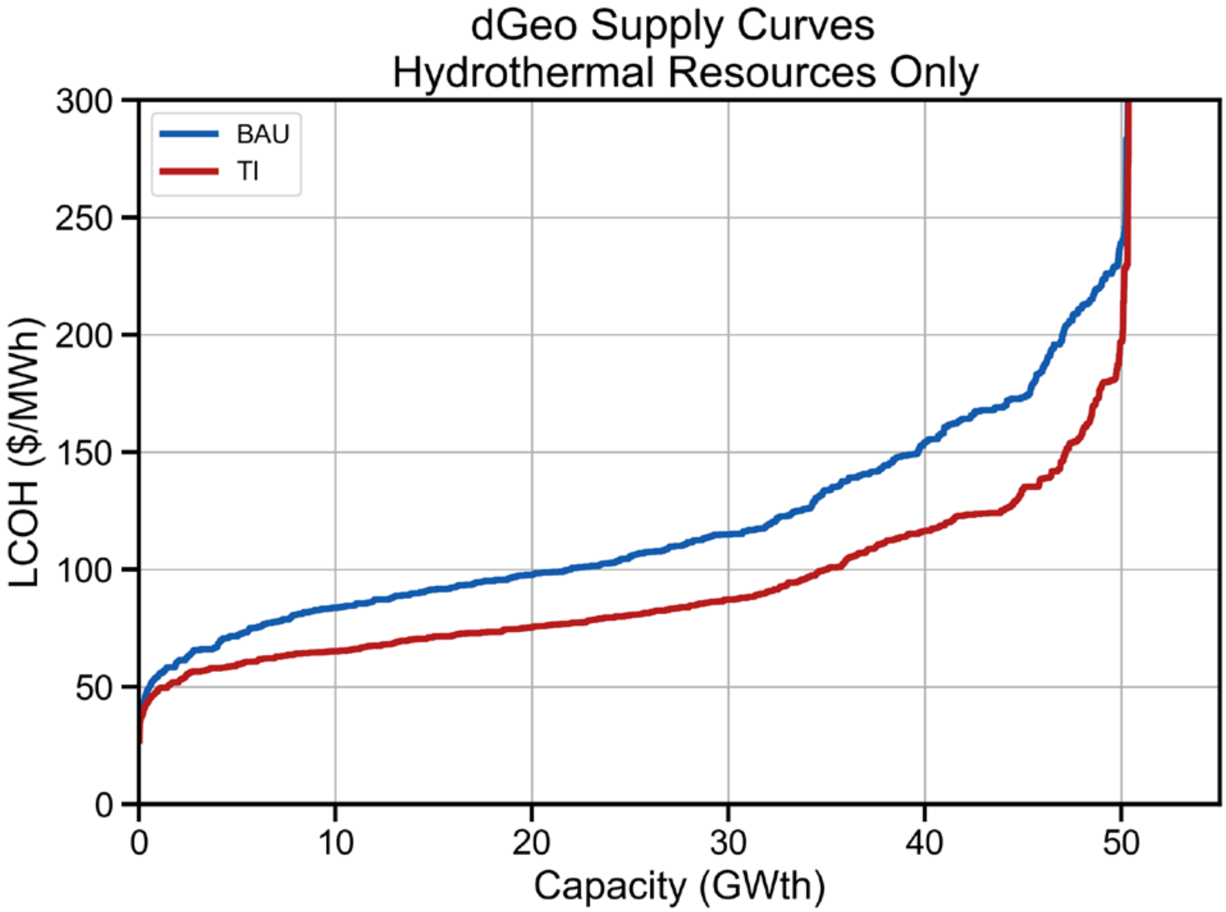

Figure 8. Supply curves for the BAU and TI scenarios—only hydrothermal resources are shown.

5 Analysis of dGeo Results

This section provides the latest results for the BAU and TI scenarios, which are run for the years 2014 through 2050. Results are presented in terms of resource potential, technical potential, economic potential, market potential, LCOH, and average system size.

5.1 Overview

The results of the two scenarios (BAU and TI) are discussed in the following sections. Prior to 2030, only hydrothermal resources are considered for development, and the estimates for technical, economic, and market potential are moderate. After 2030, the two scenarios assume that EGS is commercially viable, and its massive resource base increases the estimates of the potential values relative to the values for hydrothermal resources only. The assumption that EGS resources become fully viable in 2030 was a modeling decision adopted by the Potential to Penetration Task Force and shared in part by this analysis—while the electricity sector modeling assumes a gradual increase in the availability of EGS resources from 2024 to 2030, the GDU analysis assumes that all resources become available in 2030. This assumption was based on consensus among the *GeoVision* Visionary Team in addition to current research efforts, such as those taking place at the DOE Geothermal Technologies Office's Frontier Observatory for Research in Geothermal Energy (FORGE) site (DOE 2018). For further discussion, see Augustine, Ho, and Blair (2019). An overview of the dGeo results is presented in this section, with more detailed descriptions of the technical (Section 5.2), economic (Section 5.3), and market potential (Section 5.4) provided in subsequent sections.

5.1.1 BAU Scenario Results

The technical potential for hydrothermal resources in the BAU case is 27 GW_{th}, the economic potential is 2.8 GW_{th}, and the market potential is 1.0 GW_{th} (see Figure 9, hydrothermal column). As expected, the estimates for the potential values of the combined resource base comprising both hydrothermal and EGS resources are significantly larger than the estimates of the hydrothermal resources alone. When EGS is available for development, the combined hydrothermal/EGS technical potential is 1,186 GW_{th} and is equal to the total thermal demand in the United States for space and water heating in both the residential and commercial sectors (assuming a capacity factor of 25%). The estimates for economic and market potential are also much greater, at 116 GW_{th} and 48 GW_{th} respectively, representing an increase of more than 40 times the hydrothermal-only potential values (see Figure 9, EGS column).

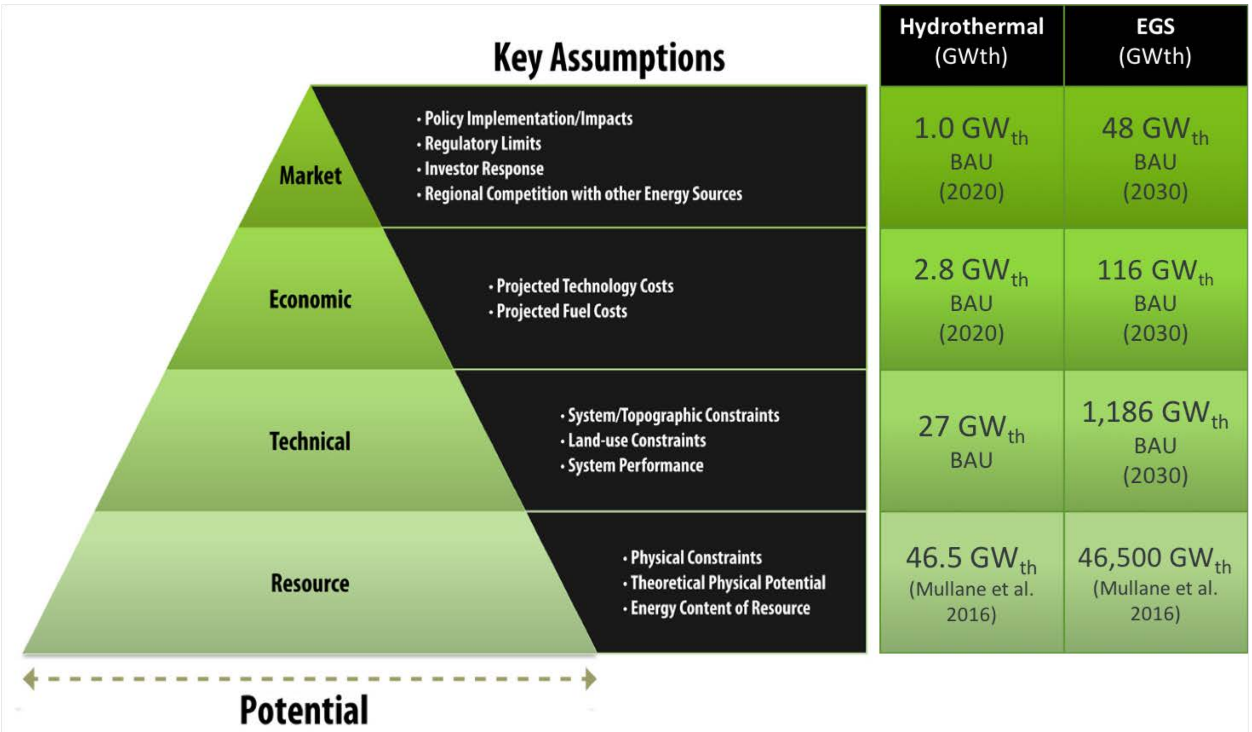

Figure 9. Estimates of potential for BAU scenario broken down by hydrothermal and combined hydrothermal/EGS resources. Technical potential for the combined resource base matches demand and varies slightly over time with demand (Figure 12); technical potential capacity shown is for the year 2030. Economic potential varies over time (Figures 13, 14); economic potential capacity shown is for the years 2020 (hydrothermal) and 2030 (hydrothermal + EGS). Market potential varies over time (Figures 19, 20); market potential capacity shown is for the years 2020 (hydrothermal) and 2030 (hydrothermal + EGS).

5.1.2 TI Scenario Results

The modeling results have a similar trend in the TI scenario, where the technical, economic, and market potential values for the combined hydrothermal/EGS resource base far exceed those of the hydrothermal resources alone (Figure 10). Comparing the results of the BAU (Figure 9) and the TI (Figure 10) scenario results, data show that the resource and technical potentials remain constant because of their independence from economic parameters, and the hydrothermal potentials show only a moderate increase between the scenarios because of their limited geographical locations in the model. The values for the combined hydrothermal/EGS resource base, however, jump up significantly between the two scenarios. With improved cost, technology, and financing parameters, the amount of economically viable GDU capacity increases from 116 GW$_{th}$ to 315 GW$_{th}$, nearly doubling the BAU scenario potential. The market potential also increases dramatically, from 48 GW$_{th}$ of total GDU potential in the BAU scenario to 172 GW$_{th}$ in the TI scenario—more than triple the amount.

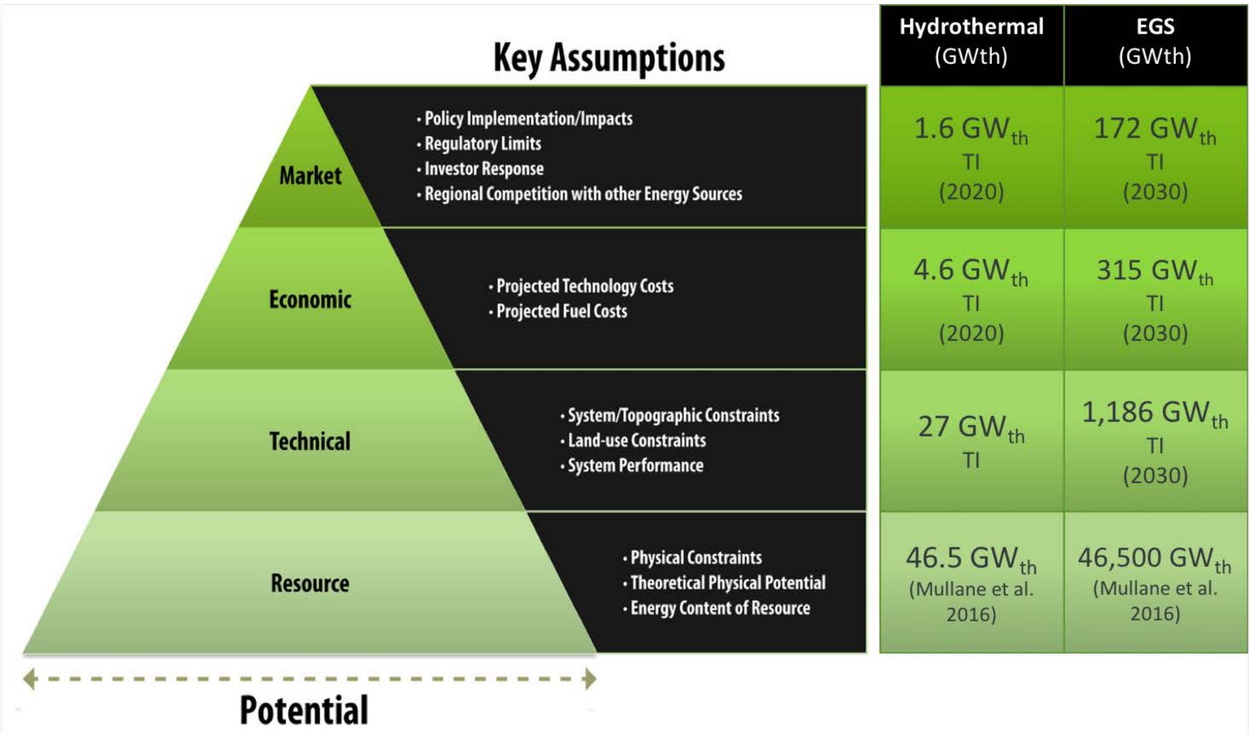

Figure 10. Estimates of potential for the TI scenario, broken down by hydrothermal and combined hydrothermal/EGS resources. Technical potential for the combined resource base matches demand, and it varies slightly over time with demand (Figure 12); technical potential capacity shown is for the year 2030. Economic potential varies over time (Figures 13, 14); economic potential capacity shown is for the years 2020 (hydrothermal) and 2030 (hydrothermal + EGS). Market potential varies over time (Figures 19, 20); market potential capacity shown is for the years 2020 (hydrothermal) and 2030 (hydrothermal + EGS).

5.2 Technical Potential

As mentioned in Section 2.2.1, the technical potential represents the quantity of energy generation potential of these resources that is technically feasible without considering whether that potential is economically viable or likely to be deployed. Figures 11 and 12 plot the technical potential of the two scenarios modeled in this effort: the BAU and TI scenarios. The figures are separated into charts showing years prior to 2030 (Figure 11) and all model run years (Figure 12) to better view the magnitudes of technical potential associated with each resource type. As is expected for technical potential, which is agnostic to economic parameters, the value is largely unchanging over time. Figure 11 represents the amount of technically feasible (i.e., colocated with demand) capacity of hydrothermal resources and is constant at 27 GW_{th} through 2028.

When the EGS resource is available in 2030, the amount of colocated resource and demand increases dramatically. The resource far exceeds the total thermal demand for space and water heating in both the residential and commercial sectors, so the technical potential reported is capped at the total U.S. thermal demand in each year. This value increases slightly over time to reflect the thermal load growth over time but remains largely constant at approximately 1,190 GW_{th}.

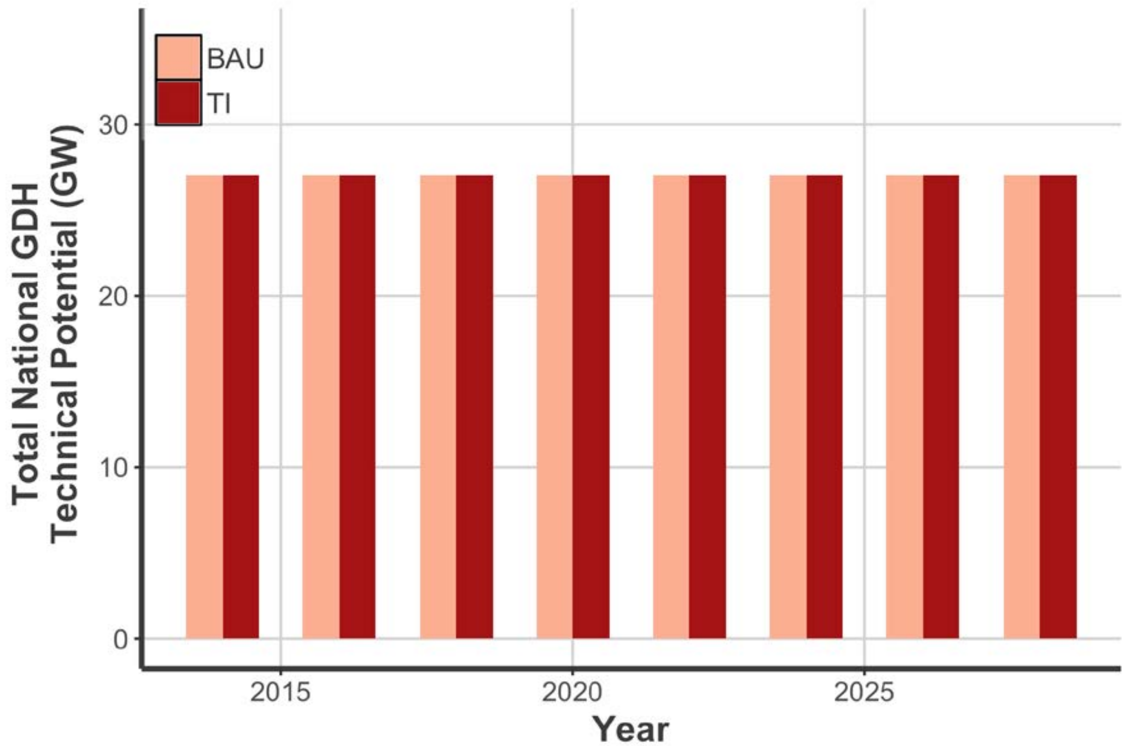

Figure 11. Technical potential for hydrothermal resources. The technical potential does not change over time because the hydrothermal resources are known and unchanging in their properties throughout the model run.

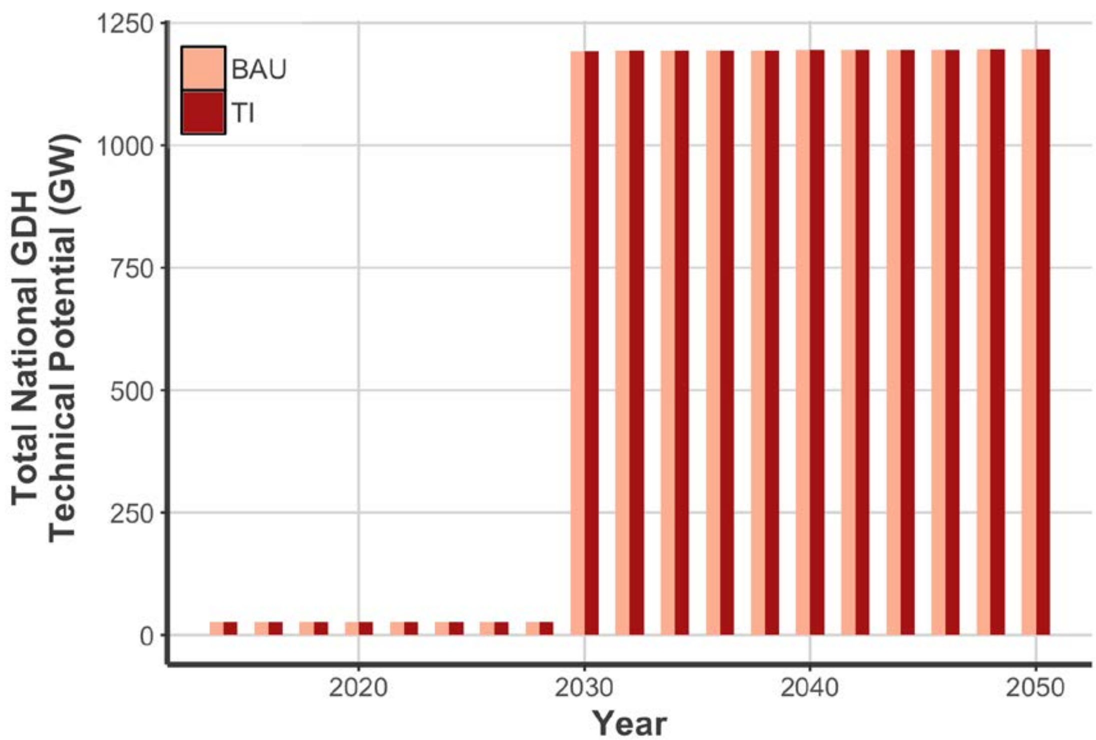

Figure 12. Technical potential for all resources (hydrothermal + EGS). The large increase in potential beginning in 2030 is due to the modeling assumption that EGS resources all become available in that year. Though imperceptible given the figure scale, the technical potential from

2030–2050 increases slightly to match increased demand, a result of building and thermal load growth.

5.3 Economic Potential

5.3.1 BAU and TI Scenarios

The estimation of the economic potential for GDU is shown in Figures 13 and 14. Because the economic potential calculation considers time-variant factors such as thermal load growth, incentive availability, or user-defined cost and technology inputs, the plots of potential over time capture these time-dependent trends. In particular, fuel prices have a significant effect on the economic viability of a GDH system, and fuel price variability can drive the attractiveness of GDH as fossil fuel prices increase. Figure 15 shows the national average price inputs for the four main fuel types modeled in dGeo (EIA 2016d) and demonstrates their time-dependency. The dip in fuel prices in 2016 and the subsequent recovery are reflected in Figure 13, where the economic potential for both scenarios follows a similar trend; as fossil fuel prices increase, so does the economic potential for GDH systems. As mentioned in Section 1.1.1, a spike in the number of GDU installations throughout the 1970s and 1980s correlated with high fossil fuel prices. The model results from dGeo show a similar relationship between fuel prices and economic and market potential, further demonstrating the strong linkage between the deployment of GDH systems and energy prices.

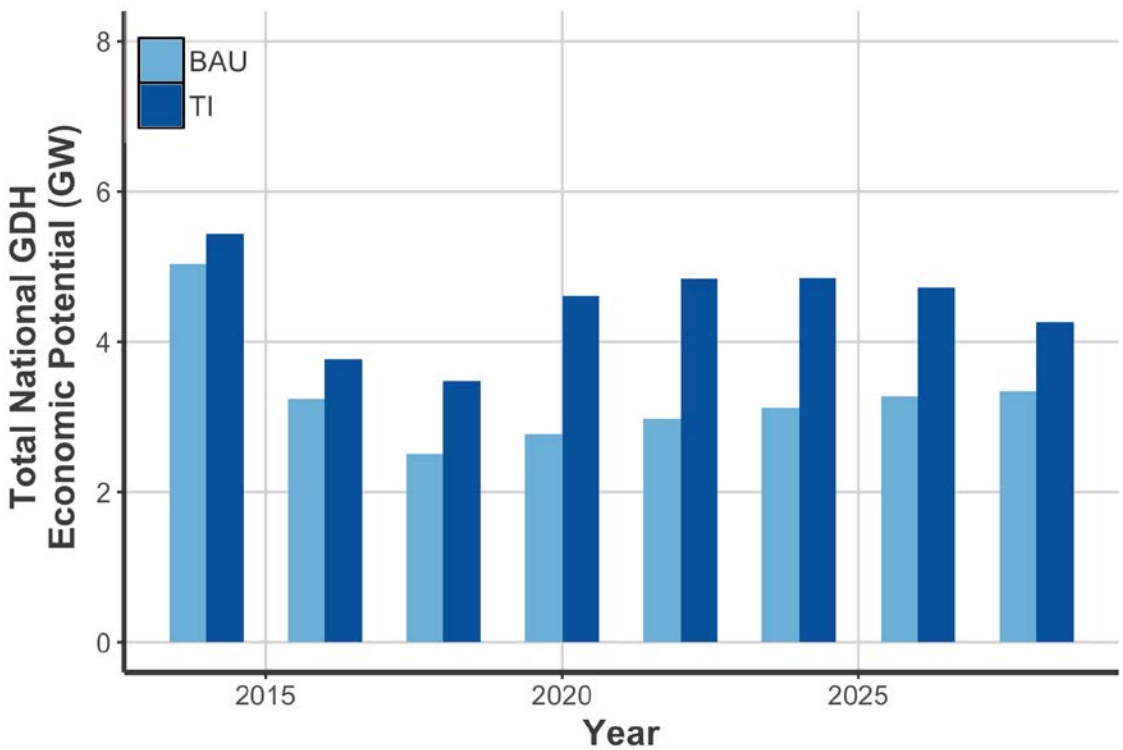

Figure 13. Economic potential for hydrothermal resources. The change in economic potential reflects the dependence on time-dependent parameters such as fuel prices, building/load growth, and any user-defined inputs that vary with time (e.g., exploration cost improvements or plant financing terms).

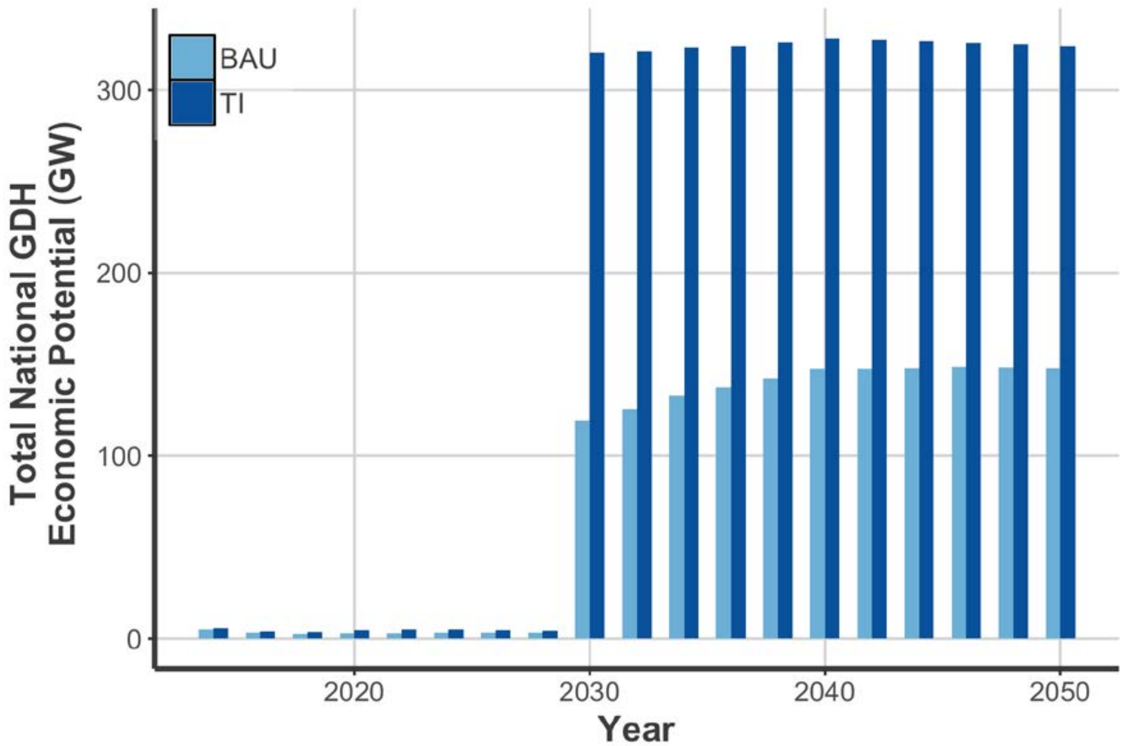

Figure 14. Economic potential for all resources (hydrothermal + EGS). The large increase in potential beginning in 2030 is due to the modeling assumption that EGS resources all become available in that year. The change in economic potential reflects the dependence on time-dependent parameters such as fuel prices, building/load growth, and any user-defined inputs that vary with time (e.g., exploration cost improvements or plant financing terms).

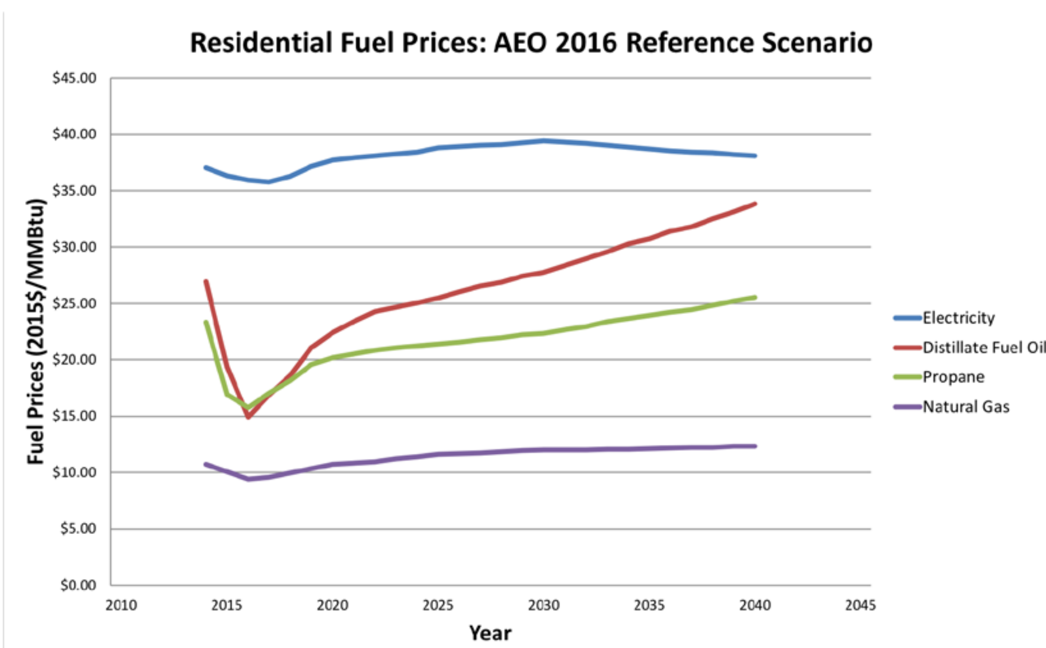

Figure 15. National averages of residential sector fuel prices for the main fuels modeled in dGeo

5.3.2 Fossil Fuel Price Scenarios

To further explore the effect of increased fuel prices on economic potential, two sensitivity studies were completed. Specifically, the two studies use the *Annual Energy Outlook* Low Oil and Gas Resource and Technology and High Oil Price scenarios. Figure 16 demonstrates the price trends compared with the Reference scenario. The Low Resource scenario shows a larger increase in natural gas prices over time compared to the reference case, whereas the High Oil Price scenario shows larger increases in the other fuels (especially fuel oil) over time compared to the reference case.

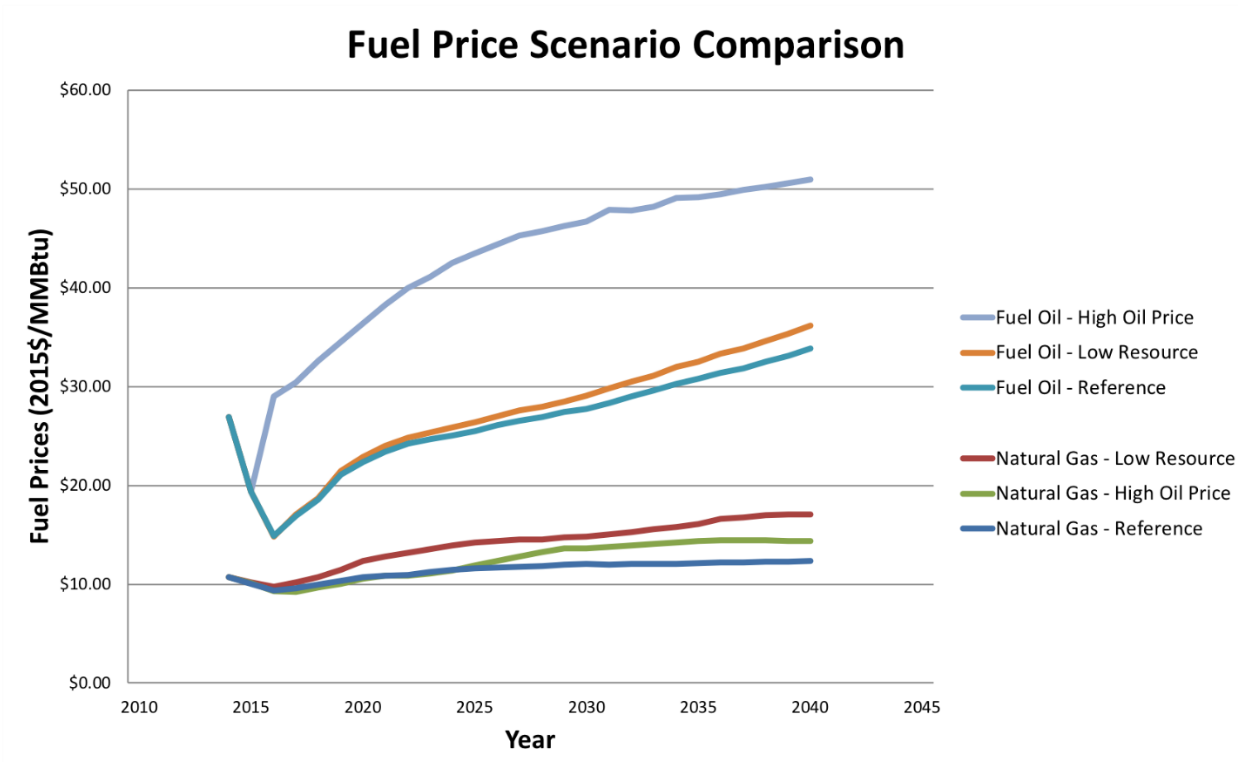

Figure 16. Natural gas and fuel oil prices for residential sector (national average), comparison among *Annual Energy Outlook* Reference, Low Oil and Gas Resource and Technology, and High Oil Price scenarios

Figures 17 and 18 show the effect of the fuel price sensitivities on the economic potential in the BAU case for hydrothermal and all resources (hydrothermal + EGS), respectively. There is a clear increase in the amount of economically viable district heating capacity when fuel prices are increased. This is intuitive because as the price of the "competition" (e.g., baseline heating, ventilating, and air-conditioning technologies and fuels) increases, the more attractive a low-cost alternative (GDH) becomes. The plots show that the potential is most sensitive to the High Oil Price scenario, where all fuels see an increase in price relative to the reference case, but the more expensive fuels especially see a large increase. This is also intuitive because the more expensive fuels (e.g., fuel oil) already represent the most attractive replacement for a district heating system; increasing these already high prices has an increased effect than increasing only natural gas prices.

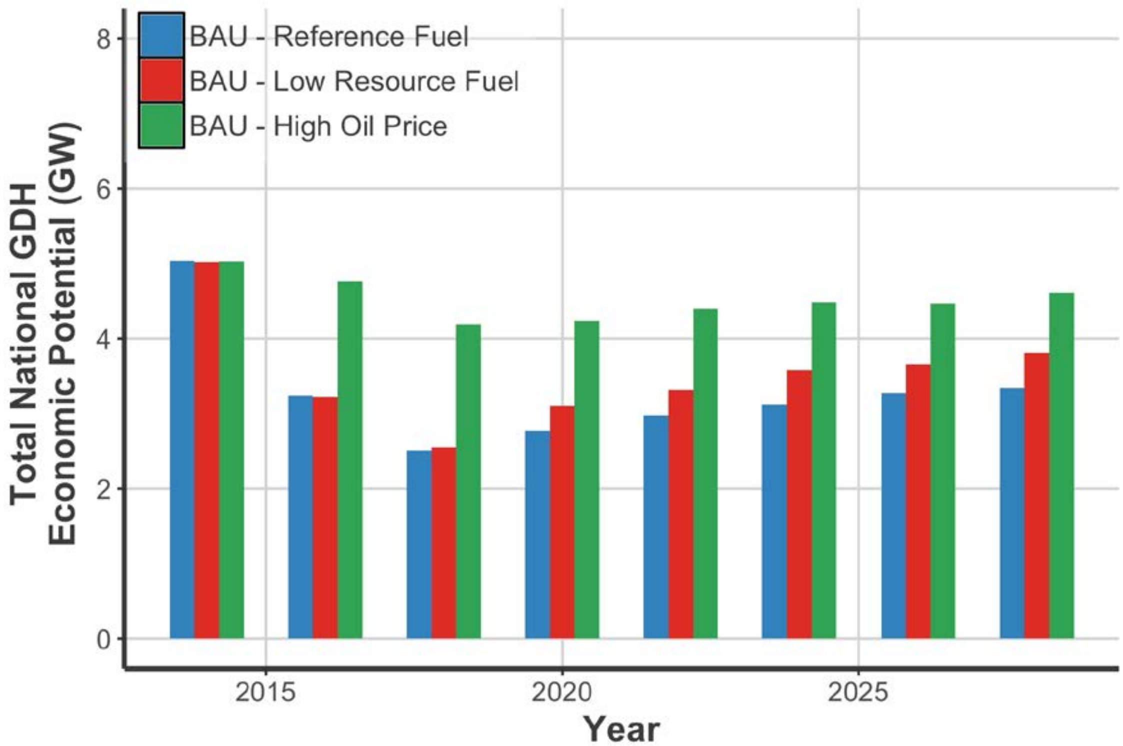

Figure 17. Sensitivity of economic potential (BAU scenario) to different fuel price projections for hydrothermal resources. The fuel price projections are based on AEO scenarios (EIA 2016d) and represent future price projections for each of the heating fuels modeled in dGeo (e.g., natural gas, electricity, propane, fuel oil). For example, the "BAU – Low Resource Fuel" bar in the graph represents the BAU assumptions for costs and technology inputs combined with the AEO Low Oil and Gas Resource and Technology scenario, which projects higher natural gas prices than the

Reference Fuel conditions (and, to a lesser extent, higher fuel oil, propane, and electricity prices as well).

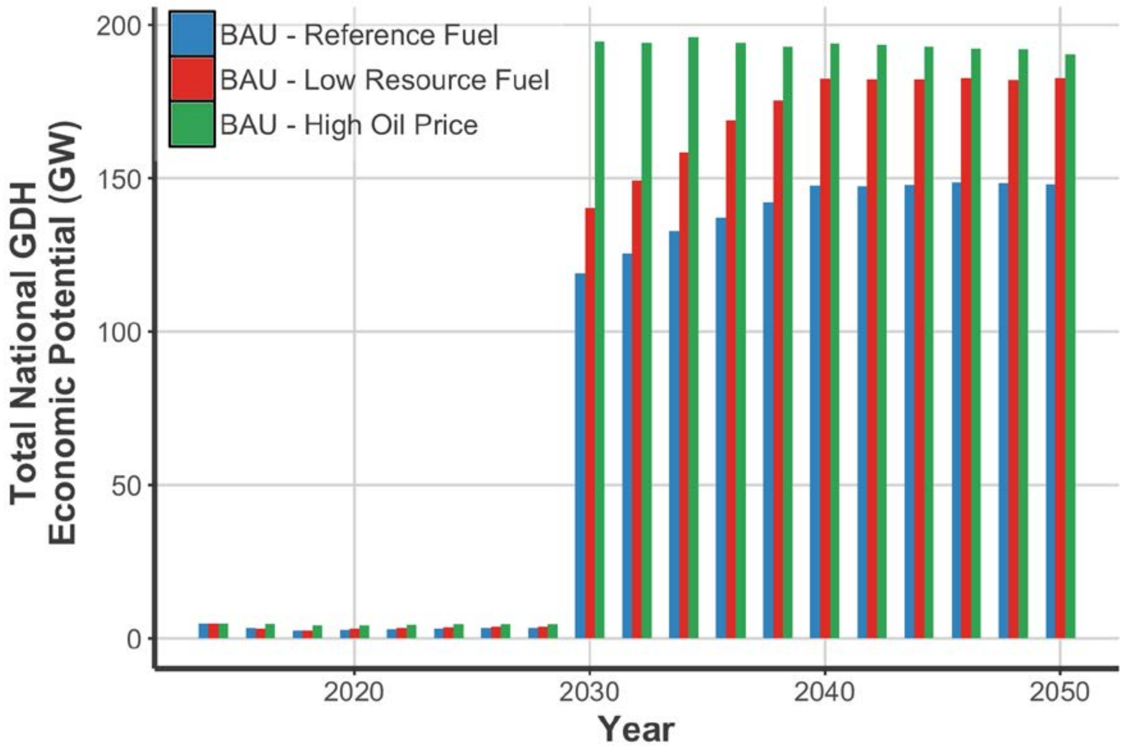

Figure 18. Sensitivity of economic potential (BAU scenario) to different fuel price projections for all resources (hydrothermal + EGS). The large increase in potential beginning in 2030 is due to the modeling assumption that EGS resources all become available in that year. The fuel price projections are based on AEO scenarios (EIA 2016d) and represent future price projections for each of the heating fuels modeled in dGeo (e.g., natural gas, electricity, propane, fuel oil).

5.4 Market Potential

As stated previously in Section 2.2.3, the market potential, as calculated in dGeo, considers the amount of GDH that is likely to be deployed given the reaction of consumers in the market to economic factors. The difficulty in quantifying this relationship between economic attractiveness and market share means that there is an inherent and unavoidable amount of uncertainty when moving from economic potential to market potential. The calculation of market potential relies on a single, empirically derived curve that is not specific to GDH technology and instead was developed in the context of the adoption of rooftop photovoltaic systems. Future work could be done to better characterize the relationship between monthly bill savings and max market share; for the results presented here, the magnitude of uncertainty suggests that the estimates of market potential should be considered an upper bound.

Because the market potential represents a subset of the economic potential, the temporal trends in the plotted results are similar when viewed by resource type and by scenario. The same factors that influence the economic potential exist in market potential, such as load growth, fuel prices, and user-defined cost and technology inputs. Figures 19 and 20 follow the same structure as Figures 13 and 14 in the economic potential results section. Figure 19 highlights the market potential values for hydrothermal resources only, and Figure 20 shows all the results through 2050, especially capturing the EGS results after 2030.

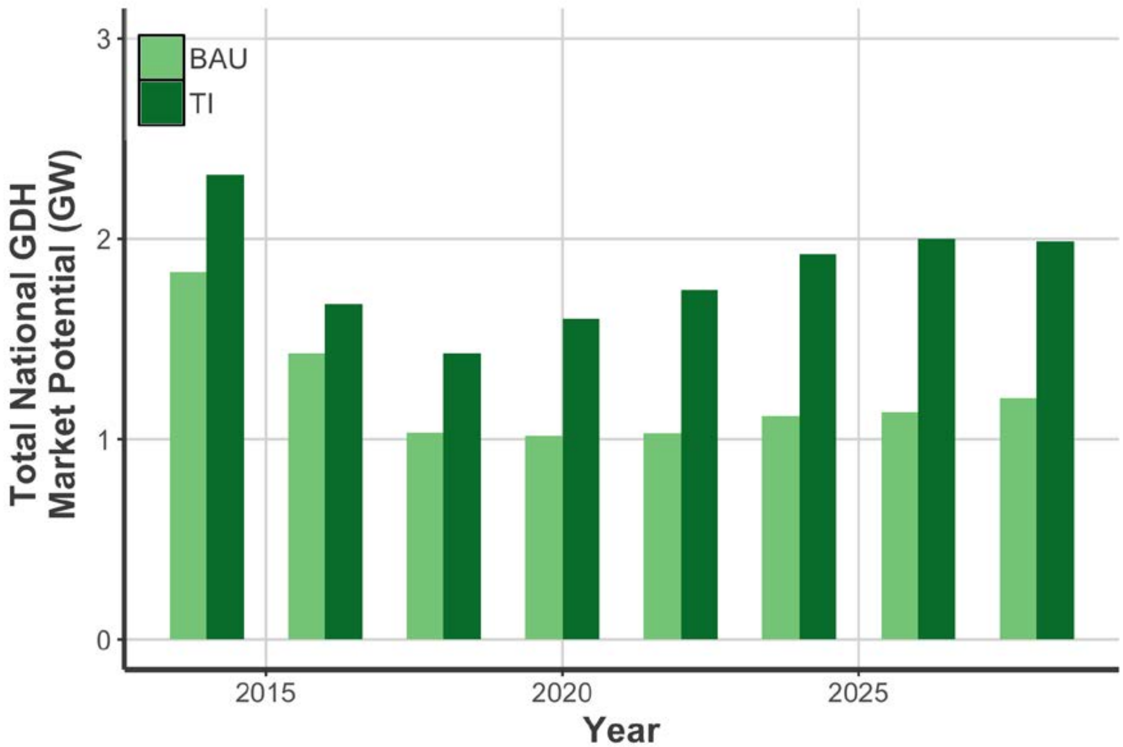

Figure 19. Market potential for hydrothermal resources. The change in market potential reflects the dependence on time-dependent parameters such as fuel prices, building/load growth, and any user-defined inputs that vary with time (e.g., exploration cost improvements or plant financing terms).

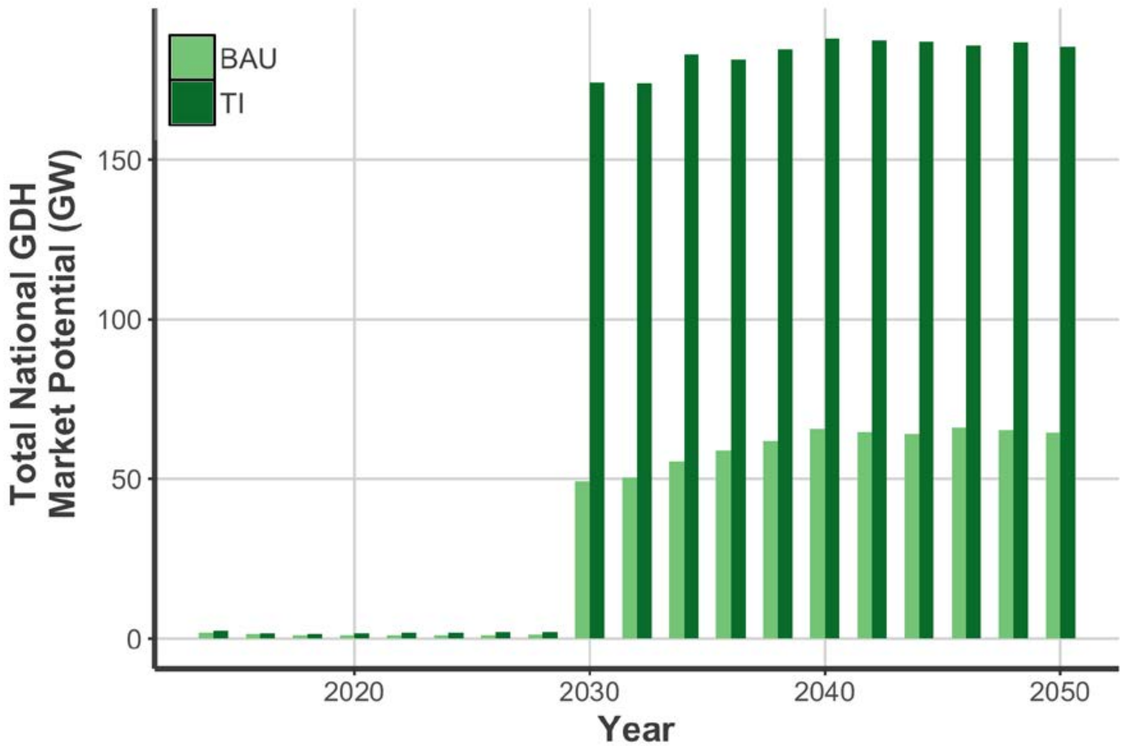

Figure 20. Market potential for all resources (hydrothermal + EGS). The large increase in potential beginning in 2030 is due to the modeling assumption that EGS resources all become available in that year. The change in market potential reflects the dependence on time-dependent parameters such as fuel prices, building/load growth, and any user-defined inputs that vary with time (e.g., exploration cost improvements or plant financing terms).

6 Spatial Trends in GDH System Viability

This section provides several maps that show model outputs at the county-level resolution, such as LCOH values for both consumers and geothermal resources, the "relative favorability" for district heating systems, and economic potential. These outputs are all functions of underlying spatial trends in the data, especially the regional fuel prices and predominant fuel types in each region of the United States.

6.1 Current Fuel and Agent LCOH

Figure 21 shows relevant fuel types plotted at the county resolution. In areas where heating source is most expensive—for example, in areas where fuel oil or electricity are the predominant sources—it is expected that the viability for geothermal district heating systems would be heightened.

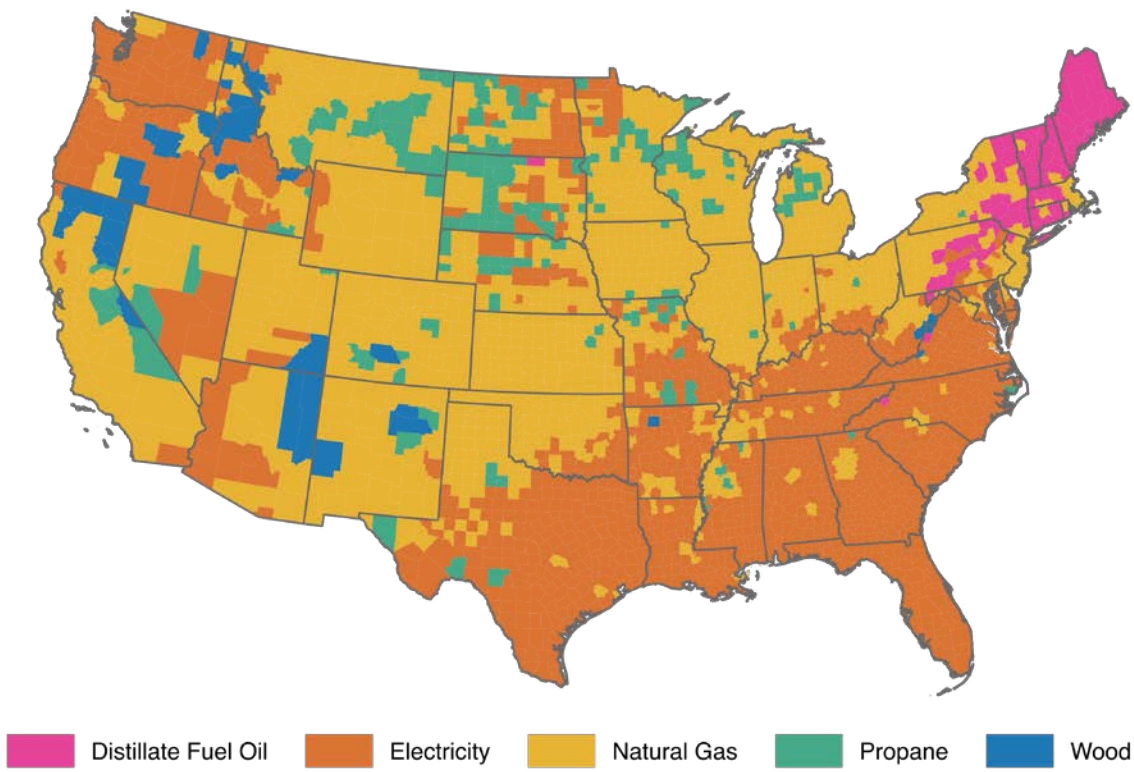

Figure 21. Map of predominant heating fuel by U.S. county

Figure 22 shows the average agent LCOH value by U.S. county for the BAU scenario in 2050. Here, agent LCOH is defined as the weighted average of space and water heating costs by fuel, calculated as:

$$LCOH = \frac{E_{spht} * P_{spht} + E_{wtht} * P_{wtht}}{E_{spht} + E_{wtht}} \quad \text{(Eq. 2)}$$

where *LCOH* is the agent LCOH value, E_{spht} and E_{wtht} are the space heating and water heating consumption values [kWh] for the agent, and P_{spht} and P_{wtht} are the fuel price values [$/kWh] for the agent's fuel type. There is a clear trend of increased agent LCOH values that exists in the northeast (New England) and mid-Atlantic regions of the United States and to a lesser extent in the Pacific Northwest. This closely follows the geospatial trends seen in Figure 21, where areas that predominantly use more expensive heating fuel types (e.g., fuel oil and electricity) demonstrate higher LCOH values.

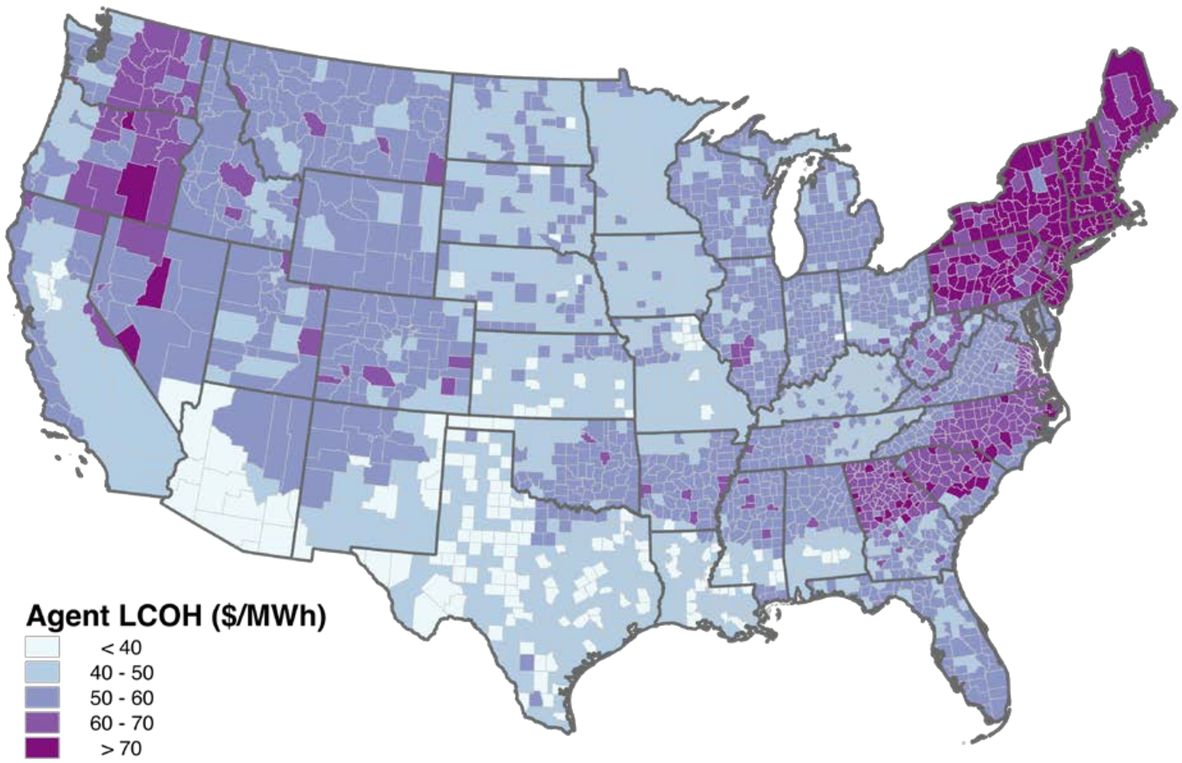

Figure 22. Agent LCOH values summarized at the county level—BAU scenario (2050)

6.2 BAU Scenario: GDH Resource LCOH and Favorability

Similarly, Figure 23 shows a map of the average resource LCOH by county. The regional trends for the geothermal resources exist on a larger scale, where virtually the entire northern half of the United States demonstrates a relatively reduced LCOH value for the aggregated resources available by county. In terms of GDH viability, a low resource LCOH is favorable and is calculated as a function of a number of parameters, including the user-defined cost, technical, and financial parameters, and perhaps most importantly, the total heat demanded in a given region. In the southern half of the United States, where total heating consumption is relatively low, the decreased capacity factor results in an increased resource LCOH.

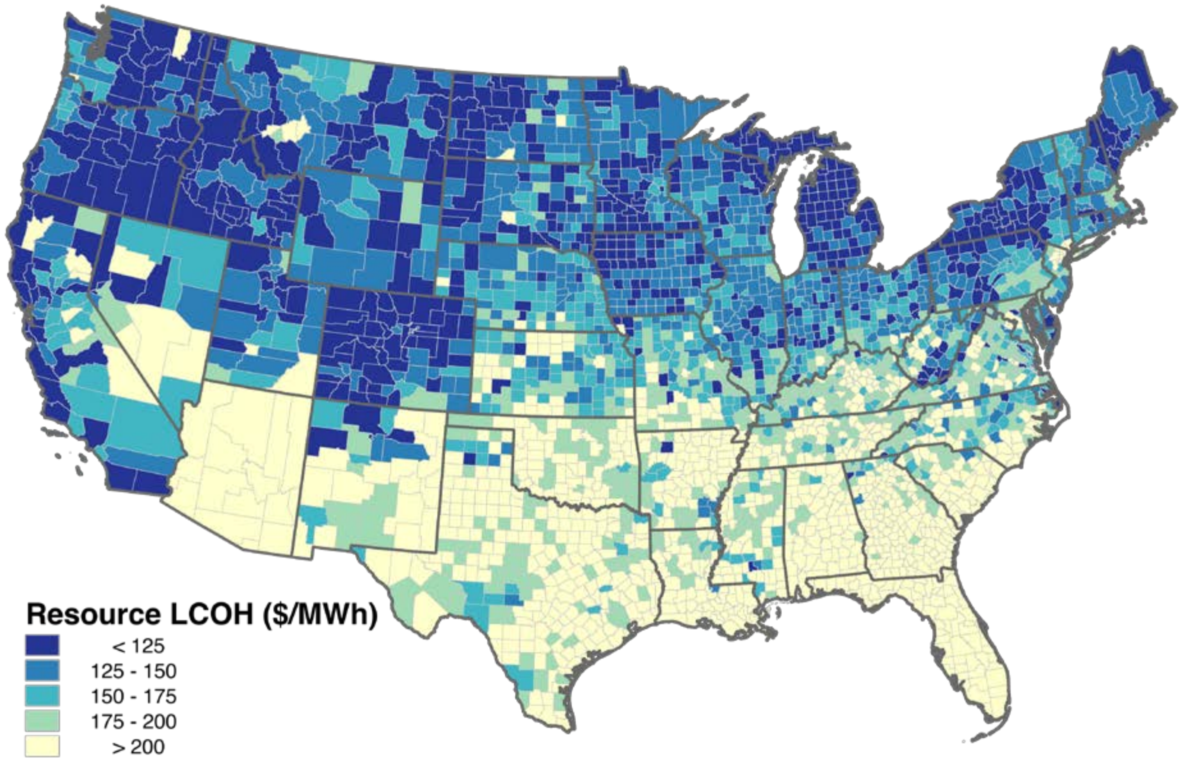

Figure 23. Resource LCOH values summarized at the county level—BAU scenario (2050)

When the county-level values for agent and resource LCOH, as shown in Figures 22 and 23, are combined, a "relative favorability" value can be calculated. This is loosely defined as the difference between the agent LCOH and resource LCOH, where the areas of "Poor" favorability are generally valued at a difference of -$100/MWh and below and the areas of "Good" favorability represent those near the breakeven point ($0/MWh difference). Where this difference between agent LCOH and resource LCOH is greatest, the relative favorability of a geothermal district heating system over the baseline alternative is also greatest, represented for the BAU scenario in Figure 24 by the areas in green.

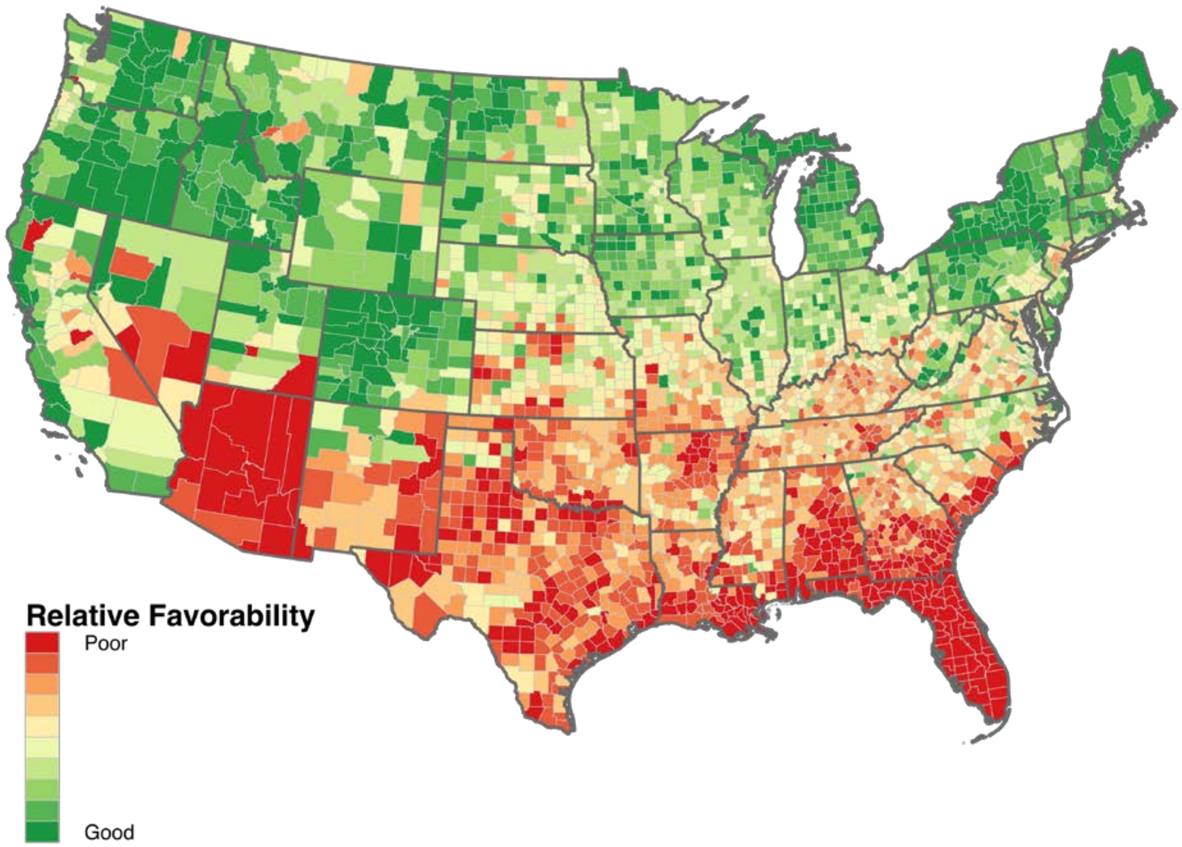

Figure 24. Relative favorability of geothermal district heating systems in the BAU scenario (2050)

6.3 TI Scenario: GDH Favorability and Economic Potential

Although similar figures for agent and resource LCOH for the TI scenario are not shown here, the relative favorability map is given in Figure 25, which demonstrates the effect of reduced costs, improved technology, and favorable financing on the viability of district heating systems by county. In the TI scenario, the areas of "Good" favorability increase dramatically, given the same scale from the BAU map (Figure 24). While the favorability scale is meant to be qualitative in nature, the map demonstrates that improved cost, technology, and financing parameters can improve the outlook for GDH in nearly every region of the United States.

To visualize this more quantitatively, the county-level map of economic potential for the TI scenario is shown in Figure 26, where the aggregate capacity of GDH systems is given in units of MW_{th}. Again, spatial trends that follow previously mapped layers emerge in the map of economic potential—most notable are the Northeast and New England regions, which tend to use more expensive heating fuels and therefore have higher fuel costs and agent LCOH values. Another key geospatial trend illuminated by Figure 26 is the colocation of elevated economic potential and population centers throughout the United States (e.g., the Twin Cities area in Minnesota and the metropolitan areas surrounding Denver and Seattle). This demonstrates that the viability of GDH systems depends not only on the existence of a feasible geothermal resource, but also on the proximity of a demand center which can utilize this supply.

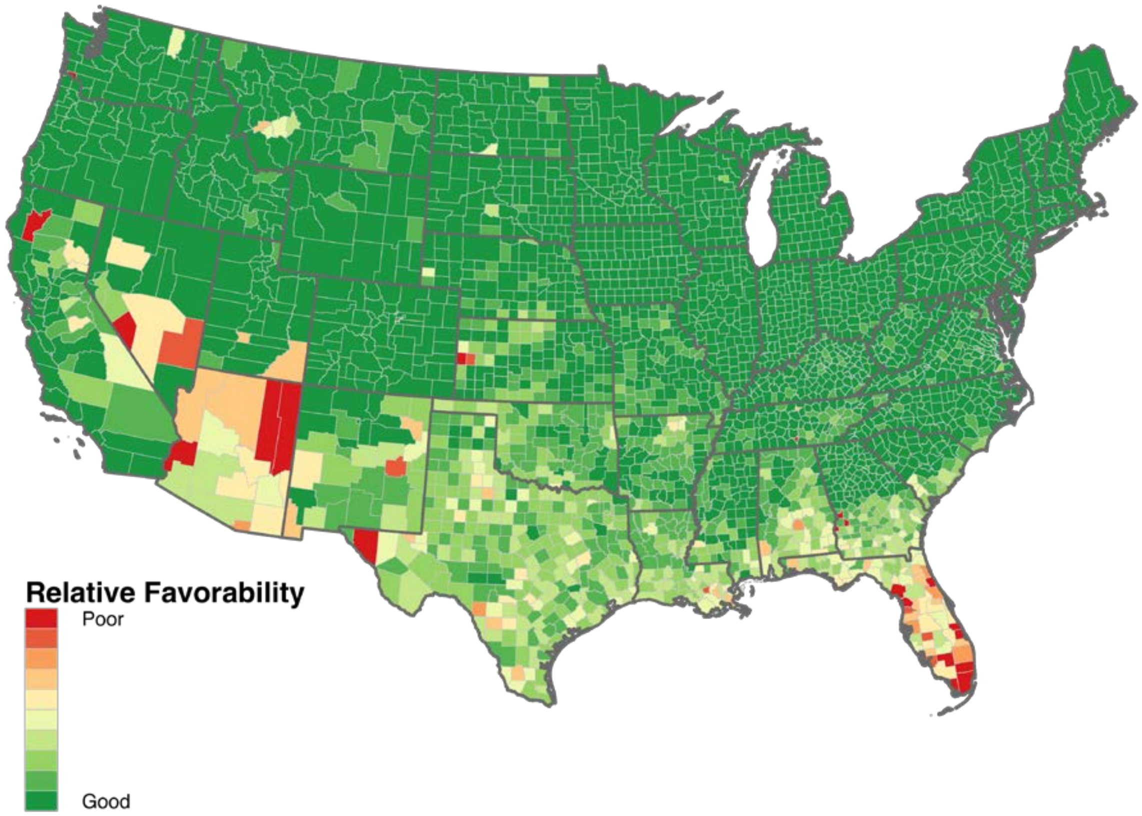

Figure 25. Relative favorability of geothermal district heating systems in the TI scenario (2050)

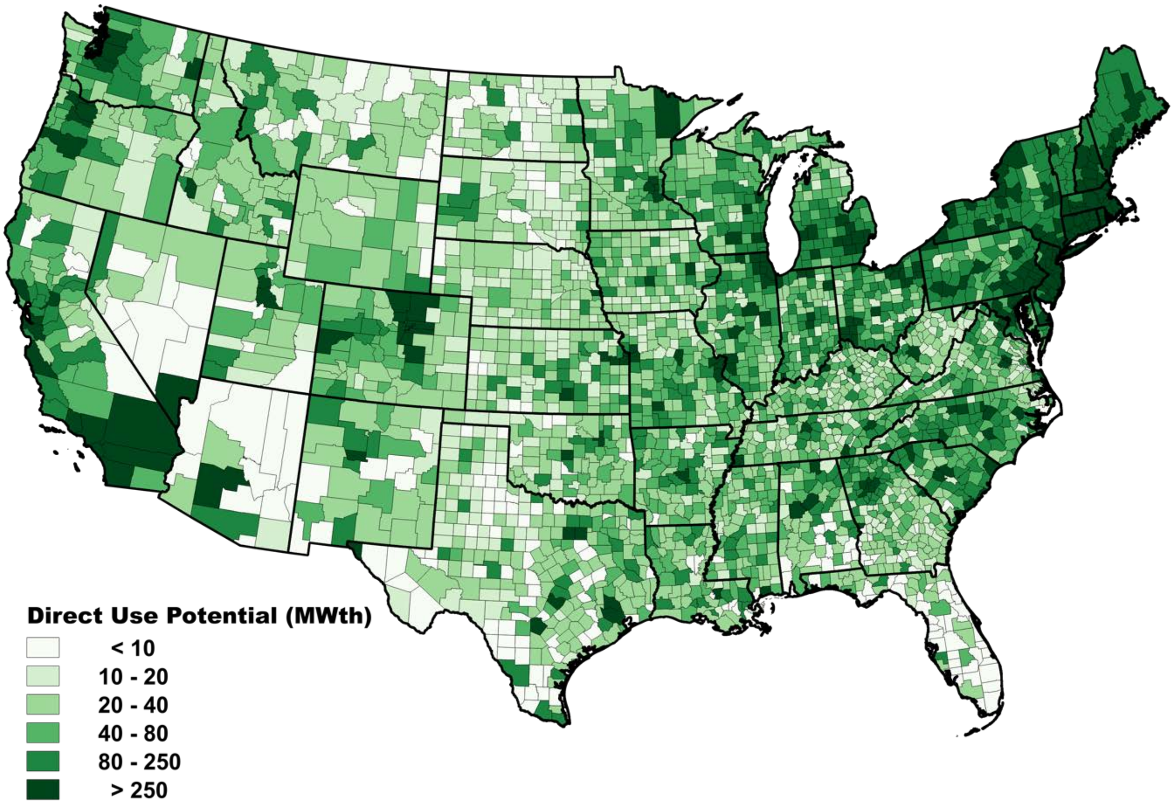

Figure 26. Economic potential (MW_{th}) of GDH systems in the TI scenario (2050)

7 Comparison of dGeo Results

Results from dGeo runs were compared to values found in the literature to check for reasonableness, including the results for market potential, GDH system size, and GDH LCOH.

7.1 Comparison of Market Potential Results

The hydrothermal market potential calculated by dGeo (Section 5.1) is 1 GW_{th} in the BAU scenario and 1.6 GW_{th} in the TI scenario. These dGeo market potential numbers are compared in Figure 27 with the current hydrothermal installed capacity in United States, European countries, and Europe. The dGeo-estimated market potential of 1 to 1.6 GW_{th} is considered reasonable because it is of the same order of magnitude as current installed capacity in Europe (4.7 GW_{th}).

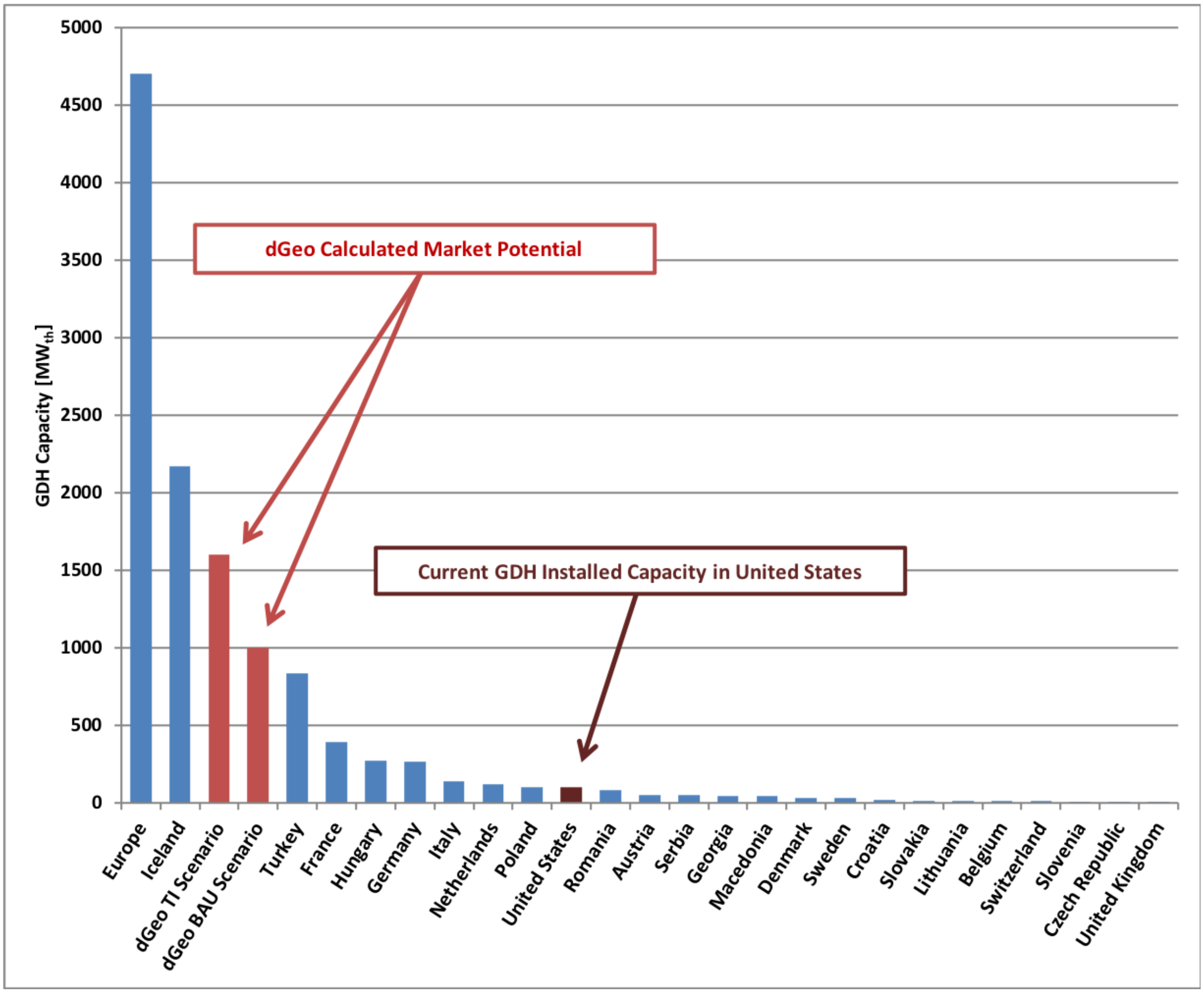

Figure 27. Comparison of dGeo calculated hydrothermal market potential (in MW_{th}) with current installed capacity in the United States and European countries. Current values for the European countries are taken from EGEC (2016) and for the United States from Snyder, Beckers, and Young (2017).

Compared to the current installed capacity in the United States (100 MW_{th}), achieving the full market potential by 2050 would mean deploying 1 to 1.6 GW_{th} during the next 40 years, corresponding to 25 to 50 MW_{th}/year. These deployment numbers are comparable to recent deployments in Europe: Iceland installed 2 GW_{th} in 40 years (from 1970 to 2010) (Petursson 2015), and the current European deployment rate during the last 4 years ranged between 93 to 150 MW_{th}/year, as shown in Figure 28. Market potential for EGS resources cannot be compared with actual deployment data from the literature because only a few EGS demonstration sites exist. Developing the full EGS market potential in the United States starting in 2030 through 2050 would require deployment rates of 2.5 GW_{th}/year in the BAU scenario and 10 GW_{th}/year in the TI scenario. These deployment rates are about two orders of magnitude higher than current deployment rates of hydrothermal GDH systems in Europe.

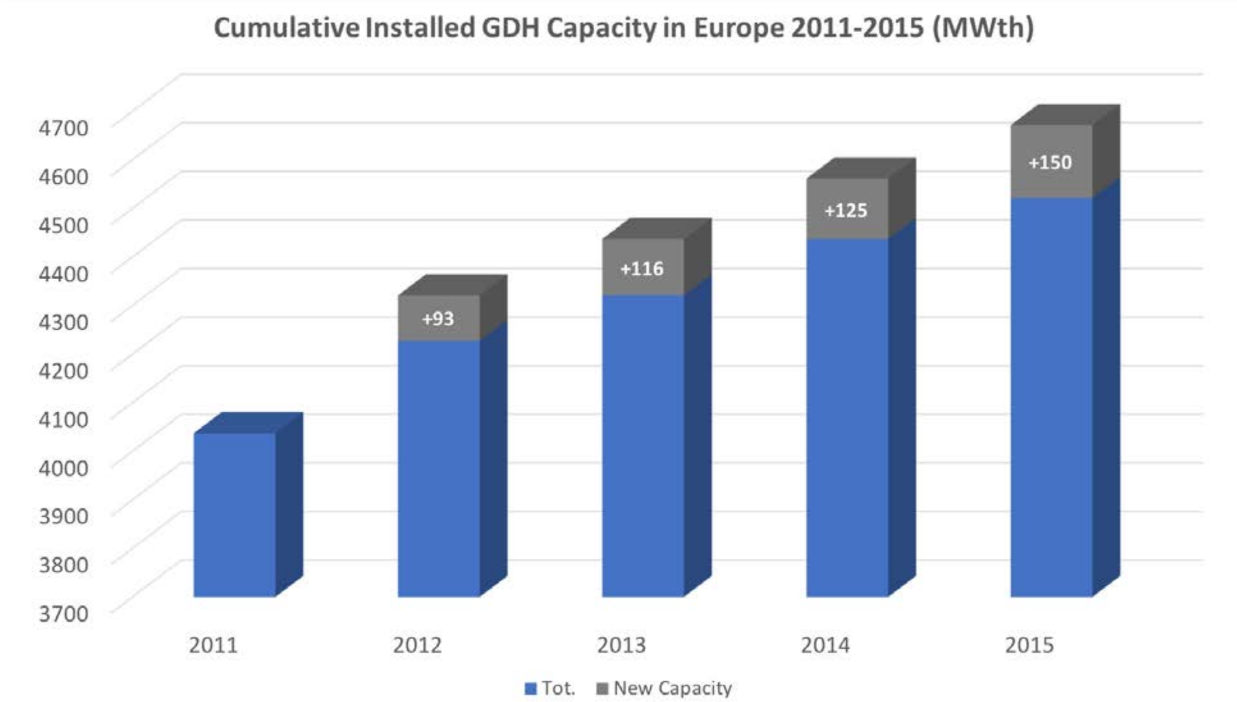

Figure 28. Cumulative installed GDH capacity in Europe and the deployment rate from 2011 to 2015 (EGEC 2016)

Reasons for increased deployment in Europe include increased prices for alternative heating sources such as natural gas (see Figure 29) and aggressive government targets and support schemes for developing renewable resources in Europe. Figure 30 shows binding 2020 targets for share of renewable energy in gross final energy consumption for several European countries and actual share in 2005 and 2015. The gross final energy consumption includes all energy uses (electricity, transportation, heating, etc.). For some countries, the targets are more than 30%. The current share of renewables in gross energy consumption in the Unites States is about 10% (EIA 2016d). Table 1 provides an overview of government support schemes for renewable (and nonrenewable) heat-based district heating systems for seven European countries. The main type of support is government support with the initial investment—this broadly includes government-provided financial incentives and public financing mechanisms, such as France's renewable heat support scheme Fonds Chaleur, which provides U.S. $455 million to support renewable heat in the industrial, residential, and district heating sectors (REN21 2016).

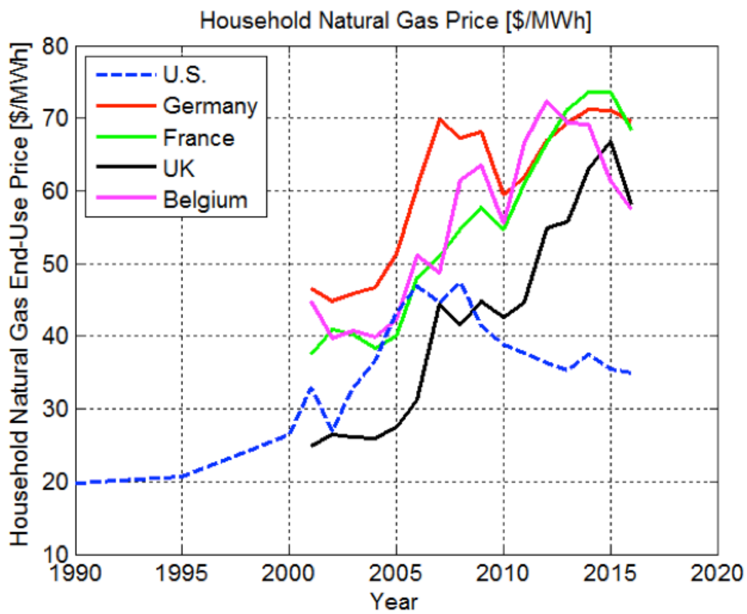

Figure 29. Household natural gas end-use price (in $/MWh) in the United States and select European countries. The household natural end-use price has been up to 50% less in the United States with respect to several European countries during the last 15 years because of the development of shale gas predominantly in North America, Argentina, and China but not in other parts of the world.

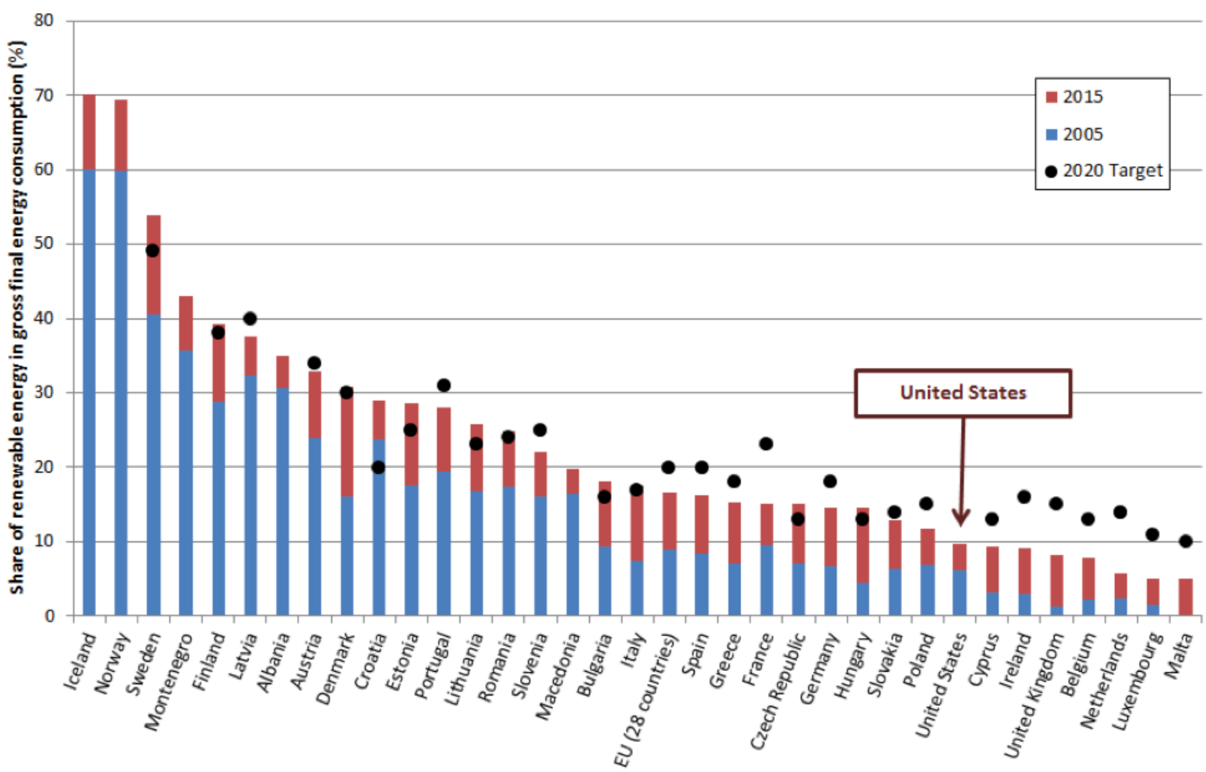

Figure 30. Share (in percentage) of renewable energy in gross final energy consumption for European countries and the United States in 2005 (blue bars) and 2015 (red bars). Binding 2020 targets for European Union countries set by the 2009 Renewable Energy Directive are included as

black circles. Data for Europe is from Eurostat (2016). Data for the United States is from EIA (2017).

Table 1. Government Financial Support Schemes for Renewable Heat-Based District Heating Systems and District Heating System in General in Selected European Countries[a]

Country	Renewable Heat-Based District Heating Support	General District Heating Support
Austria	Investment support (government-provided financial incentives, public financing mechanisms)	Investment support (national and regional level)
Denmark	District heating investment support	Tax advantage and investment support
Estonia	Investment support	None
Germany	Investment support at federal and municipal level	Investment support at federal and municipal level
Hungary	Investment support	Reduced tax level
Poland	Low-interest loans	None
Sweden	Carbon dioxide emissions taxes	None

[a] Table modified from Towards2030 (2015)

7.2 Comparison of GDH System Size Results

The average GDH system size calculated by dGeo in the BAU and TI scenarios is 9.3 MW_{th} and 18.4 MW_{th}, respectively. These values are considered reasonable because they fall in the range of values for average system size in European countries, as shown in Figure 31. The current average system size for Europe is 18.3 MW_{th} (4,702 MW_{th} for 257 systems).

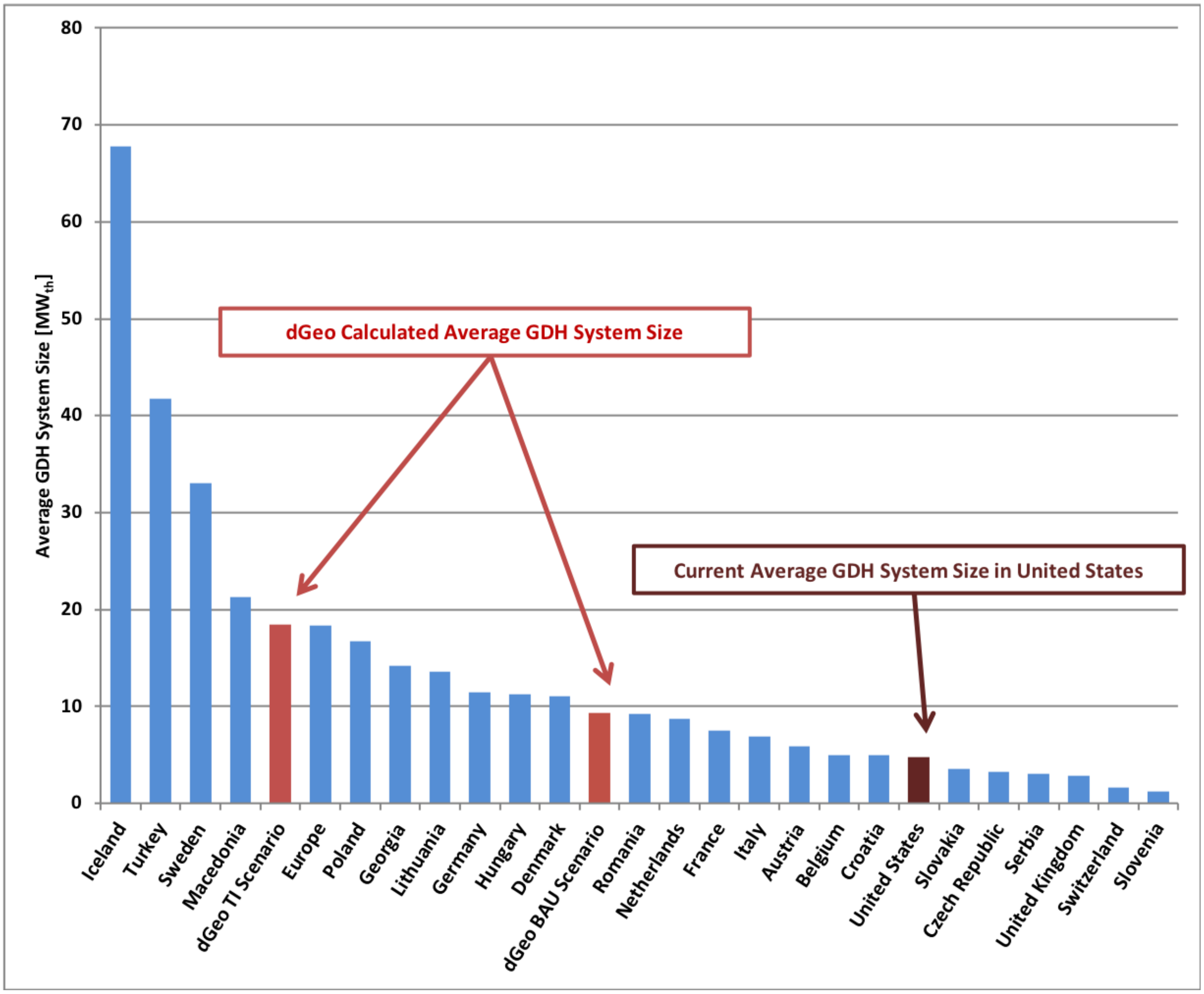

Figure 31. Average GDH system size in Europe, United States, and calculated by dGeo for the BAU and TI scenarios. System size values for Europe are taken from EGEC (2016) and for the United States from Snyder, Beckers, and Young (2017).

7.2.1 Comparison of GDH LCOH Results

The GDH LCOH values estimated in the dGeo model matched well with published values for LCOH of existing and modeled GDH systems.

The average market potential LCOH value for hydrothermal resources calculated in dGeo for the BAU scenario is \$68/MWh, with an interquartile range of \$56 to \$79/MWh. For EGS resources, the average is \$89/MWh, with an interquartile range of \$78 to \$102/MWh. For the TI scenario, the values for hydrothermal are \$63/MWh and \$51 to \$71/MWh, and for EGS \$68/MWh and \$55 to \$75/MWh. A comparison of these numbers with actual and simulated values reported in the literature for the United States and Europe is provided in Table 2. The dGeo hydrothermal LCOH values for the BAU scenario (\$56 to \$79/MWh) are higher than the values for two existing U.S. GDH systems (\$27 and \$51/MWh). This is expected because the Bluffdale and Lakeview systems have limited distribution network costs because they each provide heating to only one customer (a prison). In comparison with current hydrothermal systems in Europe (\$21 to \$85/MWh), the dGeo values fall in this range but are on the high end. This is explained by:

1. On average, reduced heat distribution network and retrofit costs in Europe because of more compact cities and mostly hydronic-based heating systems
2. Higher-grade hydrothermal resources, especially in Iceland, Turkey, and Italy (i.e., reduced drilling costs and/or more thermal energy per well).

The dGeo-simulated LCOH values for EGS in the BAU scenario ($78 to $102/MWh) and TI scenario ($55 to $79/MWh) are comparable to the simulation values for EGS GDH systems in New York and Pennsylvania by Reber (2013) for the Initial Learning scenario ($65 to $115/MWh) and the Commercially Mature scenario ($40 to $73/MWh). Differences can be explained by different assumptions made by Reber, such as an increased weighted average cost of capital (4% versus up to 2% to 3.2% in dGeo), reduced flow rates (30 to 80 L/s vs. 40 to 110 L/s in dGeo), and increased capacity factor (up to 50% versus about 25% to 35% in dGeo).

Table 2. Comparison of GDH LCOH Values Simulated by dGeo with Actual and Simulated Values Reported in the Literature for the United States and Europe[a]

Site/Location	Year	LCOH ($/MWh)	Notes	Reference
Contiguous United States	2016	56 to 79 Average = 68	dGeo simulation for hydrothermal in BAU scenario	This study
Contiguous United States	2030	78 to 102 Average = 89	dGeo simulation for EGS in BAU scenario	This study
Contiguous United States	2016	51 to 71 Average = 63	dGeo simulation for hydrothermal in TI scenario	This study
Contiguous United States	2030	55 to 79 Average = 68	dGeo simulation for EGS in TI scenario	This study
New York and Pennsylvania	2013	40 to 73	Range for estimated EGS LCOH for “Commercially Mature” scenario	(Reber 2013)
New York and Pennsylvania	2013	65 to 115	Range for estimated EGS LCOH for “Initial Learning” scenario	(Reber 2013)
Bluffdale, Utah, Prison	2008	27	LCOH calculated for existing 2-MW_{th} hydrothermal GDH system	(Thorsteinsson and Tester 2010)
Lakeview, Oregon, Prison	2008	51	LCOH calculated for existing 2.4-MW_{th} hydrothermal GDH system	(Thorsteinsson and Tester 2010)
Europe	2014	21 to 85 Average = 64	Range and average estimated for all existing	(Dumas and Angelino 2015)

Site/Location	Year	LCOH ($/MWh)	Notes	Reference
			European hydrothermal GDH systems	
Europe	2010	53	Estimated average for European hydrothermal GDH systems	(Ungemach 2012)
France (mostly Paris)	2012 to 2014	64 to 74	Values based on survey for existing hydrothermal GDH system in France	(CFG Services and Ross Offshore 2016)
Pomarance, Italy	2014	56 to 67	Range of cost of MWh sold for eight existing hydrothermal GDH systems with total capacity of 60 MW_{th}	(GeoDH 2015a)
Podhale, Poland	2014	61	Reported cost of MWh sold for existing 41-MW_{th} hydrothermal GDH system	(GeoDH 2015b)
Lendava, Slovenia	2014	84	Reported cost of MWh sold for existing 7-MW_{th} hydrothermal GDH system	(GeoDH 2015c)
Reykjavik, Iceland	2013	32	Reported average for Reykjavik hydrothermal GDH systems	(Petursson 2015)
Benedikt, Slovenia	2005	37	Calculated LCOH for existing 2.5-MW_{th} hydrothermal GDH system	(Kralj 2005)

[a] The dGeo simulated LCOH values are similar to those found in the literature.

8 Barriers to Direct-Use Deployment

Analysis of the dGeo simulation output and GDH case studies (Fleischmann 2007; Thorsteinsson and Tester 2010; Snyder, Beckers, and Young 2017) has identified several barriers for widespread GDH development in the United States:

1. **Policy/market barriers**, including:
    A. Competition from currently cheap alternative heating sources, especially natural gas
    B. Lack of federal or state government incentives, such as subsidies or tax credits, in comparison with other countries or even with other renewable energy technologies
    C. Absence of geothermal professionals, consultants, and businesses as well as the aging of the current geothermal workforce.
2. **Social-acceptance barriers**, including a lack of knowledge and perceptions of high cost and risk by local authorities and the public
3. **Technical barriers**, such as:
    A. Limited colocation of high-grade geothermal resources (predominantly occurring in the western United States) and high heat demand (mainly in the eastern United States)
    B. Large diversity in heating/cooling systems in the United States, which complicates and increases the costs of the retrofitting process
    C. High upfront project costs because of costly geothermal well drilling. The latter barrier is augmented by relatively high exploration risks.

9 Discussion

The improvements that can have the largest impact on reducing the LCOH of GDH systems are reducing drilling costs, increasing well flow rates, and reducing discount rates. Drilling costs could be reduced by decreasing drilling time—for example, through the development of advanced drill bits with longer lifetime (to reduce tripping time) or through advanced drilling techniques to better handle lost circulation zones. Increasing well flow rates could be achieved by proper reservoir design and management, better characterization of subsurface features, such as faults, and the development of advanced reservoir stimulation techniques to reduce reservoir impedance. Discount rates could be reduced by decreasing risk—for example, through resource exploration or by having a public entity (instead of a private company) develop the project with longer time horizons and access to low-interest financing (e.g., municipal bonds).

The market scenario modeling results show significant market potential for hydrothermal GDH through 2050: 1 GW_{th} in the BAU and 1.6 GW_{th} in the TI scenario. These deployment capacities account for market penetration levels of approximately 0.1% and 0.16%, respectively. This equates to a 10- to 16-fold increase from the current level of deployment of 100 MW_{th} (corresponding to 0.01% current thermal market). A comparison with Europe suggests that the increased deployment levels of GDH and other GDU projects in the European Union are because of the increased price of alternative fuels (e.g., natural gas and heating oil) and increased levels of government support for renewable heating options. Increased levels of GDU deployment have been seen historically in the United States as well—for example, when fossil fuel prices were high in the 1970s.

When considering EGS, the market potential increases by two orders of magnitude in the TI scenario. dGeo estimates an EGS market potential of 49 GW_{th} in the BAU scenario and 174 GW_{th} in the TI scenario, which, if developed, would bring the market penetration of GDH in the United States up to 5%. This analysis shows that although the assumed technology improvements play a role in bringing the LCOH down, it is the development and deployment of EGS technology that would make geothermal a major player across the United States in providing space and water heating to the residential and commercial sectors.

The dGeo simulations were constrained to analyzing the use of low-temperature geothermal energy for space and water heating, although other applications could be feasible and economically attractive. In the future, dGeo could be expanded to model market potential for using geothermal heat for other uses, such as industrial thermal applications, agricultural applications, and combined heat and power.

This study highlights the potential to increase GDU in the United States by overcoming barriers to deployment, such as improving federal or state government incentives for GDU, increasing the social acceptance of geothermal, and working to reduce the high upfront costs and risks associated with developing geothermal systems.

References

Antics, M., R. Bertani, and B. Sanner. 2016. "Summary of EGC 2016 Country Update Reports on Geothermal Energy in Europe." Presented at the European Geothermal Congress.

Augustine, C., J. Ho, and N. Blair. 2019. *GeoVision Analysis Supporting Task Force Report: Electric Sector Potential to Penetration* (NREL/TP-6A20-71833). Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/71833.pdf.

Bass, F.M. 1969. "A New Product Growth Model for Consumer Durables." *Management Science* 18: 215-227.

Batocletti, E.C., and W.E. Glassley. 2013. "Measuring the Costs and Benefits of Nationwide Geothermal Heat Pump Deployment (GHPsRUS)." Bob Lawrence & Associates, Inc. DE-EE0002741. https://cgec.ucdavis.edu/wp-content/uploads/08-28-2014-DE-EE0002741_Final-Report_28-Feb-2013.pdf.

Beckers, K, and K. Young. 2016. "Thermal Applications Technical Memo on Areas with High Potential for Impact on Geothermal Direct-Use Techno-Economic Feasibility" (Technical Memo for Geothermal Technologies Office on November 30, 2016). Washington, D.C.

Beckers, K.F., and K.R. Young. 2017. "Cost, Performance, and Financial Parameters of Geothermal District Heating Systems for Market Penetration Modeling under Various Scenarios." Presented at the 42nd Workshop on Geothermal Reservoir Modeling, Stanford University, Palo Alto, California, United States.

BP. 2018. *BP Statistical Review of World Energy*. Accessed July 2018. https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf.

Brown, A., P. Beiter, D. Heimiller, C. Davidson, P. Denholm, J. Melius, A. Lopez, D. Hettinger, D. Mulcahy, and G. Porro. 2016. *Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results* (NREL/TP-6A20-64503). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy15osti/64503.pdf.

CFG Services and Ross Offshore. 2016. "Towards the Industrialisation of Geothermal Energy in Denmark: A look at 35 Years of Success in Geothermal Energy for District Heating in France." http://www.energy-cities.eu/IMG/pdf/st_denmark_cfg_services_and_ross_offshore_09.14.2016.pdf.

Distributed Wind Energy Association. 2015. *DWEA Distributed Wind Vision—2015–2030*. Norman, OK. Accessed May 2017. http://distributedwind.org/wp-content/uploads/2012/08/DWEA-Distributed-Wind-Vision.pdf.

Doughty, C., P. Dobson, A. Wall, T. McLing, and C. Weiss. 2018. *GeoVision Analysis Supporting Task Force Report: Exploration* (LBNL-2001120). Berkeley, CA: Lawrence Berkeley National Laboratory. Accessed June 18, 2018. https://escholarship.org/uc/item/4v7054cw.

Dumas, P., and L. Angelino. 2015. "GeoDH: Promote Geothermal District Heating Systems in Europe." *Proceedings of the World Geothermal Congress*, Melbourne, Australia, April 19–25. https://pangea.stanford.edu/ERE/db/WGC/papers/WGC/2015/07007.pdf.

Eller, A., and A. Dehamna. 2016. *Residential Energy Storage: Advanced Lead-Acid, Flow, and Lithium ion Battery Systems for Residential Applications—Global Market Analysis and Forecasts.* Boulder, CO: Navigant Research. https://www.navigantresearch.com/.

European Geothermal Energy Council (EGEC). 2016. *Market Report 2015: 5th Edition*. Brussels, Belgium: European Geothermal Energy Council.

Eurostat. 2016. "Share of Renewable Energy in Gross Final Energy Consumption." http://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=t2020_31.

Fleischmann, D.J. 2007. *An Assessment of Geothermal Resource Development Needs in the Western United States*. Washington, D.C.: Geothermal Energy Association. http://geo-energy.org/reports/States%20Guide.pdf.

Foris, A. 2016. "Well Cost Drivers" (Technical Memo from Sandia National Laboratories on October 17, 2016). Albuquerque, New Mexico.

Gagnon, P., R. Margolis, J. Melius, C. Phillips, and R. Elmore. 2016. *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment* (NREL/TP-6A20-65298). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65298.pdf.

GeoDH. 2015a. "Pomarance Geothermal District Heating Case Study." http://geodh.eu/project/pomarance/.

GeoDH. 2015b. "Podhale Geothermal District Heating Case Study." http://geodh.eu/project/podhale-region/.

GeoDH. 2015c. "Lendava Geothermal District Heating Case-Study." http://geodh.eu/project/lendava/.

Gleason, M., K. McCabe, M. Mooney, B. Sigrin, and X. Liu. 2017. *The Distributed Geothermal Market Demand Model (dGeo): Documentation* (NREL/TP-6A20-67388). Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/67388.pdf.

Kastovich, J.C., R.R. Lawrence, R.R. Hoffmann, and C. Pavlak. 1982. *Advanced Electric Heat Pump Market and Business Analysis* (ORNL/Sub/79-2471/1). Prepared under subcontract for Oak Ridge National Laboratory by Westinghouse Electric Corp. Oak Ridge, TN: Oak Ridge National Laboratory.

Kralj, P. 2005. "Geothermal Project Benedikt: Possibilities for Geothermal Energy Use in Small Communities." *Proceedings of the World Geothermal Congress*, Antalya, Turkey, April 24–29. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/2321.pdf.

Labistida, R.R. and D. Gauntlett. 2016. *U.S. Distributed Renewables Deployment Forecast: Solar PV, Distributed Wind, and Biogas to Electricity Capacity and Revenue Forecasts—2016–2025.* Boulder, CO: Navigant Research. https://www.navigantresearch.com/.

Lantz, E., B. Sigrin, M. Gleason, R. Preus, and I. Baring-Gould. 2016. *Assessing the Future of Distributed Wind: Opportunities for Behind-the-Meter Projects* (NREL/TP-6A20-67337). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy17osti/67337.pdf.

Liu, X. 2010. *Assessment of National Benefits from Retrofitting Existing Single-Family Homes with Ground Source Heat Pump Systems* (ORNL/TM-2010/122). Oak Ridge, TN: Oak Ridge National Laboratory. http://info.ornl.gov/sites/publications/files/Pub24734.pdf.

Liu, X., J. Warner, and M. Adams. 2016. *FY16 Q3 Milestone Report for Geothermal Vision Study Thermal Application (Geothermal Heat Pump): Complete Simulations of GHP Installations for Representative Buildings* (ORNL/LTR-2016/344). Oak Ridge, TN: Oak Ridge National Laboratory. http://info.ornl.gov/sites/publications/files/Pub68872.pdf.

Liu, X., P. Hughes, K. McCabe, J. Spitler, and L. Southard. 2019. *GeoVision Analysis Supporting Task Force Report: Thermal Applications—Geothermal Heat Pumps* (ORNL/TM-2019/502). Oak Ridge, Tennessee: Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/Files/Pub103860.pdf.

Lopez, A., B. Roberts, D. Heimiller, N. Blair, and G. Porro. 2012. *U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis* (NREL/TP-6A20-51946). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy12osti/51946.pdf.

Lowry, T., J. Finger, C. Carrigan, A. Foris, M. Kennedy, T. Corbett, C. Doughty, S. Pye, and E. Sonnenthal. 2017. *GeoVision Analysis Supporting Task Force Report: Reservoir Maintenance and Development* (SAND2017-9977). Albuquerque, NM: Sandia National Laboratories. https://www.osti.gov/biblio/1394062.

McCabe, K., M. Gleason, T. Reber, and K.R. Young. 2016. "Characterizing U.S. Heat Demand for Potential Application of Geothermal Direct Use." *Geothermal Resources Council Transactions* 40. https://www.nrel.gov/docs/fy17osti/66460.pdf.

McCabe, K., B. Sigrin, E. Lantz, and M. Mooney M. 2018. *Assessment of the Economic Potential of Distributed Wind in Colorado, Minnesota, and New York* (NREL/TP-6A20-70547). Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/70547.pdf.

McCabe, K., K. Beckers, K.R. Young, and N. Blair. 2019. *GeoVision Analysis Supporting Task Force Report: Thermal Applications—Quantifying Technical, Economic, and Market Potential of Geothermal District Heating Systems in the United States* (NREL/TP-6A20-71715). Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/71715.pdf.

Millstein, D., J. McCall, J. Macknick, S. Nicholson, D. Keyser, S. Jeong, and G. Heath. 2019. *GeoVision Analysis Supporting Task Force Report: Impacts—The Employment Opportunities,* *Water Impacts, Emission Reductions, and Air Quality Improvements of Achieving High Penetrations of Geothermal Power in the United States* (NREL/TP-6A20-71933). Berkeley, CA and Golden, CO: Lawrence Berkeley National Laboratory and National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/71933.pdf.

Mullane, M., M. Gleason, K. McCabe, M. Mooney, T. Reber, and K.R. Young. 2016. "An Estimate of Shallow, Low-Temperature Geothermal Resources of the United States" (NREL/CP-6A20-66461). Presented at the 40th GRC Annual Meeting, Sacramento, California, October 23–26. http://www.nrel.gov/docs/fy17osti/66461.pdf.

Orell, A., and N. Foster. 2016. *2015 Distributed Wind Market Report* (DE-AC05-76RL01830). Richland, Washington: Pacific Northwest National Laboratory. http://energy.gov/sites/prod/files/2016/08/f33/2015-Distributed-Wind-Market-Report-08162016.pdf.

Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA). 2014. *The IEA CHP and DHC Collaborative: CHP/DHC Country Scorecard—United States*. Paris, France. https://www.iea.org/publications/insights/insightpublications/US_CountryScorecard_FINAL.pdf.

Paidipati, J., L. Frantzis, H. Sawyer, and A. Kurrasch. 2008. *Rooftop Photovoltaics Market Penetration Scenarios* (NREL/SR-581-42306). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy08osti/42306.pdf.

Petursson, B. 2015. "Renewable Energy in Iceland: With Focus on Geothermal District Heating." Presented at the EU-Eastern Partnership STI Cooperation: Energy Research and Innovation, Minsk, October 12–13. http://www.scienceportal.org.by/upload/2015/October/EaP/10%20Baldur%20Petursson%20.pdf.

R.W. Beck, Inc. 2009. *Distributed Renewable Energy Operating Impacts and Valuation Study*. Prepared for Arizona Public Service. Seattle, WA. http://files.meetup.com/1073632/RW-Beck-Report.pdf.

Reber, T.J. 2013. "Evaluating Opportunities for Enhanced Geothermal System-Based District Heating in New York and Pennsylvania." MS thesis, Cornell University, Ithaca, New York, United States.

Renewable Energy Policy Network for the 21st Century (REN21). 2016. *Renewables 2016 Global Status Report.* Paris, France: REN21 Secretariat. http://www.ren21.net/wp-content/uploads/2016/10/REN21_GSR2016_FullReport_en_11.pdf.

Schoonover, E., and M. Lawrence. 2013. *Geothermal Heat Pumps: Residential and Commercial Applications for Geothermal Heat Pumps—Global Market Analysis and Forecasts.* Boulder, CO: Navigant Research. https://www.navigantresearch.com/.

Sigrin, B., and E. Drury. 2014. "Diffusion into New Markets: Economic Returns Required by Households to Adopt Rooftop Photovoltaics." Presented at the AAAI Energy Market Prediction Symposium, Washington, November 13–15.

Sigrin, B., M. Gleason, R. Preus, I. Baring-Gould, and R. Margolis. 2016. *The Distributed Generation Market Demand Model (dGen): Documentation* (NREL/TP-6A20-65231). Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy16osti/65231.pdf.

Snyder, D.M., K.F. Beckers, and K.R. Young. 2017. "Update on Geothermal Direct Use in the U.S." (SGP-TR-212). *Proceedings of the 42nd Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, California, United States, February 13–15.

Sun & Wind Energy. 2010. "Renaissance of District Heating in the U.S." (Fact Sheet). http://www.forgreenheat.org/resources/Biomass_district_energy_in_the_US.pdf.

Thorsteinsson, H.H., and J.W. Tester. 2010. "Barriers and Enablers to Geothermal District Heating System Development in the United States." *Energy Policy* 38(2): 803–813.

Towards2030. 2015. "Renewable Based District Heating in Europe: Policy Assessment of Selected Member States." www.towards2030.eu.

Treddinick, Nick. 2013. "Why Is District Energy Not More Prevalent in the U.S.?" *HPAC Engineering*, June 7, 2013. http://hpac.com/heating/why-district-energy-not-more-prevalent-us.

U.S. Department of Energy (DOE). 1992. *1992 National Census for District Heating, Cooling and Cogeneration*. Washington, D.C. https://www.osti.gov/scitech/servlets/purl/10141462.

U.S. Department of Energy (DOE). 2012. "What Is an Enhanced Geothermal System (EGS)?" (Fact Sheet). Washington, D.C. Accessed July 11, 2018. https://www1.eere.energy.gov/geothermal/pdfs/egs_basics.pdf.

U.S. Department of Energy (DOE). 2018. "Frontier Observatory for Research in Geothermal Energy (FORGE)." https://www.energy.gov/eere/forge/forge-home.

U.S. Department of Energy (DOE). 2019. *GeoVision: Harnessing the Heat Beneath Our Feet.* Washington D.C.: U.S. Department of Energy. DOE/EE-1306. www.energy.gov/eere/geothermal/geovision.

U.S. Energy Information Administration (EIA). 2004. *The Electricity Market Module of the National Energy Modeling Systems: Model Documentation Report* (DOE/EIA-M068). Washington, DC: U.S. Department of Energy.

U.S. Energy Information Administration (EIA). 2013. "Heating and Cooling No Longer Majority of U.S. Home Energy Use." Today in Energy. Accessed May 2017. http://www.eia.gov/todayinenergy/detail.php?id=10271.

U.S. Energy Information Administration (EIA). 2014. "2009 Residential Energy Consumption Survey Data." Residential Energy Consumption Survey. Accessed May 2017. http://www.eia.gov/consumption/residential/data/2009/index.cfm?view=microdata.

U.S. Energy Information Administration (EIA). 2016a. "2012 Commercial Building Energy Consumption Survey (CBECS) Public Use Microdata." Commercial Buildings Energy

Consumption Survey. Accessed May 16, 2017. http://www.eia.gov/consumption/commercial/data/2012/index.cfm?view=microdata.

U.S. Energy Information Administration (EIA). 2016b. "Use of Energy in the United States Explained: Energy Use in Commercial Buildings." Accessed May 2017. http://www.eia.gov/energyexplained/?page=us_energy_commercial.

U.S. Energy Information Administration (EIA). 2016c. "Frequently Asked Questions: How much energy is consumed in residential and commercial buildings in the United States?" Accessed May 2017. http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1.

U.S. Energy Information Administration (EIA). 2016d. *Annual Energy Outlook 2016*. Washington, DC: U.S. Department of Energy. Accessed May 2017. https://www.eia.gov/outlooks/archive/aeo16/.

Ulloa, P. 2007. "Potential for Combined Heat and Power and District Heating and Cooling from Waste-to-Energy Facilities in the U.S.: Learning from the Danish Experience." Master thesis, Columbia University.

Ungemach, P. 2012. "Session B Geothermal: Insight into Geothermal Technology." Presented at the Annual Conference Teaming up for Renewable Heating and Cooling, Copenhagen, Denmark, April 26–27. http://www.rhc-platform.org/fileadmin/2012_RHC_Conference/Day_1_-_26.04/P_120426_1330_SessionB_Pierre_Ungemach_2.pdf.

Wendt, D.S., G. Neupane, C.L. Davidson, R. Zheng, and M.A. Bearden. 2018. *GeoVision Analysis Supporting Task Force Report: Geothermal Hybrid Systems* (INL/EXT-17-42891 and PNNL-27386). Idaho Falls, ID and Richland, WA: Idaho National Laboratory and Pacific Northwest National Laboratory. https://www.osti.gov/biblio/1460735.

Young, K., A. Levine, J. Cook, D. Heimiller, and J. Ho. 2019. *GeoVision Analysis Supporting Task Force Report: Barriers—An Analysis of Non-Technical Barriers to Geothermal Deployment and Potential Improvement Scenarios* (NREL/PR-6A20-71641). Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/71641.pdf.