References

GeoVision Analysis Supporting Task Force Reports

As noted in Chapter 1 and Appendix D, the *GeoVision* analysis relied on the collection, modeling, and assessment of robust datasets through U.S. Department of Energy national laboratory partners. Expert input was provided through seven technical task forces. The efforts of each task force resulted in at least one technical work product (report), identified as the *GeoVision* analysis supporting task force reports. Combined, these reports contain the foundational data and information for the *GeoVision* analysis and report; not all assumptions, results, and scenarios used in the analysis are contained within the main *GeoVision* analysis report. The full body of analytical work is available in the supporting task force reports identified in this reference list.

This list includes the supporting task force reports for quick reference. Appropriate citations for the supporting task force reports are also repeated in the chapter citations as necessary to confirm specific data references or refer the reader to additional details.

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Appendix A: Acronyms

National Laboratories	
INL	Idaho National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
SNL	Sandia National Laboratories

AEO	Annual Energy Outlook
ATB	Annual Technology Baseline
BAA	Balancing Authority Area
BAU	Business-as-Usual scenario (*GeoVision* analysis)
BLM	Bureau of Land Management (U.S. Department of the Interior)
BT	Breakthrough scenario (*GeoVision* analysis)
Btu	British thermal units
CAISO	California Independent System Operator
CAPEX	capital expenditure
CC	combined cycle
CCS	carbon capture and storage
CF	capacity factor
CO_2	carbon dioxide
COP	coefficient of performance
CT	combustion turbine
CX	categorical exclusion
dGeo	Distributed Geothermal Market Demand
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
EA	Environmental Assessment
EER	energy efficiency ratio
EGS	enhanced geothermal system(s)
EIA	U.S. Energy Information Administration
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EPAct	Energy Policy Act of 2005
FORGE	Frontier Observatory for Research in Geothermal Energy
FTE	full-time equivalent
GETEM	Geothermal Electricity Technology Evaluation Model

GHG	greenhouse gas(es)
GHP	geothermal heat pump
GHX	ground heat exchanger
GTO	Geothermal Technologies Office (U.S. Department of Energy)
GW_e	gigawatts-electric
GW_{th}	gigawatt(s)-thermal
GWH_{th}	gigawatt-hour(s)-thermal
HVAC	heating, ventilation, and air conditioning
IGCC	integrated gasification combined cycle
IGSM-CAM	Integrated Global System Model–Community Atmosphere Model
IQA	Information Quality Act
IRT	Improved Regulatory Timeline scenario (*GeoVision* analysis)
JEDI	Jobs and Economic Development Impact Model
km	kilometer(s)
kW	kilowatt(s)
LCOE	levelized cost of electricity
LCOH	levelized cost of heat
MMT	million metric tons
MW_e	megawatt(s)-electric
MWh	megawatt-hour(s)
MW_{th}	megawatt(s)-thermal
NEPA	National Environmental Policy Act
NF-EGS	near-field enhanced geothermal system(s)
NG-CC	natural gas combined cycle
NG-CT	natural gas combustion turbine
NO_x	nitrogen oxides
OGS	oil/gas steam turbine
O&M	operations and maintenance
PC	pulverized coal
$PM_{2.5}$	particulate matter (2.5 micrometers or smaller)
PPA	power purchase agreement
R&D	research and development
RE	renewable energy
ReEDS	Regional Energy Deployment System
SMU	Southern Methodist University
SO_2	sulfur dioxide
TES	thermal energy storage
TI	Technology Improvement scenario (*GeoVision* analysis)
TRG	techno-resource group or technology resource group
USGS	U.S. Geological Survey
VAV	variable-air volume
WACC	weighted-average cost of capital

Appendix B: Glossary

Always on	Electricity generation operating at close to a 100% capacity factor (see "Capacity factor")
Ancillary services	Capacity and energy services (e.g., operating reserve, frequency support, voltage support) that are used to ensure stable electricity delivery and optimized grid reliability. Also known as grid services
Bankable	A bank's willingness to finance a project, based on demonstrable and sufficient collateral, future cash flow, and probability of success to be acceptable to institutional lenders for financing
Baseload	The minimum amount of power that a utility or distribution company must make available to its customers, or the amount of power required to meet minimum demands based on reasonable expectations of customer requirements
Binary-cycle power plant	A geothermal power plant in which the geothermal fluid heats and vaporizes a second fluid, called the working fluid or binary fluid, that passes through a closed-loop Rankine cycle for the production of energy
Black start	A process of restoring a power station to operation without relying on the external electric power transmission network
Blockchain technology	A digital ledger in which transactions are decentralized, recorded chronologically and publicly, and protected through cryptography
Blue-sky research	Concepts or ideas that are out of the mainstream of existing research and development, with the potential to provide large-scale (as opposed to incremental) advancement in a technology area
Brackish groundwater	Water containing 0.5–30 grams of salt per liter, expressed as 0.5–30 parts per thousand salt equivalents
Brownfield	A geothermal site that has had previous development of some type (e.g., former manufacturing site)
Capacity factor	A unitless ratio of actual electrical energy output over a given period of time to the maximum possible electrical energy output over the same period of time
Capacity payment	Payment (in a power purchase agreement) based on the capacity of an electricity generation facility, not the electricity it generates
Capital expenditures	Funds spent on the purchase, installation, and construction of physical power-plant components. For geothermal power plants, this includes the wellfield and power-generation equipment.
Caprock	Rock that acts as a confining or semiconfining layer or structure to a geothermal reservoir, usually rich in low-permeability clays that form as a result of hydrothermal rock alteration
Carbon-dioxide equivalents	A summation of the greenhouse gas effects of contributing gases (e.g., methane) measured on a carbon-dioxide equivalency basis
Categorical exclusion	A category of actions that do not individually or cumulatively have a significant effect on the human environment and that have been found to have no such effect on procedures adopted by a federal agency in implementation of these regulations (National Environmental Policy Act Sec. 1507.3) and for which, therefore, neither an Environmental Assessment nor an Environmental Impact Statement is required (40 Code of Federal Regulations 1508.4)
Coefficient of performance	The ratio of useful heating or cooling provided to the work required
Compressed-air energy storage	A method of storing previously generated energy in the form of compressed air for later use by conversion into potential energy

Confirmation well	Full-sized, completed production well with temperatures and flow rates sufficient for a commercial-size geothermal well (typically 3–5 MWe), drilled at the beginning of wellfield development to confirm the presence of a commercially viable geothermal resource
Conventional geothermal (or hydrothermal) resources	Geothermal resources that can be developed using existing technologies, including hydrothermal resources and geothermal heat-pump resources
Cooling ton	One cooling ton is equal to the amount of thermal energy required to melt one ton of ice in a 24-hour period (12,000 British thermal units/hour or ~3.5 kWth)
Cost of capital	Combined cost of debt and cost of equity for a project. Represents the minimum return a project must generate in order for it to be worthwhile financially.
Cumulative expenditures	Capital and operations and maintenance spending required over the analyzed timeframe to support deployment potential modeled in the *GeoVision* analysis
Curtailment	A typically involuntary reduction in the output of a generator from what it could otherwise produce given available resources
Desalination	A process of extracting salts and mineral components from saline water
Direct use	The practice of using thermal energy directly as opposed to converting it to another form of energy (usually electricity)
Discount rate	The interest rate used in discounted cash flow analysis to determine the present value of future cash flows
Discovery rate	The rate at which the undiscovered hydrothermal resource potential is assumed to become available for deployment in the Regional Energy Deployment System model (used in the *GeoVision* analysis), measured as a percentage of total undiscovered hydrothermal resources per year. Assumed to be constant and based on a uniform distribution of hydrothermal resources becoming available each year.
District heating	A system for distributing heat generated in a centralized location for residential and commercial heating requirements, such as space heating and water heating
Drilling success rate	The rate or ratio of full-sized wells in a geothermal field that have sufficient temperatures and production rates or injection rates to be used for commercial power generation, relative to those drilled that fail to meet those criteria
Dry-steam power plant	A power plant that uses geothermal steam (at or above the saturation point of water) to directly turn a turbine and generator without the need for separation of a liquid-water phase
Economic resource potential	A portion of technical resource potential that is cost effective to recover based on technology costs and anticipated revenues
Enhanced geothermal systems	Unconventional geothermal resources that contain heat similar to conventional hydrothermal resources but lack the necessary groundwater and/or rock characteristics (e.g., permeability) to enable economic energy extraction without innovative subsurface engineering and transformation
Enthalpy	A thermodynamic quantity equivalent to the total heat content of a system
Environmental Assessment	Public documents that a federal agency prepares as required by the National Environmental Policy Act to provide evidence sufficient to determine whether a proposed agency action would require preparation of an Environmental Impact Statement or a Finding of No Significant Impact
Environmental Impact Statement	A document under U.S. environmental law required by the National Environmental Policy Act for certain actions "significantly affecting the quality of the human environment"
Environmentally sensitive area	Designation for an area that needs special protection because of its landscape, wildlife, or historical value

Financing costs	Costs associated with borrowing money, including interest charges and other expenses
Fine particulate matter	A mixture of solid particles and liquid droplets found in the air (i.e., dust, vapor, and combustion particles). Fine particulate matter represents fine inhalable particles with diameters of 2.5 micrometers and smaller.
Flash-steam power plant	A geothermal power plant that requires processing of geothermal fluids to separate steam from water for the production of energy
Flexibility	The ability of the power system to respond to variations in supply and/or demand
Frequency regulation	Rapid, real-time balancing services for the electricity grid
Full-time equivalent	The ratio of total hours worked by a group of employees over a specified time period to compensable (working) hours in that same period
Fumarole	An opening in the Earth's crust—often in areas surrounding volcanoes—that emits steam and gases, such as carbon dioxide, sulfur dioxide, hydrogen chloride, and hydrogen sulfide
Generation	The act of producing electrical power from other energy forms (such as thermal, mechanical, chemical, or nuclear), or the amount of electrical energy produced; usually expressed in kilowatt-hours or megawatt-hours
Geophysical	A discipline of the Earth sciences that pertains to the physics of the Earth and uses the physical properties of the Earth to understand the Earth's systems and processes
Gigawatt(s)-electric (also gigawatt-hour[s]-electric, kilowatt[s]-electric, megawatt[s]-electric, megawatt-hour[s]-electric)	Power available in the form of electricity generated from the conversion of heat or other potential energy
Gigawatt(s)-thermal (also gigawatt-hour[s]-thermal, kilowatt[s]-thermal, megawatt[s]-thermal, terawatt-hour[s]-thermal)	Power available directly in the form of heat
Greenfield	A geothermal site where no previous development of any type has occurred
Heat pump	A mechanical-compression cycle system that can be reversed to either heat or cool a controlled space
High pressures	Pressures above lithostatic pressures, which are confining pressures or the pressures exerted on a layer of rock by the weight of the overlying material
Hybridization, hybrid application	A technology application that marries a geothermal technology to one or more additional energy-conversion technology or end-use applications
Hydrothermal	Referring to heat energy in the presence of water. Relating to or denoting the action of heated water in the Earth's crust.
Induced seismicity	Seismic activity (minor earthquakes and tremors) that are caused by anthropogenic activities that alter the stresses and strains on the Earth's crust
Injection	The practice of returning geofluids to a reservoir through a dedicated well
Injection well	A well through which fluids are injected into the earth (see "Injection")

Investment Tax Credit	A tax incentive that allows qualifying businesses to deduct a certain amount of money from their taxes based on capital investments in renewable energy projects
Levelized cost of electricity	The net present value of the unit cost of electricity over the lifetime of a generating asset
Levelized cost of heat	The net present value of the unit cost of thermal energy (heat) over the lifetime of a thermal energy source. Analogous to levelized cost of electricity but applies to direct-use geothermal resources.
Lithostatic pressures	Confining pressures or pressures exerted on a layer of rock by the weight of the overlying material
Load following	A power plant that adjusts its power output as demand for electricity fluctuates throughout the day. Load-following plants are typically in between baseload and peaking power plants in efficiency, speed of startup and shut down, construction cost, cost of electricity, and capacity factor.
Machine learning	An application of artificial intelligence that provides systems the ability to automatically learn and improve from experience without being explicitly programmed
Magmatic	Pertaining to magma or magmatism. Magma is a mixture of molten or semi-molten rock found beneath the surface of the Earth.
Magnetotelluric	An electromagnetic geophysical method for inferring the Earth's subsurface electrical conductivity from measurements of natural geomagnetic and geoelectric field variation at the Earth's surface
Market potential (also market resource potential)	An indication of how quickly resources could actually be adopted and deployed from the economic potential given market conditions such as regulatory environment, capital availability and investor interest, and consumer demand and energy competition over time
Microseismic	Any small seismic event that causes little or no damage or disturbance to surface infrastructure
Mineral recovery	The process of extracting commercially valuable minerals or other materials (solid compounds, gases, and others) from a geothermal fluid
Municipal wastewater	Domestic wastewater from households and municipal wastewater from communities (also called "sewage") containing physical, chemical, and biological pollutants
Nameplate capacity	The maximum output a generator can produce without exceeding design thermal limits, as determined by the manufacturer
Net electricity demand	Total electricity demand less demand met by generation from variable-generation renewable energy resources
Net load profile	Difference between forecasted load and expected electricity production from variable-generation electricity sources
Nonspinning reserves	Additional capacity that is not connected to the electrical grid system but can be made available to meet demand within a specified time
Overnight capital costs	The capital expenditure required to achieve commercial operation of a plant, excluding the construction period and the financing and interconnection costs
Payback period	Amount of time required for an investment to recover its initial expenditures (e.g., project development costs, installation costs) from its profits or savings
Peaking mode	Mode of power-plant operation in which plants turn on—or a reserved portion of plant capacity is used—to generate electricity when there is high or "peak" electricity demand. Peaking plants are typically fastest in speed of startup and shut down and most expensive in cost of electricity; as such, they are only used when electricity demand drives electricity prices.
Permeability	A measure of the ability of a porous material (rock or unconsolidated material) to allow fluids to pass through it

Pre-drilling exploration activities	Non-invasive activities that do not penetrate the surface through drilling, e.g., geological and structural mapping studies, remote-sensing data acquisition, geophysical surveys, and geochemical surveys
Production Tax Credit	U.S. federal, per-kilowatt-hour tax credit for electricity generated by qualified energy resources
Production well	Well that is used to produce geothermal fluids from the ground
Ramping (ramping mode)	Mode of power-plant operation in which plants substantially change power output over time frames of seconds to minutes in order to balance rapid changes in electricity supply or demand and provide grid stability. Plants operating in this mode "ramp up"—or produce more energy when electricity demand suddenly increases—and "ramp down"—or produce less energy when electricity demand suddenly decreases.
Renewable Portfolio Standard	Regulatory mandate to reach a defined level of production of energy from renewable resources, which may include geothermal, wind, solar, biomass and other alternatives to fossil and nuclear generation. Renewable portfolio standards are usually issued at the state and/or local level.
Replacement reserve	Power generation sources that are required to be available within a certain period of time (usually an hour or less) when operating reserves are used. Replacement reserves replace operating reserves in use to provide protection against additional unforeseen electricity demand increases or supply disruptions.
Reservoir	Underground volume from which geothermal energy is extracted
Resistivity	A quantification of the resistance of a material (the Earth's crust) to the flow of electric current
Resource potential	The amount of power that could be generated from a particular resource. See "Technical resource potential," "Economic resource potential," and "Market resource potential."
Seismic	Relating to earthquakes or other vibrations of the Earth and its crust
Set-aside (as part of a Renewable Portfolio Standard)	A technology-specific goal for renewable energy generation, such as 10% of generation from geothermal energy. Generally set at the state and/or local level.
Soft costs	Nonconstruction costs incurred before project commissioning, including public perception/educating the public, utilities, regulators, and policymakers; community education; risk; financing; permitting; legal fees; insurance; workforce availability and training (including installers and small drillers); political support (e.g., policies, political terms, and regional resources); power purchase agreements; and attracting large players (e.g., oil and gas companies)
Spinning reserve	Additional, rapidly available capacity from generating units that are operating at less than their capability
Stimulation (of a well)	An operation carried out on a well during or at the end of its productive life that increases production or injection by improving the flow characteristics of the reservoir drainage area, thus enhancing the flow between the reservoir and the wellbore
Stress state	State of geologic stress that characterize the force per unit area placed on rock
Summer net capacity	The maximum output, commonly expressed in megawatts, that generating equipment can supply to system load, as demonstrated by a multihour test at the time of summer peak demand (June 1–September 30). This output reflects a reduction in capacity as a result of electricity use for station service or auxiliaries.
Technical potential	The portion of the overall resource that can technically be accessed, considering limitations such as land access, physical access to the reservoir, and efficiency of equipment

Technical resource potential	Achievable energy generation given current technology, system performance, and environmental and land-use constraints
Thermal conductivity	The measure of a material's ability to conduct heat. In the context of geothermal heat pumps, the measure of the ability of a subsurface material (e.g., soil) to conduct heat to and from the ground loop of the geothermal heat-pump system.
Thermal-hydraulic-mechanical-chemical models	Dynamic numerical models of the heat-flow, geomechanical, and geochemical properties of an Earth system
Thermoelectric power generation	Electrical power generated indirectly through burning a fossil-fuel-based energy source
Tight oil and gas	Oil and gas found in relatively impermeable reservoir rock requiring stimulation using hydraulic fracturing to create sufficient permeability to allow hydrocarbons to flow at economic rates (see "Stimulation")
Tracers	Chemical compounds or isotopes that are artificially introduced to a hydrogeological system to fingerprint water types and their flow paths
Unconventional oil and gas	Oil and gas produced or extracted using techniques other than conventional methods. Typically refers to oil and gas produced or extracted using horizontal drilling and/or hydraulic fracturing to access oil and gas trapped in low- or ultra-low permeability rock formations.
Undiscovered resource	Hydrothermal resources that lack surface manifestations and are difficult to identify with existing exploration techniques and methods
Variable renewable generation	A renewable energy source that fluctuates because of natural circumstances not controlled by the operator
Volumetric	Relating to the measurement of volume
Volumetric well flow rate	The volume of fluid produced per unit time, typically reported as gallons per minute or liters/second
Water consumption	Water evaporated, transpired, and incorporated into products or crops or otherwise removed from the immediate water environment
Water withdrawal	Water removed or diverted from a water source for use
Weighted Average Cost of Capital	Calculation of the average cost of capital for all funding sources, such as debt and equity, for a project or company, in which each category of capital is proportionately weighted
Well productivity	The measure of a well's ability to flow; specifically, the flow rate into/out from a well for a given pressure differential between the reservoir pressure and wellbore pressure at the midpoint of a producing interval in a well
Zonal isolation	The process of operationally isolating specific intervals or zones along a wellbore to perform well intervention activities, such as stimulation

Appendix C: Detailed Modeling Assumptions and Results

This appendix contains additional details on technology cost assumptions, model inputs, and modeling results for the *GeoVision* analysis. Text and graphics were sourced from *GeoVision* analysis supporting task force reports (see References) and related national laboratory reports. This appendix focuses on the most influential and study-specific costs and inputs. For details about model methodology, inputs, and assumptions, and greater insights into results and conclusions, refer to the supporting task force and national laboratory reports.

C.1 Electric Sector

C.1.1 Expanded Discussion of Geothermal Resource Estimates

Geothermal resources capable of generating electricity are divided into four groups:

- Identified Hydrothermal Resources
- Undiscovered Hydrothermal Resources
- Near-Field Enhanced Geothermal Systems (NF-EGS)
- Deep Enhanced Geothermal Systems (Deep-EGS)

Descriptions of the development and results of these resource estimates are provided in the subsequent sections. Information and graphics in this section are sourced primarily from Augustine et al. 2019.

C.1.1.1 Identified Hydrothermal Resources

The U.S. Geological Survey (USGS) 2008 geothermal assessment (Williams et al. 2008) identified 241 moderate- and high-temperature (>90°C) sites on private or accessible public land in the United States. The sites are concentrated entirely within 13 states in the western United States, Alaska, and Hawaii. The methodology used to estimate the recoverable energy from each site identified in the assessment is described in Williams et al. 2008. The USGS 2008 resource assessment predicts a mean total of 9,057 megawatts-electric (MW_e) of geothermal power-generation potential from identified hydrothermal systems on private or accessible public lands, with a 95% probability of at least 3,675 MW_e and a 5% probability of up to 16,457 MW_e of power-generation potential.

The total mean value of 9,057 MW_e for the recoverable electric-power-generation potential from the USGS 2008 assessment was adopted as the starting point for identified hydrothermal resources in the *GeoVision* analysis; site-specific data for the identified hydrothermal resources were obtained from the USGS (DeAngelo and Williams 2010). The *GeoVision* analysis applied a cutoff temperature of 110°C to this assessment database and considered only resources above this temperature threshold because cost estimates for resources at this temperature and below are prohibitively expensive. Adopting this temperature value results in the removal of 106 identified hydrothermal sites representing 460 MW_e of power-producing potential. Because of the low temperature of these removed resources, they are not likely to be commercially viable; as such, their exclusion should not impact the results of the Regional Energy Deployment System (ReEDS) modeling. The USGS 2008 assessment does not exclude currently installed generating capacity at identified hydrothermal sites. Data on installed geothermal capacity from the U.S. Energy Information Administration's (EIA's) EIA Form 860 (EIA 2016a) were used to remove existing capacity at USGS-identified hydrothermal sites. There were 2,542 MW_e of installed geothermal net summer capacity at the end of 2015, with 2,421 MW_e of this installed capacity at USGS-identified hydrothermal sites. According to these installed capacity data, some sites, such as The Geysers in California, have more existing installed capacity than potential capacity, so their potential was removed completely from the assessment. When installed capacity and sites with temperatures <110°C are removed from the USGS 2008 mean power-producing potential, the remaining mean potential capacity for identified hydrothermal sites in the United States is 6,370 MW_e. ReEDS (Section 3.1.2) only models the contiguous United States, so sites in Alaska and Hawaii were also removed. The result is that the remaining hydrothermal resource potential is 5,657 MW_e. Additional land restrictions identified in Young et al. 2019 further reduce the resource potential used as input for the ReEDS models to 5,078 MW_e for the *GeoVision* analysis Business-as-Usual (BAU) and Improved Regulatory Timeline (IRT) scenarios.[104] Assumptions about removal of some barriers (the *Land Access Improvement Scenario 2: Disruptive Improvement* in Young et al. 2019) increases the potential to 5,128 MW_e in the *GeoVision* analysis Technology Improvement (TI) scenario.

C.1.1.2 Undiscovered Hydrothermal Resources

In addition to identified hydrothermal resources, the USGS 2008 geothermal resource assessment estimated the power-production potential from undiscovered geothermal resources. USGS estimated the undiscovered resources for each state in the western United States using geographic information system-based statistical methods to analyze the correlation between spatial datasets and existing geothermal resources to derive the probability of the existence of geothermal resources in unexplored regions. The undiscovered geothermal resource power-generation potential from the study has a mean value of 30,033 MW_e, with a 95% probability of at least 7,917 MW_e and a 5% probability of up to 73,286 MW_e. The *GeoVision* analysis used the mean value of 30,033 MW_e; of this, 25,810 MW_e occurs in the contiguous United States. Land restrictions (Young et al. 2019) further reduce the value used as input for the ReEDS models to 18,830 MW_e for the BAU and IRT scenarios and 23,038 MW_e for the TI scenario.

The estimation of geothermal project costs in the Geothermal Electricity Technology Evaluation Model (GETEM) (Section 3.1.1) requires characterization of the geothermal resource. However, the actual resource characteristics of the undiscovered hydrothermal resource, such as reservoir depth and temperature, are unknown. In the absence of this data, it was assumed that the undiscovered resources would be similar in nature to identified hydrothermal sites in the same region. To characterize the undiscovered hydrothermal resource, identified hydrothermal sites were first divided into the Balancing Authority Areas (BAAs) used in the ReEDS model. The identified sites were further divided into three subgroups by temperature: 1) sites with reservoir temperatures <140°C, likely not commercially viable; 2) sites with temperatures ≥140°C and <200°C, likely binary plants; and 3) sites with temperatures ≥200°C, likely flash plants.

For the *GeoVision* analysis, the mean potential capacity from identified hydrothermal resources in each BAA subgroup was totaled. The undiscovered hydrothermal resource in each state was first apportioned among BAAs—based on the percentage of identified hydrothermal resource in each BAA in a state—and then apportioned among the designated temperature ranges based on the percentage of identified hydrothermal resource in each subgroup. For several states, such as Colorado, the entire undiscovered resource was assumed to have a temperature <140°C because all the identified hydrothermal sites in those states have estimated reservoir temperatures <140°C.

Within each BAA, a single reservoir temperature, depth, and production well flow rate was assumed for the undiscovered resource in each temperature subgroup. The temperature, depth, and flow rate of the undiscovered hydrothermal resource in each subgroup was determined by calculating the mean capacity weighted average of each of those parameters from the identified hydrothermal sites in each subgroup. Because the reservoir characteristics were determined using the potential power capacity weighted average, the undiscovered resource is assumed to be more similar to the large identified hydrothermal sites in each state that have significant power-producing potential. This means, for example, that the high-temperature undiscovered

104 The *GeoVision* analysis looked at three primary scenarios for evaluating the future potential of geothermal electricity generation in the United States: 1) Business-as-Usual (BAU): assumes that the geothermal industry continues on its current trajectory; 2) Improved Regulatory Timeline (IRT): assumes an improved regulatory environment leading to accelerated geothermal permitting processes and development timelines; and 3) Technology Improvement (TI): assumes a future where technology advances, cost reductions, and favorable financing options reduce the cost of geothermal technologies; includes IRT assumptions.

resource characteristics in California are heavily influenced by the characteristics of large sites such as The Geysers and the Salton Sea.

C.1.1.3 Near-Field Enhanced Geothermal System Resources

Near-field EGS resources consist of the areas around existing hydrothermal sites that lack sufficient permeability and/or *in-situ* fluids to be economically produced as a conventional hydrothermal resource. These resources require the application of EGS reservoir engineering techniques to become economic producers of electricity. Because these resources are proximal to existing hydrothermal sites, they tend to be relatively hot and shallow, and they are likely to be the first and least expensive EGS projects to be commercially developed. Estimates of near-field and deep-EGS potential around a selection of existing sites were developed as part of the USGS 2008 geothermal resource assessment. The USGS supplied a list of these sites, including estimates of the resource potential, temperature, depth, and location (Williams 2013). For areas around 21 producing hydrothermal fields considered in this study, the near-field EGS potential was 1,493 MW_e. Additional land restrictions (Young et al. 2019) further reduce the values used as input for the ReEDS models to 1,382 MW_e for the BAU and IRT scenarios and 1,443 MW_e for the TI scenario.

C.1.1.4 Deep Enhanced Geothermal System Resources

Deep-EGS resources consist of all the thermal energy stored in the Earth's crust at depths that can be accessed with existing drilling technology (but not necessarily developed with existing technology). The cost of electricity from an EGS site depends heavily on the depth and temperature of the reservoir to be developed. For the *GeoVision* analysis, the U.S. deep-EGS resource potential is defined as the thermal energy stored in rock at depths between 3 and 7 km below the Earth's surface, at temperatures exceeding 150°C, and within the contiguous United States. The deep-EGS resource potential estimate is based on temperature-at-depth maps developed by the Southern Methodist University (SMU) Geothermal Laboratory (Blackwell et al. 2011). The deep-EGS electricity-generation resource-potential estimate was updated for the *GeoVision* analysis by Augustine 2016.

The *GeoVision* analysis used the following methodology to generate the resource-potential estimate: First, the subsurface is divided into intervals 1 km thick, similar to the SMU maps (Blackwell et al. 2011). Then, the amount of thermal energy in place in a given volume of rock is calculated assuming an overall average reservoir temperature decline of 10°C over the life of the reservoir. Next, the amount of this thermal energy that can be recovered is calculated, assuming a recovery factor of 20%. The recovered thermal energy is then converted to electric energy potential on a megawatts-electric per cubic kilometer (MW_e/km^3) basis by a power plant at the surface, assuming a plant lifetime of 20 years and a power-plant conversion efficiency (DiPippo 2004) based on the temperature intervals from the SMU maps. Finally, the values of electric energy potential are used to estimate the electricity-generation potential at a location, based on the temperature values from the SMU maps.

The updated deep-EGS resource-potential estimate was calculated for rock at depths of 3–7 km with estimated temperatures exceeding 150°C. The results indicate a deep-EGS electricity-generation resource potential estimate of 5,157 gigawatts-electric (GW_e). A summary of the EGS electricity-generation potential for the contiguous United States, as a function of temperature and depth, is shown in Table C-1. The total deep-EGS resource is 5,156,956 MW_e. Identified land barriers (Young et al. 2019) reduce the deep-EGS resource estimate available in ReEDS to 3,375,275 MW_e for the BAU and IRT scenarios and to 4,248,879 MW_e for the IT scenario.

		Deep-EGS Electricity-Generation Potential (MW_e)								
		Resource Temperature (°C)								
		150–175	175–200	200–225	225–250	250–275	275–300	300–325	325–350	>350
Depth (km)	3–4	74,217	2,592	100	—	—	—	—	—	—
	4–5	740,466	233,228	11,886	325	84	32	—	—	—
	5–6	517,601	724,689	373,680	57,281	4,654	195	128	—	—
	6–7	635,384	491,641	700,330	453,610	120,677	12,116	1,883	—	157

Table C-1. Updated Deep Enhanced Geothermal Systems Electricity-Generation Potential (MWe) for the Contiguous United States, Binned by Temperature and Depth Intervals (Augustine 2016)

C.1.2 Technology Cost and Performance Assumptions

As introduced in Section C.1.1, the *GeoVision* analysis looked at three primary scenarios for evaluating the future potential of geothermal electricity generation in the United States:

- Business-as-Usual: assumes that the geothermal industry continues on its current trajectory
- Improved Regulatory Timeline: assumes an improved regulatory environment leading to accelerated geothermal permitting processes and development timelines
- Technology Improvement: assumes a future where technology advances, cost reductions, and favorable financing options reduce the cost of geothermal technologies; includes IRT assumptions.

The scenario assumptions and values were used to develop cost and performance inputs for GETEM (Section 3.1.1). GETEM was run for each geothermal site or resource class, and the resulting project overnight capital costs[105] as well as operations and maintenance (O&M) costs outputs were used to develop the supply curves that serve as inputs to ReEDS. Because of the large number of geothermal sites, detailed site information was not considered when estimating costs in GETEM. Even though drilling costs can vary by location, a single set of drilling cost curves was assumed for all sites.

Technology improvements can affect more than capital and O&M costs derived from GETEM. For example, technologies that decrease risk associated with geothermal projects can lower borrowing costs, and reductions in development timelines can lower the cost of financing. These factors are inputs in the ReEDS model and impact the net present value of a project. The impact of scenario assumptions on ReEDS inputs are discussed below and summarized in the discussion on the ReEDS model inputs (Section 3.2.1).

C.1.2.1 Business-as-Usual Scenario

The BAU scenario assumes cost and performance inputs for GETEM representative of existing technology and costs. Different inputs are applied depending on the technology type (hydrothermal or EGS). GETEM inputs are based on the default inputs in GETEM described in the *GETEM User Manual* (Mines 2016). In a project funded by the U.S. Department of Energy's Geothermal Technologies Office, a levelized cost of electricity (LCOE) analysis team developed these default inputs from 2011–2013. This team determined inputs through a series of interviews with industry subject-matter experts to validate the approaches used in GETEM and the reasonableness of estimated project-development costs.

105 Overnight capital costs reflect the capital expenditure required to achieve commercial operation of a plant, excluding the construction period and the financing and interconnection costs.

The *GeoVision* analysis task forces also reviewed the default inputs for accuracy and reasonableness. The most significant change was the consideration of an updated set of drilling cost curves developed by the Reservoir Maintenance and Development Task Force (Lowry et al. 2017) in place of the default GETEM drilling cost curves (Figure C-1). A full list of default assumptions used in GETEM for the BAU scenario is provided in Augustine 2019.

The capital and O&M costs for all geothermal resources were estimated on a site-by-site basis using GETEM. First, site-specific resource definitions were input to GETEM, including resource temperature, depth to reservoir (i.e., drilling depth), technology type, plant type, and plant size. As in previous supply-curve reports (Petty and Porro 2007, Augustine 2011), a reservoir depth of 1.524 km (5,000 feet) was used when site-specific estimates were not available and was applied mostly to identified hydrothermal sites. Technology options considered include hydrothermal or flash steam, with the plant types being either 1) binary with temperatures less than 200°C, or 2) flash with temperatures equal to or greater than 200°C. EGS projects are always assumed to use binary plants with air-cooled condensers, which reinject all water that is produced from the reservoir, to minimize water requirements and potential scaling in the reservoir. Identified hydrothermal and near-field EGS plant sizes were based on resource potential and limited to a maximum size of 60 MW_e. If the resource targeted was larger than 60 MW_e, the analysis assumed that multiple plants would be developed at the site. For undiscovered hydrothermal and deep EGS, plant sizes of 25–40 MW_e were used.

C.1.2.2 Improved Regulatory Timeline Scenario

The IRT scenario explored the impact of an improved regulatory environment that leads to accelerated geothermal permitting processes and development timelines. The IRT scenario was based on analysis of non-technical barriers to geothermal deployment (Young et al. 2019), which considered a number of pathways and potential combinations of approaches to streamline and reduce project development timelines. The net impact of the IRT scenario was twofold. First, it decreased the construction timeline. The hydrothermal construction timeline was shortened from eight years in the BAU scenario to four years in the IRT, and the EGS construction timeline was shortened from 10 years in the BAU scenario to five years in the IRT. Second, it increased the amount of resource exploration, resulting in an increase in the discovery rate for undiscovered geothermal resources from 1% per year to 3% per year.[106] This assumption was based on the following reasoning: decreasing the time it takes to get exploration permits can increase the amount of exploration that is performed each year, resulting in more resource discoveries per year. *GeoVision* Visionaries, including geothermal developers, reviewed this assumption and deemed it reasonable.

All remaining assumptions in the IRT scenario, including technology cost and performance values, were identical to the BAU scenario. Because the GETEM inputs were identical, the supply curves for the IRT scenario are the same as those for the BAU scenario. The financing assumptions used in ReEDS are also identical to the BAU scenario. The result is that the IRT scenario shows the impacts on geothermal deployment if soft costs, construction timelines, and barriers are reduced, even with current technology.

C.1.2.3 Technology Improvement Scenario

The TI scenario examined the impacts of aggressive technology advances and cost reductions developed by the *GeoVision* analysis task forces for use as GETEM inputs related to the potential for geothermal deployment. These improvements greatly benefit EGS, reducing costs to the point where EGS is commercially competitive. The improvements are also beneficial for hydrothermal technologies. The TI scenario incorporates the IRT scenario assumptions, which lead to both a threefold increase in the discovery rate of hydrothermal resources (from 1% per year to 3% per year) and a decrease in the project construction timelines. Technology improvements in exploration and drilling also lead to decreased project risk, which translates into reduced financing costs. The TI scenario assumed that geothermal projects are able to obtain financing at rates (weighted-average cost of capital) similar to other power-generation technologies.

106 The 3% per year discovery rate is based on interviews with geothermal developers as part of the *GeoVision* analysis regarding the impact that decreased permitting times for activities associated with exploration would have on the amount of exploration developers could achieve in a given amount of time.

The TI scenario assumed that large utility-scale power plants continue to be the primary goal of project developers and that geothermal providers have advanced significant technology breakthroughs from a confluence of improvements. The improvements were developed by the *GeoVision* analysis task forces in their respective areas, based on analysis of existing and future technologies. Improvements were incorporated as GETEM inputs as part of the bottom-up analytical framework of the *GeoVision* analysis. Improvements include, for example, the availability of big data to optimize exploration and drilling; advanced exploration drilling techniques such as micro-hole drilling; reductions in costs and improvements in drilling success rates overall; and the development of EGS techniques, such as multistage stimulation of horizontal wells that increase the productivity and longevity of EGS reservoirs. Changes to the GETEM inputs from the BAU scenario are summarized in Table C-2. The TI scenario assumed the BAU values for all other GETEM inputs.

GETEM Input		**Business-as-Usual**		**Technology Improvement**	
		Hydro	**EGS**	**Hydro**	**EGS**
RESOURCE EXPLORATION	*Exploration — Pre-Drilling Costs ($/project)*	$600K–$1.2M	$250K	Same as BAU	
	Exploration — Drilling Costs ($/project)	$3.3M–$5.4M	$1.5M–$5M	2/3 of BAU	
	Full-Sized Confirmation Well Costs[107]	Base + 20%	Base + 50%	Ideal + 0% (no premium)	
	Full-Sized Confirmation Well Success Rate	50%	50%	75% (with stimulation)	
	Number of Full-Sized Confirmation Wells Required	3	9	3	
DRILLING	Drilling success rate	75%		90%	
	Drilling costs	Base		Ideal	
GEOFLUID GATHERING SYSTEM AND PUMPING		*No changes*			
RESERVOIR CREATION	Wells stimulated?	No	Yes	Yes	
	Well flow rate (flow rate per production well)	Binary: 110 kg/s Flash: 80 kg/s	40 kg/s	Binary: 110 kg/s Flash: 80 kg/s	
	Well productivity	4.6 kg/s/bar 5.8 gpm/psi	0.46 kg/s/bar 0.58 gpm/psi	4.6 kg/s/bar 5.8 gpm/psi	
O&M		*No changes*			
POWER PLANT		*No changes*			

Table C-2. Summary of Changes to Business-as-Usual Geothermal Electricity Technology Evaluation Model Inputs for Technology Improvement Scenario

Table Notes: (1) Exploration pre-drilling activities typically involve geological, geophysical, and geochemical surveys. These surveys might include, but are not limited to, activities such as geological and structural mapping, remote-sensing data analysis, geophysical assessments of resistivity and temperature data, and geochemical surveys of groundwater and surface water and rock alteration. (2) The TI scenario assumes that the construction of large utility-scale power plants continues to be the predominant goal of project developers and that geothermal providers have advanced technology breakthroughs from a confluence of technology improvements. These improvements include the availability of big data to optimize exploration and drilling, advanced exploration drilling techniques such as micro-hole drilling, reductions in costs and improvements in the success rate of drilling overall, and the development of EGS techniques such as multistage stimulation of deviated wells that increase the productivity and longevity of EGS reservoirs. (3) The TI scenario assumes the BAU values for all other GETEM inputs. The GeoVision analysis used identical GETEM inputs for the geofluid gathering system and pumping, O&M, and power plant for both the BAU and TI scenarios. Values for these inputs can be found in Augustine et al. 2019. (3) kg/s = kilograms per second; kg/s/bar = kilograms per second per bar.

107 GETEM inputs were structured assuming that the costs of confirmation wells are more expensive than standard production wells drilled during the field-development phase. Costs of standard production wells are based on the drilling cost curves considered as the basis for the *GeoVision* analysis and as elaborated in Lowry et al. 2017. Costs of full-size confirmation wells consider the standard production well cost plus the indicated premium as a percentage of the standard well cost. Lowry et al. 2017 and Augustine et al. 2019 provide a complete description of geothermal well construction sizes, their cost-benefit relationships, and the manner in which costs are integrated within GETEM and the *GeoVision* analysis.

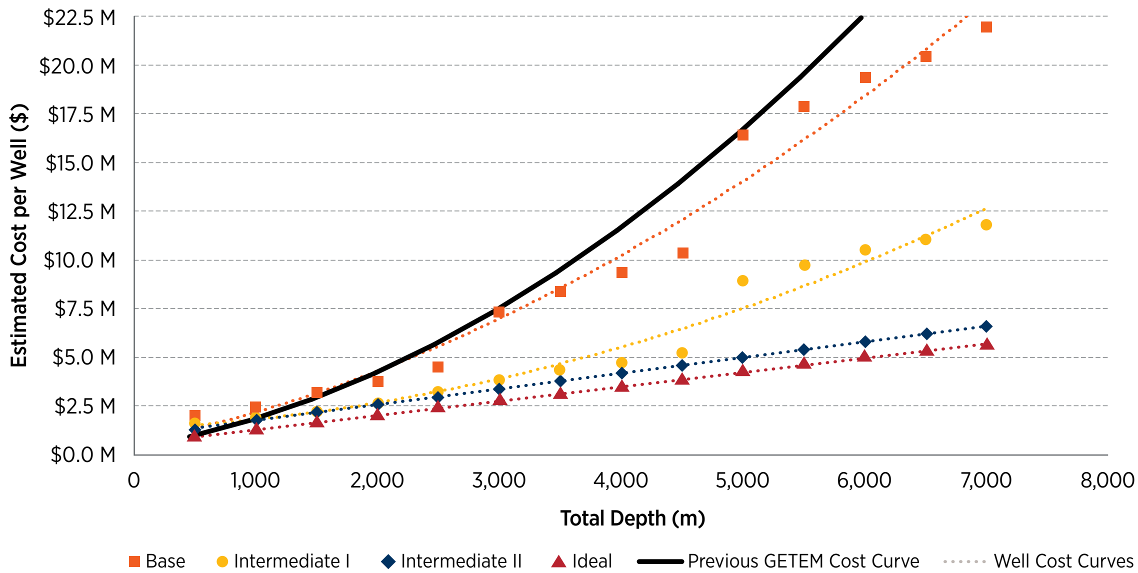


Figure C-1. Well-cost curves used in the *GeoVision* analysis (Lowry et al. 2017) relative to previous well-cost curve used in the Geothermal Electricity Technology Evaluation Model

Figure Note: Curves shown are for large-diameter vertical wells with an open hole. The TI scenario uses the Ideal cost curve.

Modeling assumptions with the largest impacts are drilling and well completion costs, and EGS reservoir creation and performance improvements. In the TI scenario, advances in drilling technology lead to significant reductions in drilling and well-completion costs for both hydrothermal and EGS. Based on research and analysis by the *GeoVision* analysis Reservoir Maintenance and Development Task Force, several well-cost curves were developed for the *GeoVision* analysis (Figure C-1). The "Ideal" well-cost curve was used for the TI scenario. Lowry et al. (2017) details the well-cost curves.

The TI scenario assumed that improvements in EGS technologies will allow for multistage stimulation of deviated wells in the creation of EGS reservoirs. The geothermal industry was assumed to be able to adapt directional drilling and multizonal isolation techniques from the oil and gas industry and to develop reservoir stimulation technologies to create EGS reservoirs with volumes and surface areas large enough to support commercial production-well flow rates for decades. The result is that EGS reservoirs are assumed to have flow and productivity characteristics similar to hydrothermal reservoirs: production-well flow rates of 80 kg/s for flash plants and 110 kg/s for binary plants[108], and well injectivity/productivity index of 4.6 kg/s/bar.[109]

Applying EGS technologies enables the replication of the high success rates seen in the unconventional-shale industry. Based on task force recommendations and reviews by *GeoVision* Visionaries, the *GeoVision* analysis assumed a 90% drilling success rate and a 90% stimulation success rate for EGS applications. Hydrothermal resources are also able to leverage EGS technologies for well stimulation to increase the effective well success rate, resulting in a 90% success rate with EGS techniques used on unproductive wells. With this 90% success rate, GETEM assumes that only unproductive wells (in the drilling phase) are stimulated.

108 Binary plants generally have higher production-well flow rates than flash plants because the wells can be pumped to increase flow rates. Geothermal brine temperatures at flash plants are usually above the maximum operating temperature for downhole pumps or have two-phase (liquid and gas) flow in the well that would cause cavitation in the pump, and therefore they must be self-flowing.

109 kg/s = kilograms per second; kg/s/bar = kilograms per second per bar

C.1.2.4 Geothermal Electricity-Sector Supply Curves

A supply curve is the combination of the technology resource potential and the cost to develop the resource. It shows how much of a resource is available and the cost of a given technology to develop that resource into a power plant to deliver electricity to the grid. When graphed as electricity-generation capacity versus cost, a supply curve is a visual representation of the amount of resource available for development as a function of cost. Supply curves that serve as inputs for the ReEDS model for geothermal electricity-generation resources were generated for each of the scenarios using the overnight capital costs derived from GETEM, based on the inputs for each scenario. The ReEDS model used the capital costs, along with model inputs such as financial parameters and construction timelines, to calculate the levelized cost of electricity for geothermal resources.

The resulting supply curves showing available new capacity as a function of overnight capital costs and levelized cost of electricity are shown in Figures C-2, C-3, and C-4. The supply curves for hydrothermal resources are shown in Figure C-2, and the supply curves for NF-EGS and deep EGS are shown in Figure C-3 and Figure C-4, respectively. Some axes have been truncated in Figures C-3 and C-4 to make the data readable (see Figure Notes). The BAU and IRT scenarios have identical capital cost supply curves, but their LCOE supply curves differ. This is because of the difference in construction timeline assumptions between the scenarios. The capacity for deep-EGS resources extends beyond 4,200,000 MW_e, and the overnight capital costs extend beyond $100,000/$kW_e$ for the BAU scenario. Both of these values are irrelevant in practice, however, because it is unlikely that any resources at those costs would deploy in a BAU scenario. The overnight capital costs remain below $10,000/$kW_e$ for the entire deep-EGS supply curve in the TI scenario. The BAU and IRT scenarios use the same supply curves as inputs for ReEDS.

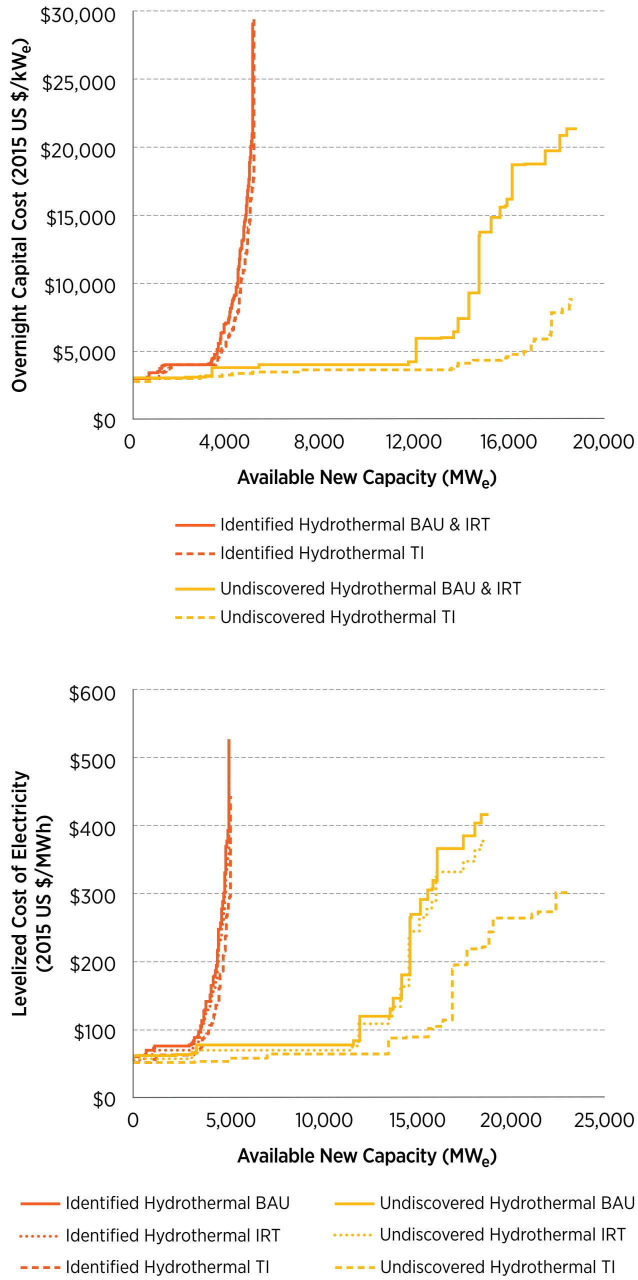


Figure C-2. Identified hydrothermal and undiscovered hydrothermal supply curves. Available new capacity by overnight capital cost (top) and levelized cost of electricity (bottom) for the Business-as-Usual, Improved Regulatory Timeline, and Technology Improvement *GeoVision* analysis scenarios.

Figure Note: Identified hydrothermal capital costs are competitive for high-temperature resources, but they increase quickly as the resource temperature drops. This "hockey stick" shape is a characteristic shared by many geothermal supply curves due to the abundance of small, low-temperature resources at the tail of the curve. The low temperatures lead to reduced power-generation potential and increased drilling costs relative to the amount of power generated per well.

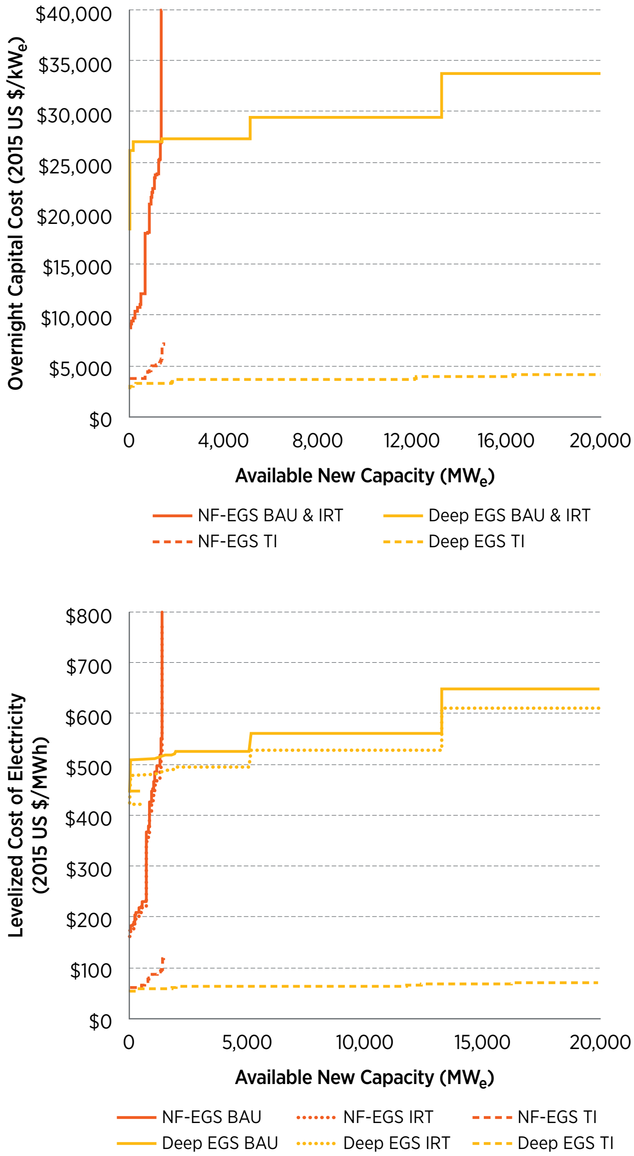


Figure C-3. Near-field enhanced geothermal system and deep enhanced geothermal system supply curves. Available new capacity by overnight capital cost (top) and levelized cost of electricity (bottom) for the Business-as-Usual, Improved Regulatory Timeline, and Technology Improvement *GeoVision* analysis scenarios.

Figure note: The axis for available capacity has been truncated to make the near-field EGS (NF-EGS) costs readable.

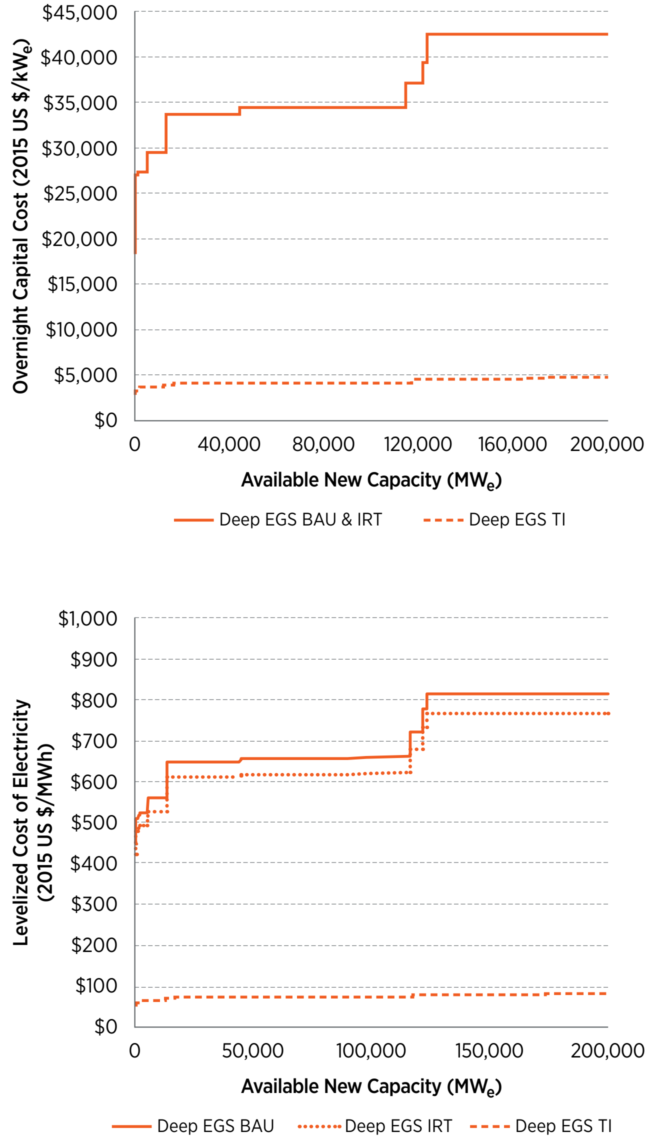


Figure C-4. Deep enhanced geothermal system supply curves. Available new capacity by overnight capital cost (top) and levelized cost of electricity (bottom) for the Business-as-Usual, Improved Regulatory Timeline, and Technology Improvement *GeoVision* analysis scenarios.

Figure note: The axis for available capacity has been truncated. These curves are the same deep-EGS supply curves as those in Figure C-3, but are plotted at larger net-capacity and cost scales.

C.1.3 Regional Energy Deployment System Model—Additional Inputs and Assumptions

The ReEDS model (National Renewable Energy Laboratory [NREL] 2018a) is a capacity expansion and dispatch model for the contiguous U.S. electric-power sector. The model relies on system-wide, least-cost optimization to estimate the type and location of future generation and transmission capacity. To represent the competition among the many electricity generation, storage, and transmission options throughout the contiguous United States, ReEDS identifies the cost-optimal mix of technologies that meet regional electric-power demand based on grid reliability (reserve) requirements, technology resource constraints, and existing policy constraints, such as state renewable portfolio standards. ReEDS performs this cost minimization for each of 21 two-year periods from 2010–2050. Some of the major outputs of ReEDS include the amount and location of generator capacity and annual generation from each technology, storage capacity expansion, transmission capacity expansion, total electric-sector costs, electricity price, fuel demand and prices, and carbon dioxide (CO_2) emissions.

Within ReEDS, load is served and power plants are constructed in 134 model BAAs that overlay the contiguous United States (Figure C-5). The model BAAs are not designed to represent or align perfectly with real BAAs; instead, they represent model nodes where electricity supply and demand are balanced. The ReEDS transmission network connects those BAAs and comprises roughly 300 representative lines across the three asynchronous interconnections: the Western Interconnection, Eastern Interconnection, and Electric Reliability Council of Texas. The BAAs also respect state boundaries, allowing the model to represent individual state regulations and incentives. The BAAs are further subdivided into 356 resource regions to describe wind and solar resource supply and quantity with more spatial granularity than allowed by the BAA regions alone. Additional geographical layers include three electricity interconnects, 18 model regional transmission operators designed after existing regional transmission operators, 19 North American Electric Reliability Corporation reliability subregions, and nine census divisions, as defined by the U.S. Census Bureau.

In ReEDS, load is served and operational reliability is maintained over 17 time slices in each model year. Each of the four seasons is modeled as a representative day of four time slices: overnight, morning, afternoon, and evening. The 17th time slice is a summer "superpeak" representing the top 40 hours of summer load. This schedule allows the model to capture seasonal and diurnal variations in demand, wind, and solar profiles. However, the schedule is insufficient to address some of the shorter timescale challenges associated with unit commitment and economic dispatch, especially under scenarios with high penetration of variable renewable generation. To more accurately represent how grid integration of renewable generation might

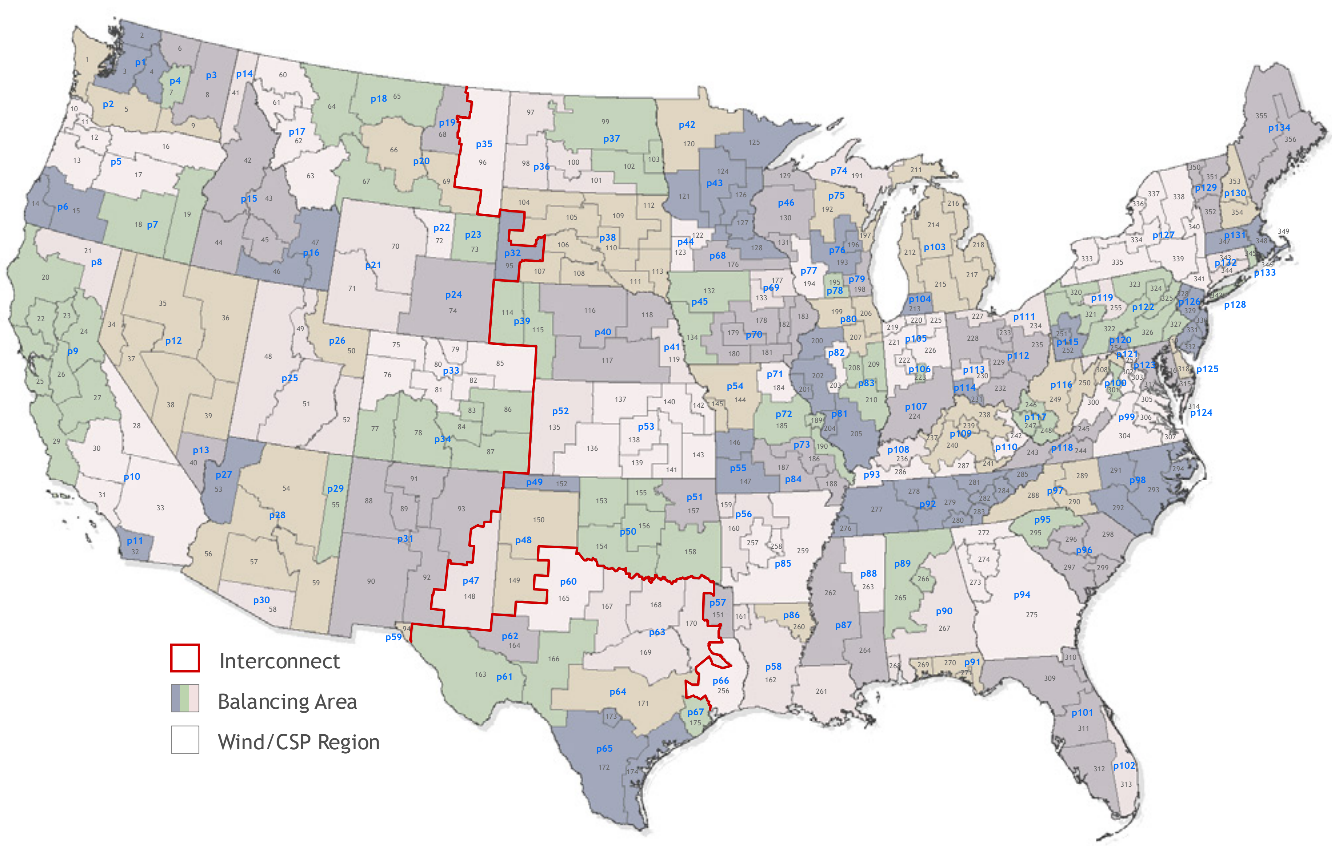


Figure C-5. Map showing the Regional Energy Deployment System regional structure

Figure Note: ReEDS includes three interconnections, 134 model BAAs, and 356 wind and concentrating solar power resource regions.

affect investment and dispatch decisions, the ReEDS model includes statistical parameters designed to address intra-time-slice variability and the generation variability of wind and some other renewable resources. The major conventional thermal-generating technologies represented in ReEDS include simple and combined-cycle natural gas, several varieties of coal, oil/gas steam, and nuclear. In addition to representing these technologies, ReEDS includes many renewable technologies using several kinds of resources, including geothermal, hydropower, biopower, wind, and solar. Electricity storage technologies in the model include pumped hydropower storage, compressed-air energy storage, batteries, and concentrating solar power with thermal storage.

ReEDS is structured as a sequence of 21 individual but interacting optimization problems, each representing a two-year period from 2010–2050. Each ReEDS scenario launches with an infrastructure base representing installed generation and transmission capacity as of December 31, 2010. New infrastructure that came online from 2011 through the present is prescribed into the ReEDS system in the proper model year, and recently decommissioned units are removed in the same way. Similarly, high-likelihood, pending generators are included as prescribed builds in near-term future years, and scheduled retirements are set to be removed from the fleet, as appropriate. Additionally, ReEDS inputs include an equipment lifetime for each technology as a means to retire capacity as it ages. In certain scenarios, some existing stock might be underused because of, for example, high fuel prices or emissions standards. ReEDS facilitates "economic" retirements of underused coal capacity if usage (i.e., capacity factor) falls below a certain threshold. Economic coal retirement in ReEDS is applied starting in 2022 with an increasingly stringent threshold of underuse through 2040.

ReEDS tracks emissions of CO_2, sulfur dioxide (SO_2), nitrogen oxides (NO_X), and mercury from both generators and storage technologies. Annual electric loads and fuel-price supply curves are exogenously specified to define the system boundaries for each period of the optimization. The source for most load and fuel inputs is the EIA's *Annual Energy Outlook* (AEO). Coal and uranium fuels are assumed to be price inelastic; prices for coal and uranium do not change in the model no matter how much of those fuels ReEDS uses for optimization. However, natural-gas prices are defined by regional supply curves and respond to changes in electric-sector demand for gas.

C.1.3.1 General Regional Energy Deployment System Model Inputs and Assumptions

ReEDS models future capacity installations on grids for the contiguous United States based on projections of electricity demand and the cost of developing new generation capacity within and among regions. ReEDS is an optimization routine, and it selects capacity additions among the available electricity-generating technologies that minimize system costs within the model constraints and requirements based on the technology and fuel costs provided by the user. For the *GeoVision* analysis, the Annual Technology Baseline (ATB) (NREL 2018b) was used to provide detailed cost and performance data (both current and projected) for non-geothermal renewable and conventional technologies. The ATB is a set of input assumptions updated annually by NREL to support and inform electric-sector analysis in the United States. The products of this work include assessments of current and projected technology cost and performance through 2050 for renewable and conventional electricity-generation technologies. The ATB includes Low, Mid, and High technology-cost projections for renewable energy technology costs and performance based on values reported in public literature. The *GeoVision* analysis used the 2016[110] version of the ATB (Cole et al. 2016b, NREL 2016) and assumes the Mid-case scenario technology cost projections.

ReEDS also requires projections of electricity demand and fuel prices. The National Renewable Energy Laboratory (NREL) annually documents a diverse set of potential futures of the U.S. electricity sector that includes technology cost and performance assumptions from the ATB. These potential futures are called the *Standard Scenarios*. The Standard Scenarios comprise a range of power-sector scenarios that provide quantitative examination of how ranges of values of specific inputs impact the development of the power sector (NREL 2018b). The *GeoVision* analysis used the

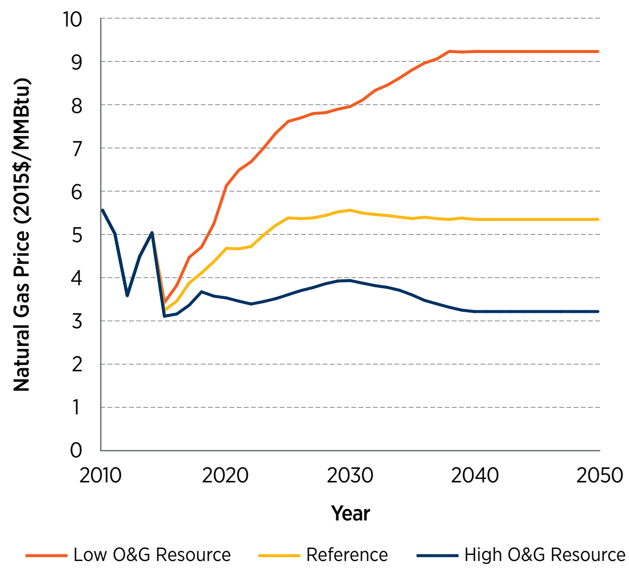
110 The 2016 versions of the ATB and Standard Scenarios were the most recent data available at the time this analysis was performed. The 2018 ATB has since been published and uses lower cost projections for some technologies (notably wind and solar technologies) than the 2016 ATB. Using the updated cost projections would make wind and solar technologies—and perhaps others—more competitive, likely resulting in lower geothermal deployment projections than those presented in this report. See Section C.1.5 for more information.

2016 version of the Standard Scenarios (Cole et al. 2016a) and assumes the NREL Mid-case scenario for all modeling runs, unless otherwise noted. The Mid-case scenario is used in the Standard Scenario analysis as a reference case reflecting business-as-usual conditions. The default assumptions used in the Mid-case scenario reflect median or midline expectations for model inputs (e.g., Reference-case fuel prices, Mid-case technology costs) based on current information. The Mid-case scenario is used in the *GeoVision* analysis for the same purpose—to represent present and future costs of non-geothermal technologies. The Mid-case scenario uses the following assumptions:

- Electricity demand growth: AEO 2016 Reference case (EIA 2016b) (Figure C-6)
- Fuel prices: AEO 2016 Reference case (EIA 2016b) (Figure C-7)
- Existing fleet retirement: lifetime retirements based on ABB Ability™ Velocity Suite database (ABB 2016)
- Policy/regulatory environment: includes federal and state policies enacted as of April 1, 2016, with the exception of the federal Clean Power Plan. The Clean Power Plan was not assumed to be in effect in the *GeoVision* analysis ReEDS runs.

Non-geothermal electricity-generation technology costs assume the 2016 ATB Mid-case projections. Mid-case projections for the major electricity-generation technologies in ReEDS are shown for current (2015) and projected future (2030 and 2050) years in Table C-3 and Table C-4, respectively.

Major financing assumptions in ReEDS for all non-geothermal electricity-generation technologies are shown in Table C-5.



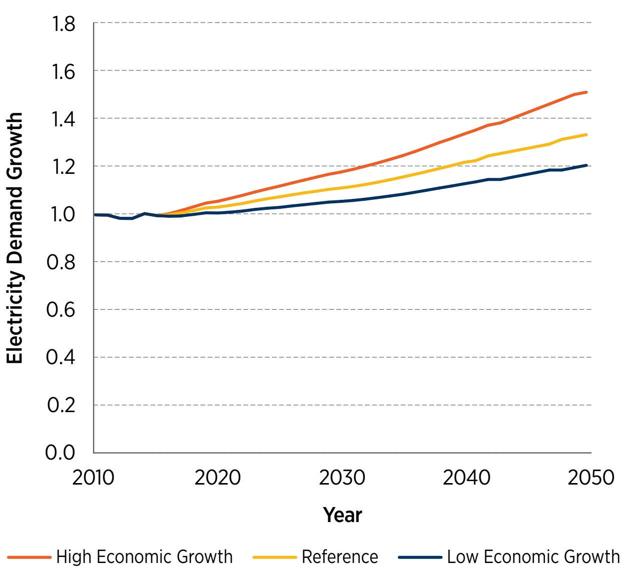


Figure C-6. Demand growth trajectories relative to 2010 demand from the Energy Information Administration (2016b)

Figure Note: The Standard Scenario Mid-Case used in the GeoVision analysis assumes the Reference demand growth curve.

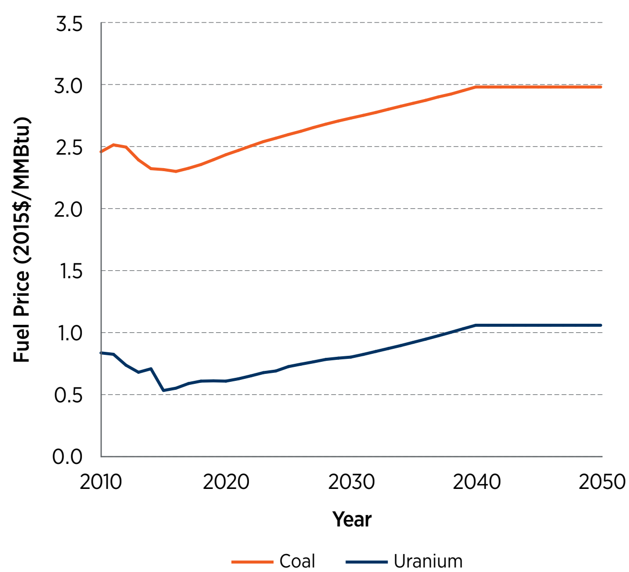


Figure C-7. Fuel price trajectories from the Energy Information Administration (2016b)

Figure Note: The Standard Scenario Mid-Case used in the GeoVision analysis assumes the Reference natural-gas price curve.

Technology		CF Range		CAPEX Range					LCOE Range	
		Low (%)	High (%)	Low ($\$/kW_e$)	High ($\$/kW_e$)	Fuel Costs ($\$/MWh_e$)	Fixed O&M ($\$/kW_e/yr$)	Variable O&M ($\$/MWh_e$)	Low ($\$/MWh_e$)	High ($\$/MWh_e$)
2015										
Coal	PC	61%	85%	$4,103	$4,103	$19	$32	$5	$89	$115
	IGCC	61%	85%	$4,403	$4,403	$18	$52	$7	$98	$126
	IGCC-CCS	61%	85%	$7,595	$7,595	$21	$74	$9	$153	$201
Gas	CT	5%	30%	$869	$869	$32	$7	$13	$85	$292
	CC	48%	87%	$1,056	$1,056	$22	$14	$3	$42	$55
	CC-CCS	48%	87%	$2,198	$2,198	$24	$32	$7	$66	$95
Nuclear		92%	92%	$6,369	$6,369	$6	$95	$2	$104	$104
Biopower		52%	52%	$3,991	$3,991	$3	$5	$3	$150	$150
Geothermal		80%	90%	$5,049	$13,464	$0	$155	$0	$78	$225
CSP with 10-hr TES		42%	59%	$7,915	$7,915	$0	$64	$4	$160	$223
2030										
Coal	PC	61%	85%	$3,941	$3,941	$20	$32	$5	$87	$112
	IGCC	61%	85%	$4,080	$4,080	$17	$52	$7	$92	$119
	IGCC-CCS	61%	85%	$6,821	$6,821	$19	$74	$9	$139	$183
Gas	CT	5%	30%	$805	$805	$53	$7	$13	$102	$295
	CC	48%	87%	$983	$983	$36	$14	$3	$56	$68
	CC-CCS	48%	87%	$1,930	$1,930	$41	$32	$7	$80	$105
Nuclear		92%	92%	$6,098	$6,098	$8	$95	$2	$103	$103
Biopower		52%	52%	$3,750	$3,750	$3	$5	$3	$145	$145
Geothermal		80%	90%	$5,049	$13,464	$0	$155	$0	$78	$225
CSP with 10-hr TES		42%	59%	$3,671	$3,671	$0	$40	$4	$78	$109
2050										
Coal	PC	61%	85%	$3,737	$3,737	$21	$32	$5	$85	$109
	IGCC	61%	85%	$3,700	$3,700	$18	$52	$7	$87	$12
	IGCC-CCS	61%	85%	$5,977	$5,977	$20	$74	$9	$127	$166
Gas	CT	5%	30%	$744	$744	$51	$7	$13	$98	$277
	CC	48%	87%	$913	$913	$35	$14	$3	$53	$65
	CC-CCS	48%	87%	$1,643	$1,643	$40	$32	$7	$74	$96
Nuclear		92%	92%	$5,422	$5,422	$11	$95	$2	$97	$98
Biopower		52%	52%	$3,452	$3,452	$3	$5	$3	$139	$139
Geothermal		80%	90%	$5,049	$13,464	$0	$155	$0	$78	$225
CSP with 10-hr TES		42%	59%	$3,671	$3,671	$0	$40	$4	$78	$109

Table C-3. Dispatchable Electricity-Generation Technology Cost and Performance Data from the 2016 Annual Technology Baseline Mid-case Scenario by Generation Technology

Table Note: CF=capacity factor, CAPEX=capital expenditure, O&M=operations and maintenance, LCOE=levelized cost of electricity, PC=pulverized coal, IGCC=integrated gasification combined cycle, CCS=carbon capture and storage; CT=combustion turbine, CC=combined cycle, CSP=concentrating solar power, TES=thermal energy storage (NREL 2016).

Technology		CF Range Low (%)	CF Range High (%)	CAPEX Range Low ($/kWe)	CAPEX Range High ($/kWe)	Fuel Costs ($/MWhe)	Fixed O&M ($/kWe/yr)	Variable O&M ($/MWhe)	LCOE Range Low ($/MWhe)	LCOE Range High ($/MWhe)
2015										
Wind	Land-Based	13%	52%	$1,723	$2,186	$0	$51	$0	$47	$228
	Offshore	34%	49%	$5,739	$7,344	$0	$148	$0	$162	$223
Photovoltaic	Utility	14%	28%	$1,942	$1,942	$0	$16	$0	$81	$162
	Commercial	11%	19%	$2,249	$2,249	$0	$14	$0	$137	$225
	Residential	13%	21%	$3,096	$3,096	$0	$18	$0	$170	$282
Hydropower		60%	66%	$3,895	$7,261	$0	$77	$0	$90	$162
2030										
Wind	Land-Based	17%	56%	$1,567	$2,578	$0	$49	$0	$40	$194
	Offshore	37%	54%	$4,321	$5,501	$0	$115	$0	$112	$154
Photovoltaic	Utility	14%	28%	$1,041	$1,041	$0	$8	$0	$43	$86
	Commercial	11%	19%	$1,270	$1,270	$0	$8	$0	$77	$127
	Residential	13%	21%	$1,487	$1,487	$0	$10	$0	$82	$137
Hydropower		60%	66%	$3,895	$6,996	$0	$77	$0	$90	$156
2050										
Wind	Land-Based	18%	59%	$1,558	$2,618	$0	$46	$0	$37	$180
	Offshore	38%	55%	$4,087	$5,196	$0	$112	$0	$104	$143
Photovoltaic	Utility	14%	28%	$852	$852	$0	$8	$0	$36	$72
	Commercial	11%	19%	$988	$988	$0	$8	$0	$61	$100
	Residential	13%	21%	$1,194	$1,194	$0	$10	$0	$67	$111
Hydropower		60%	66%	$3,895	$6,646	$0	$77	$0	$90	$150

Table C-4. Non-Dispatchable Electricity-Generation Technology Cost and Performance Data from the 2016 Annual Technology Baseline Mid-case Scenario by Generation Technology

Table Note: CF=capacity factor, CAPEX=capital expenditure, O&M=operations and maintenance, LCOE=levelized cost of electricity (NREL 2016).

Type of Assumption	Value Used
Evaluation period	20 years
Inflation rate	2.5%
Interest rate—nominal	8%
Rate of return on equity—nominal	13%
Debt fraction	60%
Combined state and federal tax	40%
Discount rate—nominal (real)	8.1% (5.4%)
Modified accelerated cost recovery system (non-hydropower renewables)	5 years
Modified accelerated cost recovery system (nuclear, combustion turbines)	15 years
Modified accelerated cost recovery system (other fossil, hydropower, storage)	20 years

Table C-5. Major Financial Assumptions from the 2016 Annual Technology Baseline for Non-Geothermal Electricity-Generation Technologies used in the Regional Energy Deployment System Model for the *GeoVision* Analysis

C.1.4 Supplemental Modeling Results

This section provides results from the ReEDS model for the *GeoVision* analysis scenarios. The following projections through 2050 are presented for each scenario:

- Capacity-deployment projections by geothermal resource type
- Total electric-sector capacity deployment projections for all technologies
- Total electric-sector generation projections for all technologies.

C.1.4.1 Business-as-Usual Scenario

Figure C-8 illustrates the installed geothermal capacity by year for the *GeoVision* analysis BAU scenario. The results of this scenario show that—absent any substantial changes to the industry—geothermal will continue to be a niche player in the electricity-generation market, with capacity additions confined to the western United States. Most new geothermal capacity additions come from undiscovered hydrothermal resources (Figure C-8), indicating that the exploration and discovery of new geothermal resources is key to additional conventional hydrothermal deployment. In the BAU scenario, EGS technologies are too costly to be competitive so none are deployed within the ReEDS model. Figure C-9 illustrates the cumulative installed capacity by year for all technologies in ReEDS under BAU, and Figure C-10 illustrates annual electricity generation by year for all technologies.

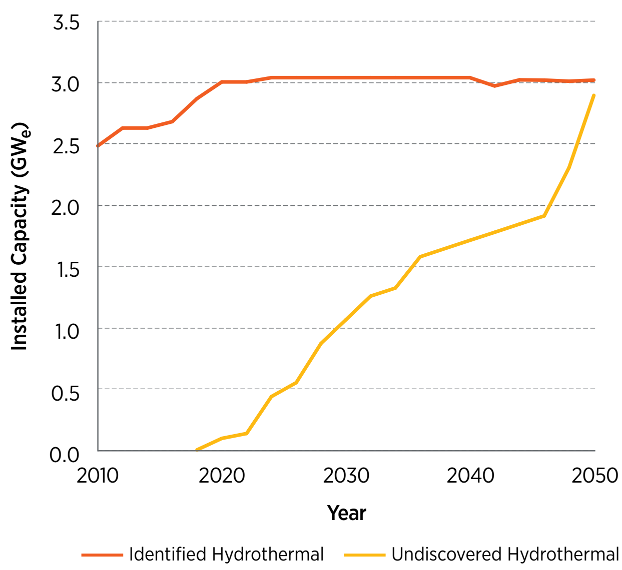


Figure C-8. Installed geothermal capacity by year for the Business-as-Usual scenario

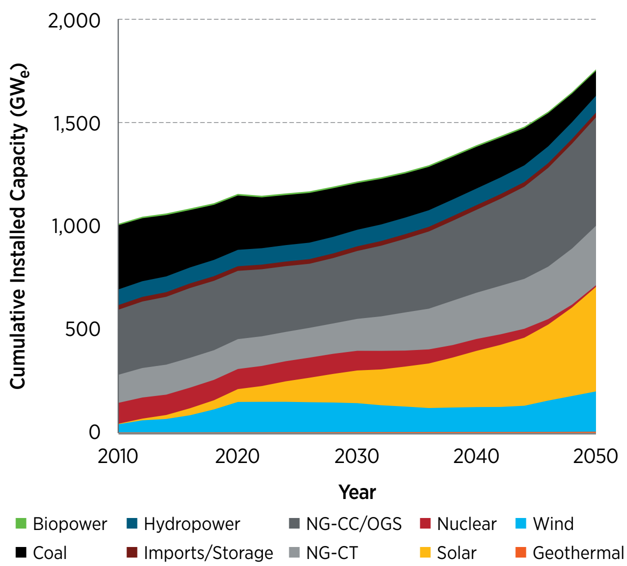


Figure C-9. Cumulative installed capacity by year for all technologies in the Regional Energy Deployment System for the Business-as-Usual scenario

Figure Note: NG-CC=Natural Gas Combined Cycle; OGS=Oil/Gas Steam Turbine; NG-CT=Natural Gas Combustion Turbine

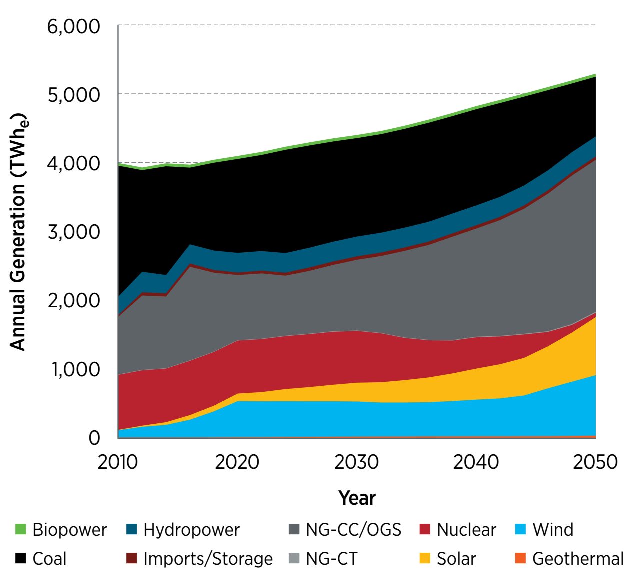


Figure C-10. Annual electricity generation by year for all technologies in the Regional Energy Deployment System for the Business-as-Usual scenario

C.1.4.2 Improved Regulatory Timeline Scenario

The *GeoVision* analysis IRT scenario results indicate that the geothermal industry could double in size through regulation reform alone (Figure C-11). Reducing construction timelines has big impacts on overall project costs and subsequent deployment absent any technology advances, meaning that hydrothermal resources could show significantly more deployment even with current technology if soft costs and barriers are reduced. As in the BAU scenario, most of the new geothermal capacity additions come from undiscovered hydrothermal resources, illustrating that the exploration and discovery of new geothermal resources remain key to additional conventional hydrothermal deployment. EGS technologies remain too costly to be deployed in the IRT scenario, despite the shorter assumed construction timeline. Figure C-12 shows cumulative installed capacity by year for all technologies in ReEDS for the IRT scenario, and Figure C-13 shows annual electricity generation by year for all technologies in ReEDS for the IRT scenario.

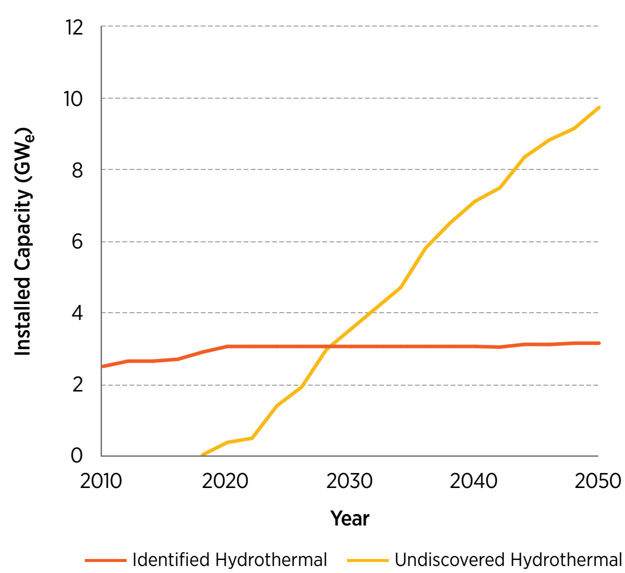


Figure C-11. Installed geothermal capacity by year for the Improved Regulatory Timeline scenario

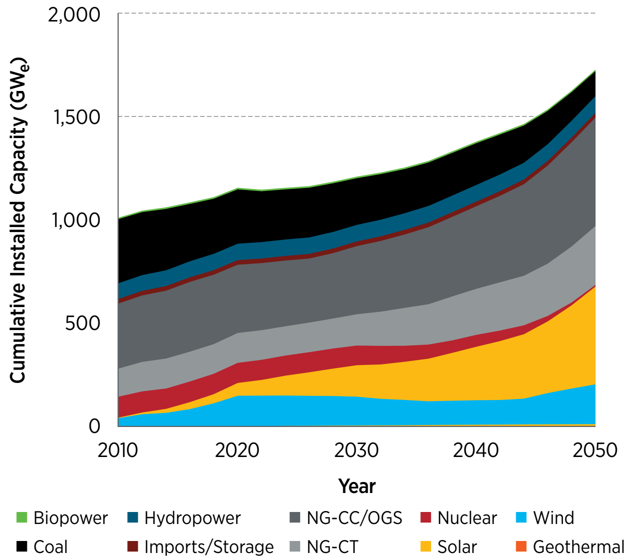


Figure C-12. Cumulative installed capacity by year for all technologies in the Regional Energy Deployment System for the Improved Regulatory Timeline scenario

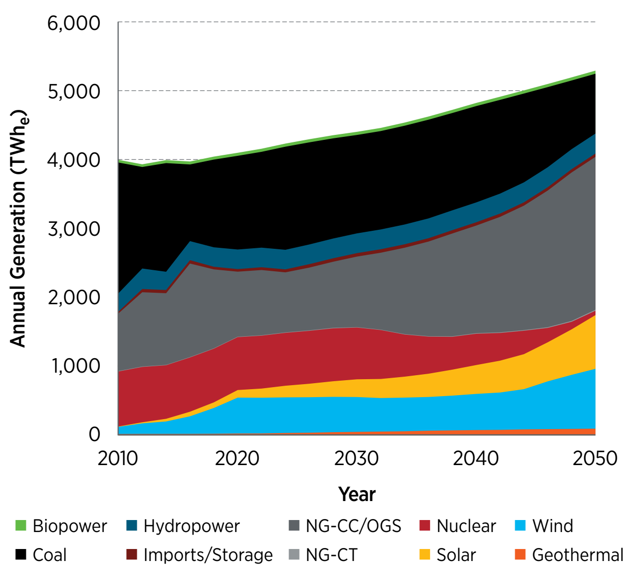


Figure C-13. Annual electricity generation by year for all technologies in the Regional Energy Deployment System for the Improved Regulatory Timeline scenario

C.1.4.3 Technology Improvement Scenario

The results of the *GeoVision* analysis TI scenario indicate that EGS can achieve notable deployment rates if there are significant technology improvements and related reductions in capital cost and risk (Figure C-14). Because of its high capacity factor, generation from a specific amount of installed geothermal capacity is higher than generation from an equivalent amount of installed capacity of other renewables. In the TI scenario, geothermal can supply 8.5% of all U.S. electricity-generation demand in 2050 from only 61 GW of installed capacity. The majority of this (43.6 GW) is from EGS deployments. These deployments do not become commercially available until 2030, but then the technology is rapidly deployed, with installed capacity steadily increasing through 2050. A significant portion of geothermal capacity comes from undiscovered hydrothermal resources as well, reaching 12.6 GW of installed capacity by 2050. This again underscores the findings from the other *GeoVision* analysis scenarios that the exploration and discovery of new geothermal resources are key to increasing conventional hydrothermal deployment. In the TI scenario, hydrothermal technologies also benefit from technology advances and lower costs, resulting in higher installed hydrothermal capacity than in the IRT scenario—even with the added competition from EGS. Figure C-15 shows cumulative installed capacity by year for all technologies in ReEDS for the TI scenario, and Figure C-16 shows annual electricity generation by year for all technologies in the ReEDS for the TI scenario.

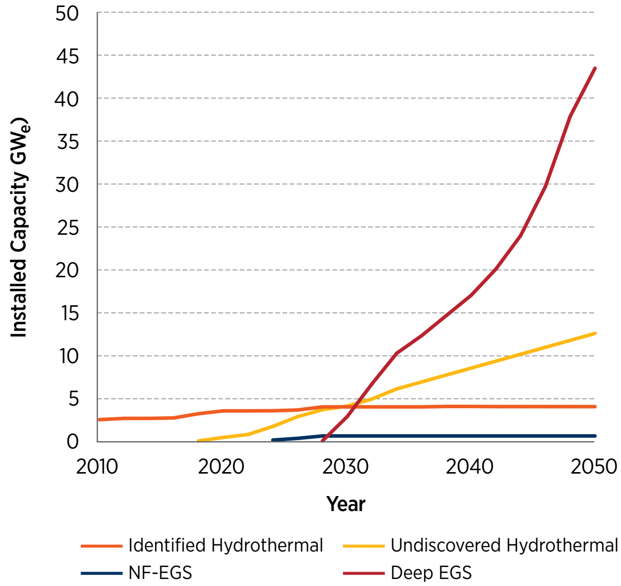


Figure C-14. Installed geothermal capacity by year for the Technology Improvement scenario

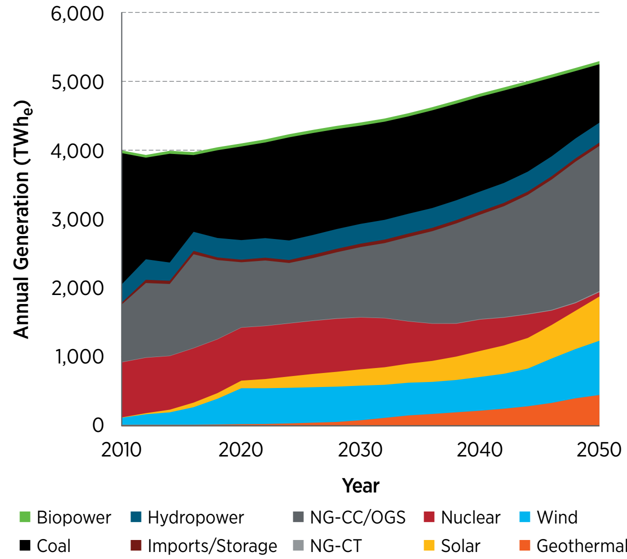


Figure C-16. Annual electricity generation by year for all technologies in the Regional Energy Deployment System for the Technology Improvement scenario

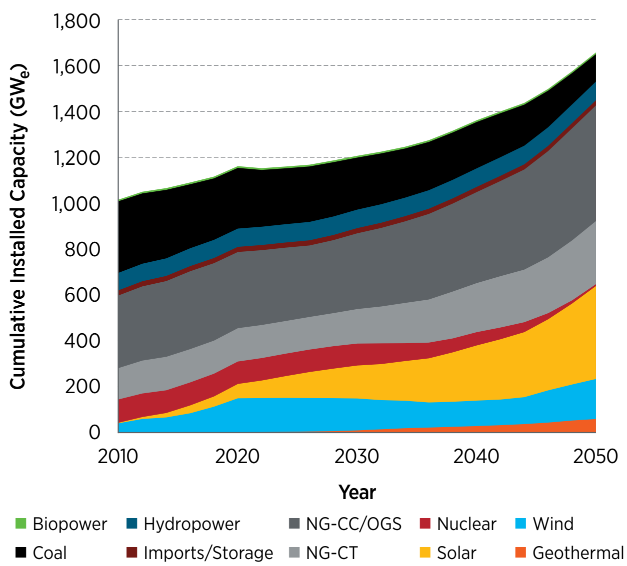


Figure C-15. Cumulative installed capacity by year for all technologies in the Regional Energy Deployment System for the Technology Improvement scenario

C.1.4.4 Standard Scenario Results

The ReEDS Standard Scenarios were run using the assumptions for the *GeoVision* analysis TI scenario for geothermal technologies. As discussed in Section C.1.3.1, the Standard Scenarios are a set of power-sector scenarios that provide a quantitative examination of how ranges of values of specific inputs impact power-sector development; these scenarios are described in detail in Cole et al. 2016a. The scenarios capture a reasonable breadth of trajectories of costs, performance, policy, and other drivers; thus, they enable assessment of a range of potential futures rather than a single, mid-case outlook. The *GeoVision* analysis assumes the Mid-case scenario for the core BAU, IRT, and TI scenarios. The main body of the report also includes discussion of the High Natural-Gas Prices scenario (Table C-6) to illustrate the potential of geothermal technologies under alternative future scenarios. The Standard Scenarios look at the sensitivity of the ReEDS model results to seven areas:

1. Electricity demand growth
2. Fuel prices
3. Electricity-generation technology costs
4. Existing fleet retirements
5. Policy/regulatory environment
6. Earth system feedbacks
7. Resource and system constraints.

Table C-6 summarizes the Standard Scenarios used for the *GeoVision* analysis sensitivity scenarios.

Group	Scenario	Notes
Electricity Demand Growth	**Reference Demand Growth**	**AEO 2016 Reference**
	Low Demand Growth	AEO 2016 Low Economic Growth
	High Demand Growth	AEO 2016 High Economic Growth
	Vehicle Electrification	Plug-in electric vehicle/plug-in hybrid electric vehicle adoption reaches 40% of sales by 2050; 45% of charging utility-controlled, 55% opportunistic
Fuel Prices	**Reference Natural Gas Prices**	**AEO 2016 Reference**
	Low Natural Gas Prices	AEO 2016 High Oil and Gas Resource and Technology
	High Natural Gas Prices	AEO 2016 Low Oil and Gas Resource and Technology
Electricity-Generation Technology Costs	**Mid-Case Technology Cost**	**2016 ATB Mid-Case Projections**
	Low RE Cost	2016 ATB Renewable Energy Low-Case Projections
	High RE Cost	2016 ATB Renewable Energy High-Case Projections
	Nuclear Technology Breakthrough	50% reduction in nuclear capital costs over all years
Existing Fleet Retirements	**Reference Retirement**	**Lifetime retirements based on ABB Velocity Suite database (ABB 2016)**
	Extended Nuclear Lifetime	Relicensing to 80 years
	Accelerated Coal Retirement	Coal power-plant lifetimes reduced by 10 years
Policy/Regulatory Environment	**Current Law**	**Includes policies as of April 1, 2016. (Does not include a Clean Power Plan for *GeoVision*)**
	Extended Incentives for RE Generation	Extend investment tax credit/production tax credit through 2030 for eligible technologies
Earth System Feedbacks	**No Climate Feedback**	**No feedback because of changes in the climate**
	Impacts of Climate Change	Impact of higher temperatures on generators, transmission, and demand; derived from IGSM-CAM climate scenario
Resource and System Constraints	**Default Resource Constraints**	**Used for the Mid-Case Scenario**
	Reduced RE Resource	25% cut to each resource in input supply curves
	Barriers to Transmission System Expansion	Expansion three times transmission capital cost; no new AC-DC-AC interties; two times transmission loss factors
	Restricted Cooling Water Use	New construction may not use fresh water for cooling

Table C-6. Summary of the Standard Scenarios

Source: Cole et al. 2016a

Table Notes: Scenarios in bold indicate assumptions used in the mid-case scenario (default assumptions). RE = renewable energy, IGSM-CAM = Integrated Global System Model–Community Atmosphere Model.

Results of all Standard Scenarios using the *GeoVision* analysis TI scenario are shown in Figure C-17. The scenarios using the *GeoVision* analysis TI inputs for geothermal technologies can be divided into three groups as described in the subsequent paragraphs.

The first group comprises scenarios where the amount of installed geothermal capacity is significantly higher than in the Mid-case scenario, consisting of the High Natural Gas Prices and High RE Cost Standard Scenarios. The High Natural Gas Prices scenario (see Figure C-7 for assumed natural-gas prices in this scenario) results in the most installed geothermal capacity, with 118 GW_e by 2050, followed closely by the High RE Cost scenario, with 107 GW_e. These scenarios show that geothermal deployment in the TI scenario can be double what it is in the Mid-case scenario in futures where the costs of competing electricity-generation technologies (e.g., natural gas, other renewables) are high. Because of the high capacity factor of geothermal power plants, geothermal accounts for about 16% of total U.S. electricity generation in 2050 for the High Natural-Gas Prices scenario. For both of these high geothermal-penetration scenarios, the additional installed geothermal capacity compared to the TI case is made up almost entirely of deep-EGS resources.

The second group comprises scenarios where the amount of installed geothermal capacity is significantly less than in the Mid-case scenario. Only the Low RE Cost scenario fits in this group. When lower-cost renewable energy generation is assumed, geothermal installed capacity drops to about 20 GW_e—or less than one-third of the value in the Mid-case scenario. In this scenario, geothermal deployment is replaced by lower-cost renewable energy options.

The third group comprises scenarios where the impact on geothermal deployment does not vary significantly from the Mid-case scenario. The rest of the scenarios fit in this group. For the majority of the scenarios, the potential scenario conditions do not significantly favor or hinder geothermal deployment compared to the Mid-case scenario; the resulting installed geothermal capacity is within +5 GW_e to (-20) GW_e of the Mid-case scenario.

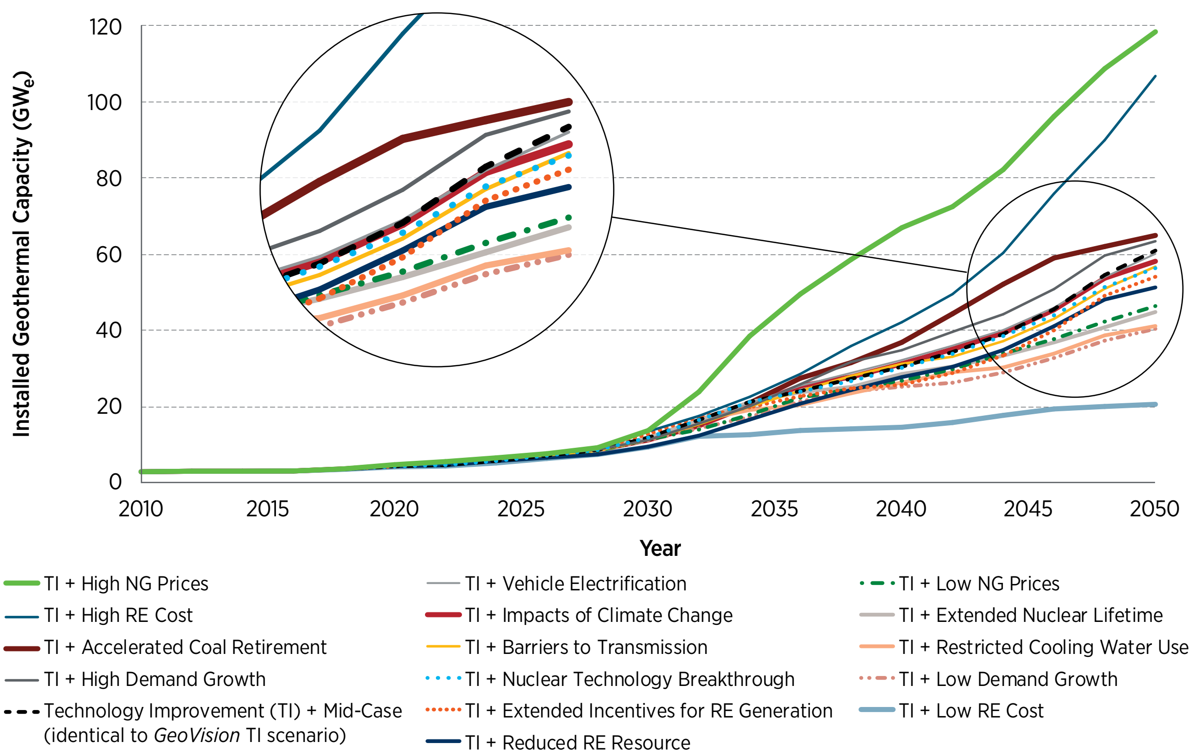


Figure C-17. Total installed geothermal capacity for the ReEDS Standard Scenarios assuming the *GeoVision* Technology Improvement case

Figure Note: The Standard Scenarios are listed in the legend in order of total installed capacity in 2050, from highest to lowest.

C.1.5 Discussion

Figure C-18 shows the electric-sector installed capacity for all technologies projections for the EIA's AEO 2016 Reference case. The technologies have been grouped to match the categories from ReEDS results to facilitate comparisons between the AEO 2016 Reference case and the *GeoVision* analysis BAU scenario (Figure C-12). The AEO's projected 7.2 GW_e installed geothermal capacity for 2040 is more optimistic than the 4.8 GW_e value in 2040 (5.9 GW_e in 2050) from the *GeoVision* analysis BAU scenario (note that both the EIA and BAU values are small enough compared to overall installed electric-generation capacity to not have much impact overall). The largest discrepancy, on a percentage basis, is the difference in nuclear installed capacity. This difference is due to exogenous assumptions about nuclear lifetimes rather than the relative competitiveness of nuclear plants with other generation technologies.[111] AEO 2016 assumes that all nuclear plants will receive a second relicense and therefore have an 80-year lifetime, resulting in 99 GW_e of installed capacity through 2040. The *GeoVision* BAU scenario, however, assumes a single relicense, giving nuclear plants a fixed 60-year lifetime. The result is that nuclear capacity drops from around 100 GW_e at the start of the model run in 2010 to 57 GW_e by 2040 and 8 GW_e by 2050.

There are also variations in capacity projections for other technologies, For instance, AEO 2016 projects more coal plant retirements. The AEO 2016 Reference case shows about 170 GW_e of installed coal capacity in 2040, whereas under the *GeoVision* analysis BAU scenario, the installed capacity of coal technologies falls to about 200 GW_e by 2040 and 120 GW_e by 2050. Additionally, the *GeoVision* BAU scenario shows substantially more growth in solar capacity, totaling 272 GW_e in 2040 vs. 158 GW_e under the AEO 2016 Reference case. Natural-gas combustion-turbine installed capacity in 2040 is also substantially greater under the *GeoVision* analysis BAU scenario than the AEO 2016: 224 GW_e vs. 142 GW_e, respectively. Natural-gas combined-cycle installed capacity projections are nearly identical between the models, as are installed capacity projections for hydropower.

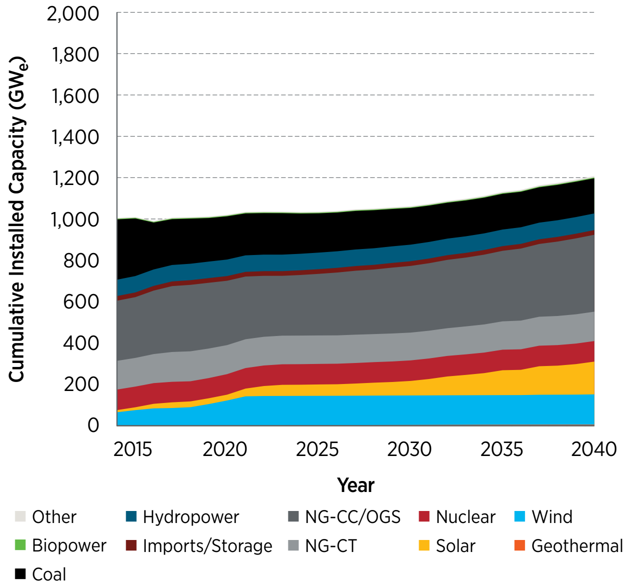


Figure C-18. Cumulative installed capacity through 2040 for electricity-generation technologies projected by 2016 Energy Information Administration Annual Energy Outlook (Reference case)

Figure Note: Technology types have been grouped to match categories from ReEDS results to facilitate comparisons (EIA 2016b)

Despite some quantitative differences, both the *GeoVision* BAU results from ReEDS and the AEO 2016 are in general agreement about the future of the U.S. electric sector. Both project that natural-gas generation and renewable energy technologies such as wind and solar will play an increasingly larger role in the future. This has implications for the *GeoVision* analysis. The ReEDS modeling in the *GeoVision* analysis is based on the 2016 ATB. EIA and NREL have since produced additional AEO and ATB updates (2017 and 2018) with projected natural-gas, wind, and solar electricity-generation costs that have all decreased compared to 2016 projections. Figure C-19 illustrates how natural-gas price projections have dropped from AEO 2016 to AEO 2018. Figure C-20 shows how the projected costs of wind and solar technologies used in the ATB Mid-case scenario have decreased from 2016 to 2018. These changes to the ReEDS inputs would make natural-gas, wind, and solar technologies more competitive and would likely decrease the deployment of geothermal (and other) technologies compared to 2016 values. Identifying the extent of decreases in geothermal

111 Both the National Energy Modeling System (used for the AEO) and ReEDS (used for the *GeoVision* analysis) have revised their nuclear retirement criteria and assumptions since the 2016 model version.

capacity additions under the 2018 cost projections was not possible within the scope of the *GeoVision* analysis. However, preliminary ReEDS model runs using 2017 ATB and Standard Scenario inputs (including updated natural-gas prices) indicated that—while geothermal capacity deployments are lower compared to using 2016 data—the general trends of increased geothermal deployment observed for the *GeoVision* scenarios are still valid. The Standard Scenario results shown in Figure C-17 support the resilience of the geothermal deployment results across a range of scenarios. Although updated ReEDS model runs using current cost data would likely reduce overall geothermal deployment numbers, the lessons learned from the *GeoVision* analysis still hold.

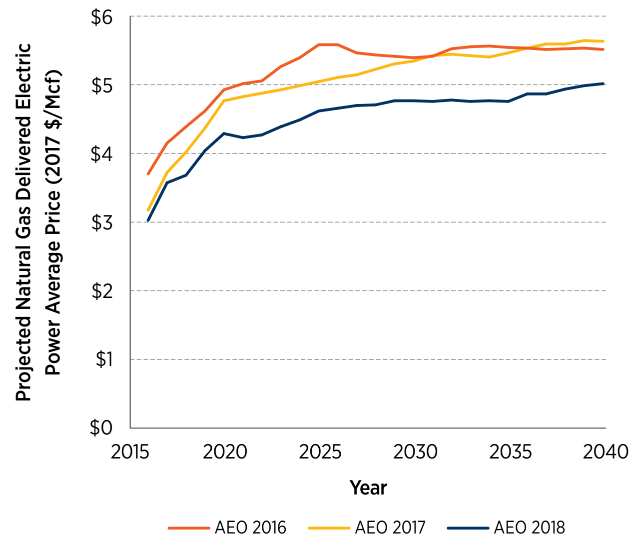


Figure C-19. Comparison of natural-gas delivered electric-power average price (2017$ per thousand cubic feet [Mcf]) projections from the Annual Energy Outlook 2016, Annual Energy Outlook 2017, and Annual Energy Outlook 2018

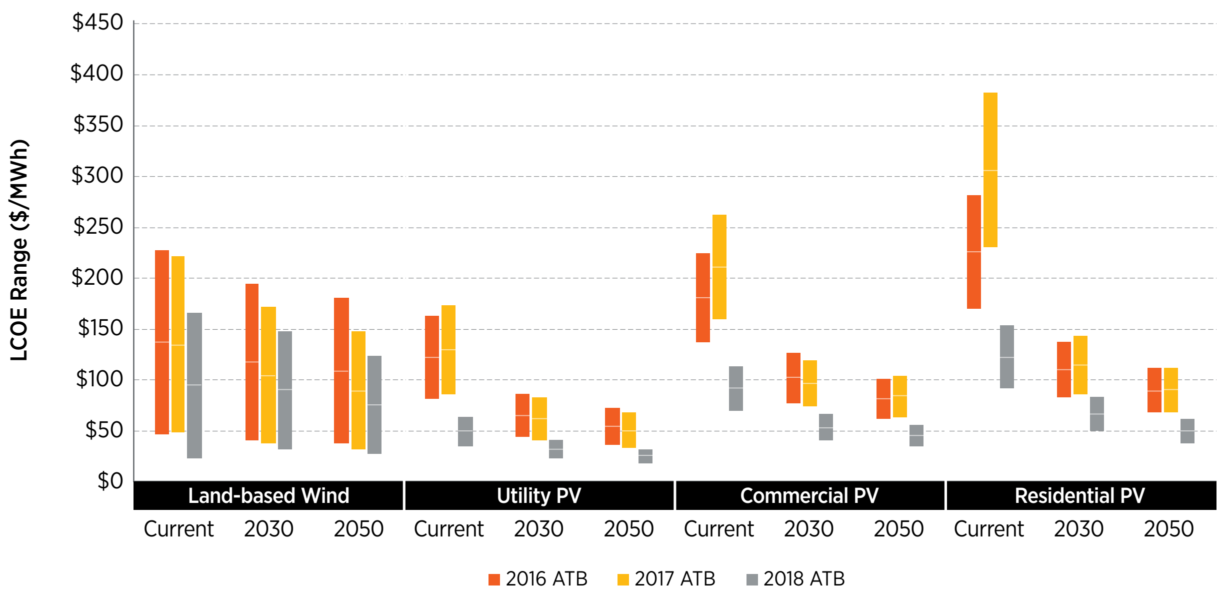


Figure C-20. Levelized cost of electricity ranges used for wind and solar technologies in 2016–2018 Annual Technology Baseline Mid-case scenarios

Source: NREL n.d. (ATB Summary)

C.2 Heating and Cooling Sector: Distributed Geothermal Market Demand (dGeo) Model

As noted in Section 3.1.3, to evaluate the non-electric heating and cooling sector, the U.S. Department of Energy developed a dedicated modeling tool called the Distributed Geothermal Market Demand (dGeo) model. The *GeoVision* analysis uses the dGeo model to evaluate the potential of geothermal heat pump (GHP) and geothermal direct-use district-heating technologies in the non-electric heating and cooling sector. Heating and cooling sector assumptions and inputs for the *GeoVision* analysis are structured around the dGeo model framework described in subsequent paragraphs. District-heating-specific and GHP-specific model inputs and results are also discussed in Sections C.3 and C.4. The information and graphics in Section C.2 are sourced primarily from Gleason et al. 2017.

The dGeo model uses a bottom-up, spatially resolved, agent-based framework to simulate the potential market for geothermal distributed energy resources. A region is modeled as a combination of agents that approximate the actual population of buildings and residences in the region. This framework shares several key traits with classical agent-based modeling, but also has some important differences (see Gleason et al. 2017).

In dGeo, each agent represents a type of commercial or residential building, complete with several key attributes. The dGeo model framework involves six main components:

1. **Agent Generation:** During agent generation, which occurs at model initialization, dGeo creates a synthetic population of agents within each region.
2. **Agent Mutation:** At each time step, agents are updated to inherit new time-dependent attributes (or change existing ones) that may affect their evaluation of the opportunity for technology adoption.
3. **Assessment of Technical Potential:** Based on the status of agents at each time step, dGeo assesses the quantity of district-heating and GHP resource that is technically feasible, given proximity to end-use thermal demand and—in the case of GHP—siting constraints.
4. **Assessment of Economic Potential:** At each time step, dGeo evaluates the economics of an investment in district-heating and GHP technologies for each agent using discounted cash-flow analysis. A similar analysis is performed for the alternative/baseline heating and cooling technology, such as a traditional heating, ventilation, and air-conditioning (HVAC) system, to represent the "competition" for district-heating and GHP technologies. These cash-flow analyses produce financial metrics that can be used to assess how economically attractive each technology is to each agent (relative to the baseline competition), as well as the overall number of agents for whom technology adoption would be economically rational.
5. **Assessment of Market Potential:** Based on empirical data that relate payback period of a given technology to the number of customers who would be willing to adopt a technology, dGeo translates economic potential into market potential at each time step.
6. **Simulation of Technology Deployment:** Finally, at each time step, dGeo simulates technology deployment based on current economic evaluations of each agent, as well as population-level interaction effects from other agents.

dGeo performs simulations beginning with a base year of 2012, and it advances in 2-year time steps through 2050. dGeo can simulate results for the continental United States; Hawaii and Alaska were excluded from the model because many of the foundational datasets underlying the model are unavailable for those locations. In terms of spatial resolution, dGeo uses U.S. Census tracts that have populations (median = 4,000 people) and geographic areas (median = 5 km^2) consistent with the upper limit of existing district-heating systems. dGeo only considers buildings in the residential and commercial sectors; it does not model the industrial sector (including manufacturing, agriculture, mining, and other subsectors) because of a lack of sufficient data to model this sector at any defensible level of fidelity.

C.3 Heating and Cooling Sector: Direct-Use District-Heating Systems

As discussed in the main body of the *GeoVision* report, analysis of geothermal direct-use applications was limited to district-heating systems (see Section 4.2.1). In addition, due to a lack of consumer behavior data on how communities adopt technologies such as district-heating systems, the analysis is limited to the resource, technical, and economic potential of district-heating systems (step 4 of the dGeo model framework). The information and graphics in this section are sourced primarily from McCabe et al. 2019, Gleason et al. 2017, and Mullane et al. 2016.

C.3.1 Resource Potential

For district heating, dGeo considers resources in the range of 30°C to 150°C and less than 3 km deep, including both hydrothermal and EGS. The resource potential in dGeo is based on a previous study by Mullane et al. 2016 investigating the location, temperature, and amount of stored heat of low-temperature (<150°C) and relatively shallow (<3,000 m) hydrothermal and EGS resources in the United States.

C.3.1.1 Hydrothermal Systems

Hydrothermal systems are classified into four model types, following the convention of Sorey et al. (1983):

1. *Isolated springs and wells:* one or a group of nearby wells or springs producing geothermal fluid; generally have a reservoir volume of less than 1 km^3

2. *Delineated-area convection systems:* characterized by an upwelling of geothermal water with subsequent lateral flow into shallow aquifers larger than 1 km^3; with or without surface manifestations

3. *Sedimentary basins:* thermal sedimentary aquifers overlain by low thermal-conductivity lithologies; contain trapped thermal fluid and have flow rates sufficient for production without stimulation

4. *Coastal plains sedimentary systems:* similar to sedimentary systems, although typically occur along coastlines and may be underlain by an intrusive igneous body producing heat by radioactive decay; natural flow rates are sufficient for production without stimulation.

Data for all four types of hydrothermal systems came primarily from three USGS studies, including (in descending order of contribution to this analysis): USGS Circular 892 (Reed et al. 1983), USGS Circular 790 (Muffler 1979), and USGS Fact Sheet 2008-3082 (Williams et al. 2008b). These studies were chosen due to their comprehensive, nationwide coverage, as well as their internal consistency in terminology and methods. USGS Circular 892 focuses on resources in the range of 15°C to 90°C, whereas the latter two studies include additional resources in the range of 90°C to 150°C. For most sites, data for most of the parameters (e.g., temperature, depth, thickness, area per production well) were available directly from the original studies or a detailed review of the associated primary sources; however, in several cases, gaps in the data were filled by searching for supplemental, site-specific studies. Data gaps occurred most commonly in location and reservoir area.

Table C-7 shows the estimated resource potential for each of the hydrothermal system models, and Figure C-21 shows their distribution within the United States. The accessible resource is quite large, but the portion that can be extracted given physical and current technological limitations (mean resource) is far less. For comparison, the total low-temperature thermal demand in the United States is roughly 12 exajoules annually.[112] The beneficial heat—representing the best estimate of how much heat can realistically be utilized for end uses with existing technology—represents roughly half of the mean resource (note: 11.2 million GWh_{th} = 40.3 exajoules).

112 An exajoule is 10^{18} joules. A joule is defined by EIA as, "The meter-kilogram-second unit of work or energy, equal to the work done by a force of one newton when its point of application moves through a distance of one meter in the direction of the force" (EIA Glossary n.d.). One quad is equal to 1.055 exajoules.

Resource Model	Accessible Resource (Exajoules = 10^{18} J)	Mean Resource (Exajoules = 10^{18} J)	Beneficial Heat (GWh_{th})
Isolated Springs and Wells	180	22	2.9 million
Delineated-Area Convection	130	7	0.7 million
Sedimentary Basins	28,000	60	7.5 million
Coastal Plains	80	1	0.1 million
Total	**28,390**	**90**	**11.2 million**

Table C-7. Resource Assessment Estimates for All Four Hydrothermal Model Types

Source: Mullane et al. 2016

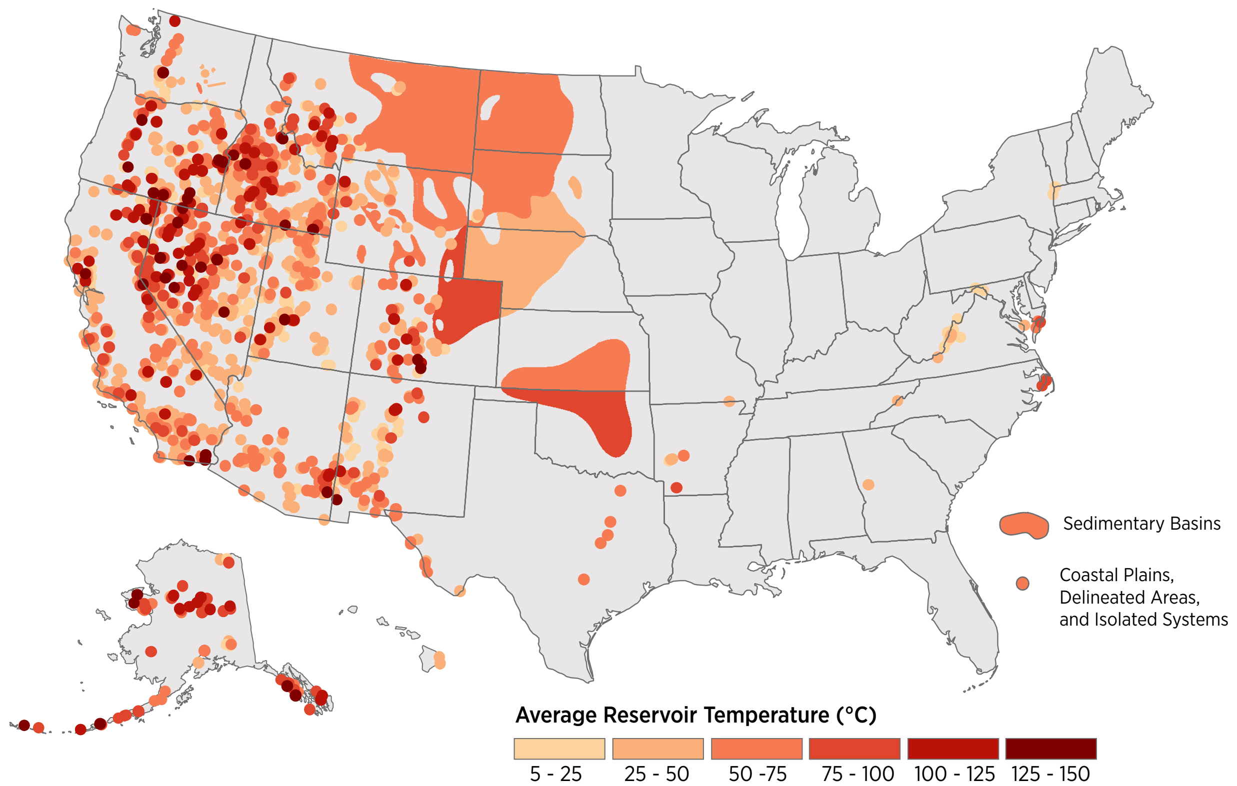


Figure C-21. Map of hydrothermal resources at specified temperatures for the United States

Source: Mullane et al. 2016

C.3.1.2 Enhanced Geothermal Systems

EGS includes two primary subtypes:

1. *EGS sedimentary basins:* differ from "hydrothermal" sedimentary systems in that they lack water and/or permeability.

2. *Shallow (<3 km) low-temperature EGS*[113]: low-conductivity basement rock at a depth of 3 km or less; in theory, may be accessed in any location given sufficient depth and reservoir stimulation. Referred to as "shallow EGS" in contrast to "deep EGS," which is generally hotter and considered for electricity generation.

In comparison to hydrothermal resources, very few studies have focused on shallow-EGS resources. For EGS sedimentary basins, the *GeoVision* analysis resource-potential estimate drew from work by Porro et al. 2012. The Porro et al. study assessed the accessible resource (i.e., heat-in-place) for 15 large sedimentary basins in the United States. Although the authors did not explicitly identify their focus on EGS resources, language in the report indicates that recovery of heat from basins in the study would require "injection and extraction of fluid" and potentially "stimulation and enhanced recovery methods." Therefore, this study was treated as an EGS resource assessment.

Table C-8 shows the accessible resource base for low-temperature sedimentary EGS for those portions of the 2012 Porro et al. study. The estimates consider only temperatures in the range of 100°C–150°C and to depths of 3 km.

Basin Name	Accessible Resource Base (Exajoules = 10^{18} J)
Denver	5,700
Great Basin	2,300
Fort Worth	1,100
Raton	280
Total	**9,380**

Table C-8. Resource Estimates for Low-Temperature Sedimentary Enhanced Geothermal Systems

Source: Mullane et al. 2016

Table Note: Estimates recalculated from Porro et al. 2012.

The geothermal resources available from shallow (≤ 3 km) low-temperature EGS have not been studied in the same detail as either low-temperature hydrothermal systems or deeper EGS systems. SMU has produced reliable, high-quality temperature-at-depth maps for the deep lithosphere (≥ 3 km) (Blackwell et al. 2011), which were used in the development of EGS resource supply curves for the electricity sector (Appendix C.1.1.3 and C.1.1.4). However, equivalent studies have not been performed at shallower depths, due at least in part to uncertainties regarding water intrusion and aquifer effects at such depths. For shallow low-temperature EGS resources, an original analysis was completed to provide a rough estimation of resources available in the shallow subsurface, relying on datasets from SMU (Blackwell et al. 2011, Blackwell et al. 2014) and the Association of American State Geologists Geothermal Data Repository 2012. Specifically, the analysis applied geostatistical interpolation methods to publicly available bottom-hole temperature data from oil, gas, and water wells to infer approximate temperature-at-depth contours for the United States at multiple depth intervals. From these contours, a rough estimate of the shallow (≤ 3km), low-temperature (30°C–150°C) accessible resource was estimated for a spatial grid covering the continental United States at a resolution of about 4 km × 4 km.

113 In the original Mullane et al. 2016 study, these resources are referred to as "low-conductivity, hot dry rock." The name is changed here to provide consistency with the electric-sector resources and prevent confusion.

Figure C-22 shows the estimates of accessible resource calculated from the temperature estimates, along with upper and lower estimates based on the 95% confidence intervals. In total, the shallow (≤3 km), low-temperature (30°C–150°C) accessible EGS resource in the continental United States is estimated to be about 800 million TWh, with 95% confidence bounds of 500 million–1,100 million TWh. These estimates are roughly consistent with an assessment by Tester et al. 2006, which estimated a total accessible EGS resource for the continental United States in the deep subsurface (3–10 km) of 13 million exajoules, or about 3,600 million TWh. Given that the *GeoVision* analysis focused on shallower depths with correspondingly lower temperatures and a total volume of less than half that studied by Tester et al. 2006, the *GeoVision* analysis estimate is expected to be less than the Tester et al. estimate, but roughly the same order of magnitude.

C.3.2 Technology Costs and Assumptions

C.3.2.1 Geothermal Direct Use Levelized Cost of Heat

The *GeoVision* analysis looks at two scenarios for evaluating the future potential of district-heating systems in the United States. The scenarios use many of the same assumptions as the scenarios of the same names in the electric-sector analysis. The district-heating scenarios generally use the same assumptions as in the electric sector to describe technology cost and performance associated with developing the subsurface geothermal resource. The district-heating scenarios are:

1. The Business-as-Usual (BAU) scenario, which incorporates existing and anticipated future technical, cost, and financial parameter values of district-heating systems, assuming similar market conditions for the next 30 years or more and no investments made to improve technology or financing parameters.

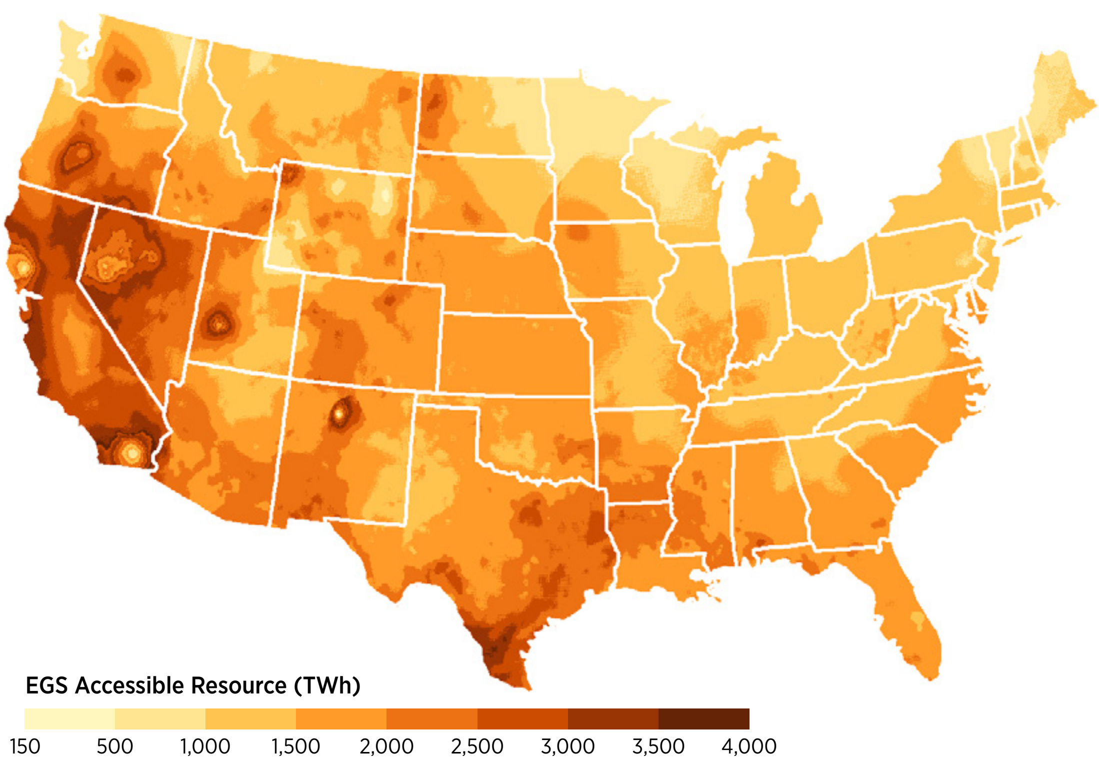


Figure C-22. Map of estimated accessible resource in the shallow subsurface (300–3,000 m)

Figure Note: The estimates presented in Mullane et al. 2016 are meant to provide only preliminary, order-of-magnitude estimates (Mullane et al. 2016).

2. The Technology Improvement (TI) scenario, which assumes improvements to some district-heating 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 liters/second (L/s) 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 district-heating TI scenario does not include the land-access barrier or construction timeline reductions that the electric-sector TI scenario does.

dGeo performs a set of simulations to derive the levelized cost of heat[114] (LCOH) associated with each of the locally available direct-use resources for district heating. These calculations are based primarily on the hydrothermal and EGS resources in each census tract, as well as on the costs associated with developing and supplying each resource to buildings in the tract. LCOH is calculated for each potentially developable well in each tract, considering the following five components:

1. **Subsurface installation costs:** The subsurface costs associated with direct-use district-heating development are primarily a function of exploration, drilling, and—for EGS—reservoir stimulation. Drilling costs in dollars are calculated based on the depth to the resource.

2. **Plant installation costs:** The costs associated with building (or expanding) a plant for each district-heating production well are calculated based on a user input of normalized costs ($\$/kW_{th}$) and the capacity of the production well. Additional costs are associated with the installation of natural-gas peaking boilers, which are used to supplement the direct-use heat utilization at times of peak demand.

3. **Distribution installation costs:** dGeo accounts for the costs of building a distribution network that can transport hot water from a central plant to buildings in the census tract. To do so, the model estimates the total required length of piping for each tract and then normalizes the cost based on the proportion of heat actually supplied by each local resource.

4. **Operating costs:** dGeo considers five main operating costs associated with each district heating plant: 1) fixed O&M for the plant, 2) fixed O&M for the wells, 3) reservoir pumping costs, 4) distribution pumping costs, and 5) natural-gas peaking boiler fuel costs.

5. **System financing:** Plant financing is modeled in dGeo as a function of a series of user-defined parameters, including inflation rate, interest rate, interest rate during construction, rate of return on equity, debt fraction, tax rate, construction period, construction finance factor, plant lifetime, depreciation period, and depreciation schedule.

A 2017 study by Beckers and Young on district-heating cost, performance, and financial parameters provides the basis for the dGeo input data for the LCOH calculation of district-heating systems (Beckers and Young 2017). The Beckers and Young study used 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* analysis supporting task forces (e.g., exploration and drilling costs) for electricity-sector assessment in the *GeoVision* analysis. Most of the parameters common to both the heat and electricity-sector analyses are subsurface related (e.g., well capital, O&M maintenance costs, EGS well flow rate, exploration costs) and were assessed by the Resource Exploration and Confirmation task force and the Reservoir Maintenance and Development task force (Doughty et al. 2018, Lowry et al. 2017). Other parameters relevant to the *GeoVision* analysis and studied by the other task forces are not directly transferable to geothermal direct use. For example, the discount rate used for calculating the cost of financing is assumed to be less for district-heating systems than power plants because district-heating systems are considered (in dGeo) to be financed with low-interest

114 Levelized cost of heat is the net present value of the unit cost of thermal energy (heat) over the lifetime of a thermal energy source. It is analogous to levelized cost of electricity, but applies to direct-use geothermal resources.

municipal bonds and run by municipalities. Finally, some parameters are unique to district heating and are based on a review of external studies (e.g., the heat distribution network and central plant capital and O&M costs, the district-heating system construction period, typical peaking boiler sizing and efficiencies). Table C-9 provides a summary of key default costs used in the dGeo model for district-heating systems.

C.3.2.2 District-Heating Supply Curves

Using the inputs described previously, dGeo calculates the LCOH for each potential direct-use district-heating production well. The model then combines these values for all potential production wells to construct a supply curve, quantifying the cumulative thermal capacity within the tract associated with increasing values of LCOH. Figure C-23 shows the resulting hydrothermal resource supply curve for the BAU and TI scenarios. The figure shows an average reduction in LCOH in the TI scenario of about 20%.

Cost Type	Input Parameter	Value
Subsurface Costs	Drilling Cost Improvement (% Reduction)	0
	EGS Reservoir Stimulation Costs ($MM/wellset)	1.25
	Hydrothermal Exploration Drilling Costs ($MM/wellset)	3.30
	EGS Exploration Drilling Costs ($MM/wellset)	5.00
	Hydrothermal Exploration Non-Drilling Costs ($MM/wellset)	0.78
	EGS Exploration Non-Drilling Costs ($MM/wellset)	3.38
Surface Plant Costs	Plant Installation Costs ($/kW$_{th}$)	100
	Natural Gas Peaking Boiler Costs ($/kW$_{th}$)	50
	O&M Labor Costs ($/kW$_{th}$/year)	25
	Plant O&M Costs (% of plant capital costs/year)	1.0
	Wellfield O&M Costs (% of well capital costs/year)	1.5
Residential and Commercial End-User Costs*	System Interconnection Costs ($)	2,000
	New or Compatible System Installation Costs ($/ft^2)	1.5 / 1.7
	Incompatible System Installation Costs ($/ft^2)	2.0 / 2.3
	Fixed O&M Costs ($/ft^2)	0.015 / 0.017

Table C-9. Default Cost Parameter Values used in dGeo for District-Heating Systems

Source: Gleason et al. 2017

*Table Notes: *Residential and commercial end-user cost values for New or Compatible System Installation Costs, Incompatible System Installation Costs, and Fixed O&M Costs are reported as residential/commercial (e.g., New or Compatible System Installation Costs for residential systems are 1.5 $/ft^2, and New or Compatible System Installation Costs for commercial systems are 1.7 $/ft^2).*

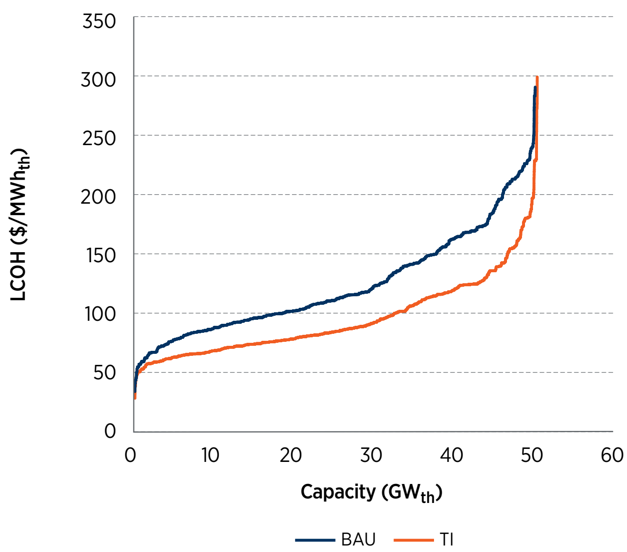


Figure C-23. Geothermal district-heating supply curves for the Business-as-Usual and Technology Improvement *GeoVision* analysis scenarios

Source: McCabe et al. 2019

Figure Note: This figure includes only hydrothermal resources as an example.

C.3.2.3 Demand-Side Levelized Cost of Heat

A 2016 study by McCabe et al. 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 (McCabe et al. 2016). 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 in Liu 2010 and Liu et al. 2016. Fuel costs and alternative-system costs were used in dGeo to estimate heating bill savings.

The model estimates demand using the mutated agents at each time step. From the agent attributes, dGeo calculates the price each agent would be willing to pay for heat provided by a district-heating system. This price is derived as the agent's LCOH, which accounts for the following three components:

1. **Interconnection and Equipment Costs:** The costs of joining a district-heating system include a one-time fixed interconnection fee and the costs of purchasing and installing the required space-heating and hot-water system to actually use the district heat supplied to the building. The latter is calculated for each agent based on the normalized equipment costs and the agent's building size.

2. **Fixed O&M Costs:** These costs consist of fixed costs of servicing and maintaining the space-heating and hot-water equipment within each building. They are derived from the agents' attributes for direct-use end-user O&M costs (district heating in this instance) and building size.

3. **Annual Costs of Heat and Hot Water:** dGeo calculates the annual costs of heat using each agent's incumbent space-heating and hot-water fuel types, site energy consumption of space heat and hot water, and costs of energy.

Table C-9 includes the values for interconnection, equipment, and fixed O&M costs. Each of these components is calculated in levelized terms by simply amortizing the costs over the expected lifetime of a district-heating system; no financial terms are included, nor are cash flows derived. dGeo calculates the LCOH by subtracting the interconnection, equipment, and fixed O&M costs from the annual costs of heat and hot water and dividing the result by the site energy consumption for space and water heating by the agent (in MWh). dGeo assumes the calculated agent LCOH is the price the agent would be willing to pay to connect to a geothermal direct-use district-heating system.

C.3.3 Economic Potential

dGeo's estimation of the economic potential for geothermal direct-use district heating is calculated by simulating the local supply and demand for district heating for each census tract and then determining the portion of supply with sufficiently low price to meet the demand. This process requires calculating LCOH for both supply and demand. dGeo combines the supply and demand curves to determine the economic potential within each tract; to do so, the model intersects the supply and demand curves to identify the settling price and quantity. The cumulative capacity associated with this intersection defines the economically viable district-heating capacity within the tract, and, therefore, its economic potential.

Meanwhile, the LCOH associated with the intersection of the demand and supply curves defines the price at which thermal energy delivered by geothermal district heating could be purchased and sold within the tract. An example is shown in Figure C-24. The sum of all economically viable geothermal direct-use capacity across all tracts determines the economic potential for district heating at each model time step.

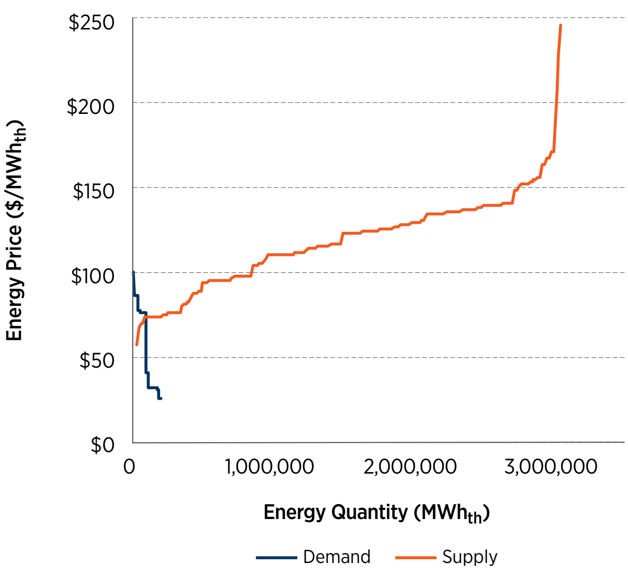


Figure C-24. Example of the overlay of demand and supply curves for a single census tract, where the point of intersection represents the settling price and quantity for heat

Source: Gleason et al. 2017

C.4 Heating and Cooling Sector: Geothermal Heat Pumps

dGeo analyzes GHP systems as individual, site-level resources for each agent. GHP systems can use several different ground heat exchanger configurations (e.g., closed-loop horizontal and vertical, standing-column wells, open- and closed-loop pond). However, dGeo only models the most common and widely applicable of these configurations: closed-loop horizontal (i.e., field loops) and vertical (i.e., borehole) systems. The information and graphics in this section are sourced primarily from Liu et al. 2019 and Gleason et al. 2017.

C.4.1 Technology Costs and Assumptions

The dGeo model includes seven categories of inputs for GHPs: GHP costs, GHP performance, HVAC costs, HVAC performance, GHP siting, financing, and Bass diffusion.[115] The assumptions and calculations for these inputs are summarized in sections C.4.1.1–C.4.1.1.5.

C.4.1.1 Geothermal Heat-Pump Cost and Performance

GHP system costs comprise the following components: heat pump, "rest-of-system" costs for the indoor energy delivery system (e.g., ductwork, piping), fixed annual O&M, and the ground heat exchanger. Rest-of-system costs are only applied to new construction. Cost values are derived from user-input parameters provided by year, sector and—in the case of ground heat exchanger costs—by system configuration (i.e., vertical and horizontal). Input parameters are provided in size-normalized values (e.g., $/cooling ton, $/ft^2, $/ft) and multiplied by the relevant agent attributes (e.g., required cooling capacity, building area, required ground heat exchanger length) to calculate actual GHP costs for each agent.

The modeled GHP systems are those typically used in the United States—central forced-air systems with two-stage GHP units for residential applications; and distributed systems with multiple single-stage GHP units for commercial applications. The typical nominal cooling efficiency of the two-stage GHP unit is 18.2 energy efficiency ratio (EER)[116] at full capacity and 27 EER at 76% of full capacity. The typical nominal heating efficiency of the two-stage GHP unit is 4 coefficient of performance (COP) at full capacity and 4.5 COP at 76% of full capacity. The typical nominal efficiencies of the state-of-the-art single-stage GHP units are 20 EER and 4.2 COP. The ground heat exchanger is sized

115 The Bass diffusion is the "diffusion of innovations" framework (Bass 1969, Rogers 2003). Under this framework, cumulative diffusion of a novel technology into a market is assumed to follow a logistic "S"-shaped trajectory.

116 The EER is the cooling capacity (in British thermal units [Btu]/hour) of the unit divided by its electrical input (in watts) at standard conditions.

to maintain the fluid temperature from the ground loop (the entering fluid temperature to the GHP unit) within the range of (-1)°C–35°C for given building load and ground thermal properties. The modeled ground heat exchangers could be vertical or horizontal closed-loop, depending on land availability and associated installation cost.

The cost of GHP equipment includes the capital costs for GHP equipment and the associated installation cost, including material, labor, overhead, and profit. The modeled commercial GHP systems use multiple small GHP equipment (usually with capacities less than 5 cooling tons) in a distributed configuration; residential GHP systems also usually have less than a 5-cooling-ton capacity. dGeo calculates the cost of GHP equipment using a correlation between the size of a GHP equipment item and its normalized cost ($/ton), which is derived from available RSMeans 2016 cost data for 1-, 2-, and 5-cooling-ton GHP equipment (Figure C-25). For commercial GHP systems, it is assumed that the average capacities of the GHP equipment is 5 cooling tons. The normalized GHP cost is multiplied by the normalized capacity of a GHP system in a given climate zone (expressed as tons/ft^2) and the floor space of the reference building to determine the total GHP equipment cost.

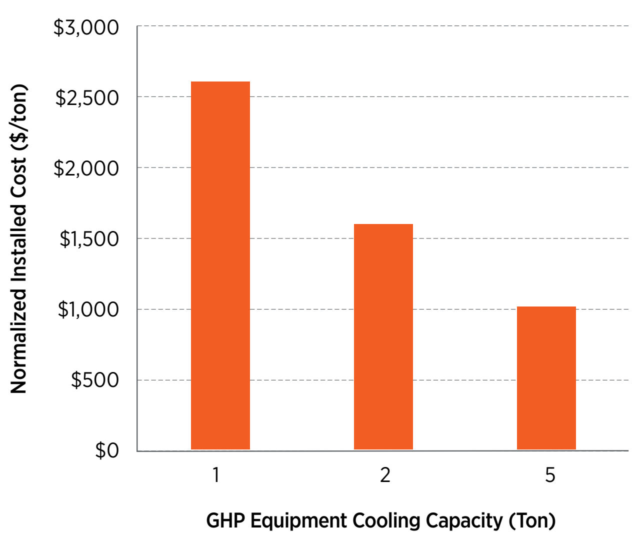


Figure C-25. Installed costs of 1-, 2-, and 5-cooling-ton GHP equipment

Source: RSMeans 2016

The rest-of-system cost (indoor energy-delivery system) includes the installed costs of all components except for the ground heat exchanger and the GHP equipment. Rest-of-system components include ductwork, hydronic piping, circulation pumps, and necessary system-level controls. The analysis assumed a normalized cost for multizone ductwork of $2,802/ton (RSMeans 2016) and $1.70/ft^2 for the hydronic piping system including circulation pumps (GBC 2016). The central air ductwork that is most commonly used in residential buildings can be used for both the GHP and conventional HVAC systems. Therefore, there is no difference in the rest-of-system cost for a GHP system and a baseline HVAC system for new constructions or retrofits. For commercial buildings, if the baseline HVAC system uses multizone ductwork, a new hydronic piping system including circulation pumps is needed to implement a distributed GHP system.

The assumptions also account for the O&M cost, which is the annual total cost for operating and maintaining a GHP system. The O&M cost is assumed to scale with the size of the system, which is represented by the total floor space served by a GHP system and expressed as $/ft^2/year. Based on a prior survey by Cane and Garnet, the log-mean of the surveyed total annual maintenance costs of various commercial GHP systems in 1996 was $0.061/ft^2 (base), $0.074/ft^2 (in-house), and $0.084/ft^2 (contractor)(Cane and Garnet 2000). The average of these three costs was adjusted with 3% inflation rate to get the 2016-dollar value of $0.13/ft^2, which is used as the commercial GHP O&M cost input to dGeo. The O&M cost for residential GHP systems and HVAC systems is negligible. This does not include the energy cost for running these systems, which is calculated separately based on annual energy consumption of the GHP system and the energy price at a given year.

The cost of the ground heat exchanger includes all the costs and markups for drilling bores (or trenching), inserting heat-exchanger loops, grouting the bores (or backfilling the trenches), and looping to the heat pump. It contributes the most to the overall cost of a GHP project. The cost of a ground heat exchanger is calculated based on the average normalized cost of ground heat exchanger at a location and the size of the ground heat exchanger required to provide needed capacity with given ground thermal properties. dGeo assumes a single normalized vertical closed-loop ground heat exchanger cost of $14/ft, equal to the nationwide median value for all geologies (Battocletti and Glassley 2013). It is assumed that the installed cost of vertical closed-loop ground heat exchangers for residential and commercial installations are equal. The installed costs of horizontal closed-loop ground heat exchangers are obtained from a major GHP manufacturer in the United States (Brown 2017). A nationwide average value of $1,850/cooling ton is used.

Ground thermal properties, including undisturbed ground temperature and effective ground-thermal conductivity, are critical parameters for sizing ground heat exchangers. Whereas the undisturbed ground temperature at a location can be estimated based on local historical weather data or using the national map of undisturbed ground temperature, the effective ground-thermal conductivity values, which accounts for different soils and rocks along the depth of a borehole and underground water movement, are affected by many factors, including moisture content, soil texture, organic content, mineralogy, and compaction in the soil, as well as the geology of the underlying bedrock. dGeo uses regional distributions of ground-thermal conductivity based on thermal conductivity values from rock samples from 68,251 oil and gas wells (SMU 2016) to populate agents with ground-thermal conductivity ranges. The model draws from census-division-level estimates of the 25th, 50th, and 75th percentiles of ground-thermal conductivity values and assigns each agent with a randomly assigned GTC value. This approach does not account for local spatial autocorrelation in ground-thermal conductivity, which is highly probable in most locations because of local or intraregional geologic conditions. As a result, dGeo economic calculations may not reflect important local variations in ground heat exchanger length, and the resolution of ground-thermal conductivity data is a component of the model that could be improved in future work.

C.4.1.2 Siting Constraints

Siting constraints of GHP systems are affected by separate inputs for vertical and horizontal ground heat exchanger configurations. For vertical systems, users must provide two parameters:

- Area per Borehole (ft^2/borehole): This input is a proxy for well spacing, and it controls the amount of land area required for each vertical borehole. dGeo assumes an area per borehole of 400 ft^2.
- Maximum Well Depth (ft): This input controls the maximum depth of each borehole. dGeo assumes a maximum well depth of 400 feet.

For horizontal systems, users provide the following two inputs:

- Trench Spacing (ft): This input specifies the distance between trenches within which horizontal loops are installed. dGeo assumes a trench spacing of 15 feet.
- Trench Length per Cooling Ton (ft/cooling ton): This parameter specifies the length of trenching required by the horizontal configuration to provide a cooling ton of capacity. All of these parameters are single inputs that do not vary over time, sector, or any other factor. dGeo assumes 150 ft/cooling ton.

C.4.1.3 Heating, Ventilation, and Air-Conditioning System Cost and Performance

As dGeo iterates over time steps, it attributes each agent with costs for prospective new conventional HVAC equipment. These costs capture the following components: HVAC equipment (e.g., furnace, air conditioner), rest-of-system costs (e.g., ductwork, piping), and fixed annual O&M. dGeo calculates these costs from user-input parameters specified by year and sector. The inputs are provided in normalized units (e.g., $/cooling ton and $/$ft^2$); dGeo multiplies these parameters by each agent's corresponding size attributes to calculate actual costs.

For residential buildings, three conventional HVAC systems are considered based on EIA's Residential Energy Consumption Survey (EIA 2013, EIA 2016b): 1) packaged air conditioner with gas/oil/propane-fired furnace, 2) packaged air conditioner with electric resistance, and 3) air-source heat pump with electric resistance. RSMeans 2016 cost data for the heating and cooling equipment of the three systems are used to derive two correlations between the heating or cooling capacity and the installed costs (Figure C-26 and Figure C-27).

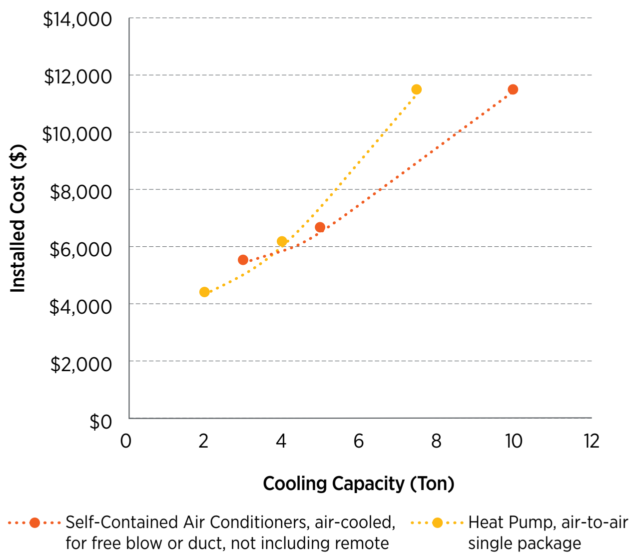


Figure C-26. Installed costs of typical residential space-cooling equipment

Source: RSMeans 2016

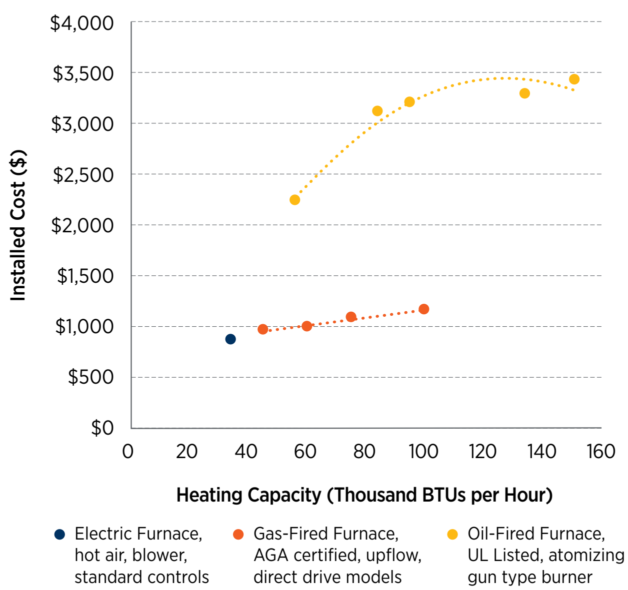


Figure C-27. Installed costs of typical residential space-heating equipment

Source: RSMeans 2016

For commercial buildings, it is assumed that the conventional HVAC system is a packaged variable air volume (VAV) system with standard features, including multizone control, electric cool, gas heat, and air-side economizer. RSMeans 2016 cost data for packaged VAV equipment (the outdoor HVAC equipment only, without ductwork inside the building) with cooling capacities ranging from 15–105 tons were used to derive a correlation between cooling capacity and the installed cost of the packaged VAV equipment (Figure C-28). The cost of the furnace pack used in the packaged VAV equipment is not very sensitive to its capacity, so the installed cost of packaged VAV equipment was based solely on its cooling capacity. It is assumed that multiple packaged VAV equipment (each with a capacity not larger than 105 tons) is used for systems with larger than 105-ton cooling capacity. For systems with less than 15-ton cooling capacity, cost was estimated by proportionally decreasing the cost of the 15-ton packaged VAV equipment.

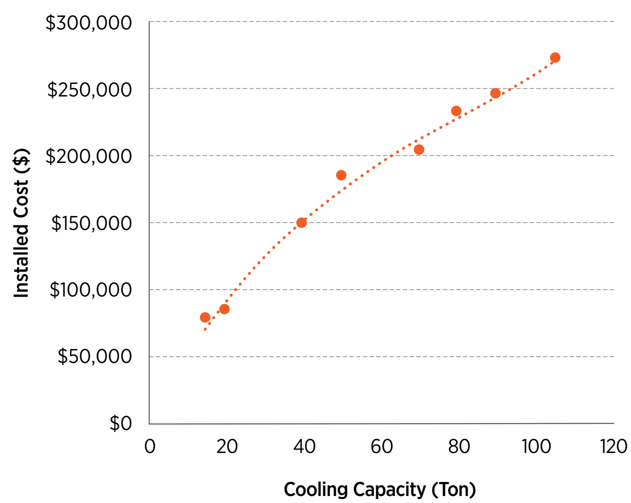


Figure C-28. Installed costs of typical packaged variable-air-volume equipment

Source: RSMeans 2016

As noted previously, the central-air ductwork that is most commonly used in residential buildings can be used for both GHP and conventional HVAC systems. Therefore, there is no difference in the rest-of-system cost for a GHP system and a baseline HVAC system for both new constructions and retrofits.

As with GHP systems, the O&M cost for residential baseline HVAC systems is negligible. The O&M cost for commercial baseline HVAC system is adopted from the result of a 1999 American Society of Heating, Refrigerating and Air-Conditioning Engineers study. The mean annual maintenance cost of packaged VAV systems is estimated as $0.64/ft²/year (in 2016 dollars, assuming a 3% inflation rate).

C.4.1.4 Fuel and Electricity Costs

Within the dGeo model framework, agents evaluate current and anticipated future expenditures associated with the energy consumed for operating the potential GHP system as well as the baseline HVAC system for space heating and space cooling. These energy costs are based on the agents' attributes for existing and future energy prices and the site energy consumptions of the GHP and the baseline HVAC system. Energy prices from the AEO 2016 (EIA 2016b) are used in dGeo to represent the price paid to operate the two systems. Figure C-29 shows projected energy prices for the four main fuels modeled in dGeo: electricity, fuel oil, propane, and natural gas. dGeo uses region-specific fuel prices for residential and commercial use.

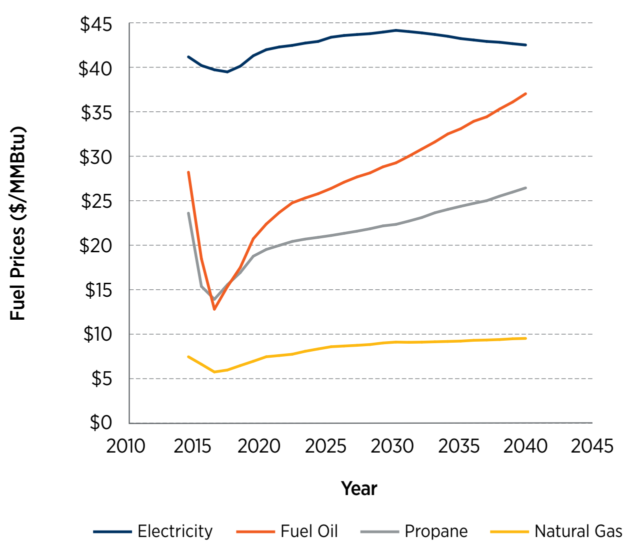


Figure C-29. Projected residential energy prices

Source: AEO 2016 Reference Scenario (EIA 2016)

C.4.1.5 Financing Assumptions

dGeo assumes that heating and cooling system installations are financed through loans. dGeo makes the following capital and financing assumptions when determining the cost and payback of heating and cooling systems:

- Every agent in the model has access to the capital required for a GHP system
- Every agent has access to the same loan terms
- Inflation: 2.5%/year in all cases
- Loan term: 15 years
- Loan rate/interest rate: 6%
- Down-payment fraction: 20% of the total loan amount
- Discount rate: 7%. This parameter is used to control the discount rate used by model agents in their financial calculations.
- Tax rate: 33%.

C.4.2 Geothermal Heat-Pump *GeoVision* Analysis Scenarios

The *GeoVision* analysis examined two scenarios for evaluating the future potential of GHPs in the United States: a Business-as-Usual (BAU) scenario and a Breakthrough (BT) scenario.

In the BAU scenario, it is assumed that there is no substantial investment in GHP-related research and development and no financial incentives or tax credits for GHPs; as such, technology advancement is slow. The scenario also assumes there will not be any cost reduction in ground heat exchangers and only a moderate increase in the operational efficiency of GHP systems through 2050. For the baseline (conventional) HVAC systems, the scenario assumes there will not be any significant change in the cost and performance during the same period. Therefore, there is only moderate change in the efficiency difference between GHPs and conventional HVAC systems: a 17% increase by 2050. It is assumed that the incremental cost increase for improving energy efficiency is offset by improvement in manufacturing efficiency and increased economies of scale. Hence, there is no change in the costs or service life of GHPs and baseline HVAC systems.

In the BT scenario, it is assumed that 1) the installed cost of ground heat exchangers is reduced by up to 30% by 2050 because of technical breakthroughs and increased economies of scale resulting from innovative business models; and 2) the operational efficiency of GHP systems is increased up to 50% from 2014 levels by 2030, with no further improvement through 2050. The projected cost reduction for ground heat exchangers is based on an analysis of ongoing global research and development to reduce these costs (Liu et al. 2019). For residential GHPs, the 50% efficiency improvement is from applying advanced GHP equipment (e.g., the ground-source integrated heat pump, which uses a variable-speed compressor, pump, and fan and can provide 100% hot water and space cooling simultaneously). For commercial GHP systems, the modeled GHP equipment is single-stage; if two-stage GHP equipment is used, the annual electricity consumption of GHP systems can be reduced by about 20%. In addition, smart pumping control can cut system power consumption by another 10%. The combination of these two effects will reduce system power consumption by 30%, which is equivalent to increasing the GHP equipment efficiency by 50%.

C.4.3 Resource and Technical Potential

The concept of resource potential has little meaning or value in the context of GHPs, because 1) the nation's GHP resource is extensive enough to support any level of GHP deployment and 2) GHPs can be installed practically anywhere. Instead, the analytical focus was on the technical potential of GHP systems. For dGeo, technical potential is the developable capacity of GHP available and was based on the amount of land available for a geothermal ground loop, technical system performance, and proximity to a suitable thermal end use. Although this definition of technical potential requires that the resource be close to a suitable end use, it is not a demand-constrained measure; in other words, the technical potential in a given location may actually exceed the amount of energy that would be used by end users in that location. This distinction is consistent with common definitions of technical potential for utility-scale power production technologies, which are typically not constrained by available electric demand.

The technical potential for GHP was calculated using dGeo from the attributes of all building types in the model at each time step. For each region, dGeo determines the maximum cooling capacity that can be installed for each model building type, or agent, for both a vertical and horizontal ground heat exchangers. dGeo multiplies the larger of the two maxima by the number of model agents for each type of model agent in the region. The model repeats this, summing across all agents in a region and then all regions in the model. This methodology amounts to summing the maximum installable capacity of ground heat exchangers across all agents in a region, and it provides an upper bound on the amount of heating and cooling capacity that could be installed in subsequent economic and market potential calculations. Under this formulation, the primary factors that drive the technical potential for GHP are the ground-thermal conductivity, user-input ground heat exchanger area requirements, and parcel sizes of the model agents. Results indicate that more than 580,000 GW_{th} of GHP resource technical potential are available nationwide.

C.4.4 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). dGeo defines the economic potential for GHP as the installable capacity of systems with a positive return on investment, determined based on a positive net present value over a 30-year time frame.

During each model time step, dGeo calculates a new estimate of economic potential for GHPs based on the current state of the model agents. These estimates leverage several agent attributes updated or inherited during the agent mutation process, such as age of space heating and space cooling systems, energy costs specific to these system types, and other user-defined inputs related to cost and performance of the systems. To derive this estimate, dGeo performs a series of calculations that determine the cashflows associated with installation and operation of a GHP system for each agent. These calculations are detailed in Gleason et al. 2017; in summary, they account for six primary components:

1. **System Payment:** The annual costs of servicing loans (principal repayment and interest) are based on the amount borrowed, loan term, and annual percentage rate. Costs associated with future replacement of the heat-pump component of the GHP system are amortized over the expected heat-pump lifetime, which is assumed to be 20 years.

2. **Fixed O&M Costs:** These costs consist of fixed costs of servicing and maintaining the system over the analysis period and are calculated based on agent attributes for GHP O&M costs and building size.

3. **Annual Energy Costs:** Agents evaluate current and anticipated future expenditures associated with the energy to operate their GHP system for heating and cooling. These costs are based on each agent's attributes for current and future costs of energy and GHP site space-conditioning energy consumption.

4. **Revenue from Incentives:** Agents can receive revenue from incentives such as the investment tax credit, if applicable.

5. **Revenue from Depreciation:** Commercial-sector agents may deduct asset depreciation over the lifetime of the GHP system. This depreciation decreases the tax burden of each applicable agent.

6. **Revenue from Interest Deductions:** All agents may deduct system interest paid from their taxable burden. These deductions provide a source of revenue at the specified taxable rate of each agent. The model assumes that the agent has a sufficient taxable burden to monetize interest deductions fully.

Using these six components, dGeo calculates the cashflows of a GHP installation for each market-eligible agent, assuming an analysis period of 30 years. To account for the value of a GHP installation relative to continued use of a conventional HVAC system, dGeo also calculates the cashflows associated with the conventional HVAC system of each agent. The cashflow calculations incorporate all of the components used in the GHP calculations, except for revenue from incentives, which the model assumes do not apply to conventional HVAC systems. Furthermore, dGeo assumes that the system payments for a new HVAC system will not begin until some future year, as determined by each agent's expected years to equipment replacement. Subsequent system replacements are amortized over the expected lifetime of a new HVAC system.

To calculate the net cashflows of a GHP system relative to a conventional HVAC system, dGeo subtracts the HVAC cashflows from the GHP cashflows. The resulting net cashflows are then evaluated to determine a series of financial metrics, including payback period, percent monthly bill savings, and net present value. Payback period is determined as the first year with a net-positive cumulative cashflow, while percent monthly bill savings are calculated as the mean annual cashflow divided by the mean annual energy costs associated with the conventional HVAC system.

Using the derived net present values for all market-eligible agents, dGeo is able to determine the overall economic potential for GHP. To do so, it identifies all agents with a positive net present value (under either of the available business models), calculates the product of the GHP capacity and the number of buildings associated with each agent, and sums across all agents to determine the total installable capacity with a positive return on investment.

C.4.5 Market Potential

Whereas economic potential considers the portion of renewable resource 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. dGeo 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. dGeo's methodology for calculating market potential is relatively straightforward. Using the output financial metrics from the economic potential calculations, including payback period and percent monthly bill savings, dGeo determines the maximum market share associated with each agent. Following the conventions of Sigrin et al. 2016 to quantify the maximum market share, dGeo relies on a series of empirically derived market-adoption curves that relate the economic attractiveness of technology adoption and maximum market share. dGeo's residential agents evaluate host-owned systems based on the payback period. Commercial agents evaluate systems similarly; however, they have the option of using time-to-doubling in addition to the payback period as metrics for evaluating the system. Section 3.2.2.3 and Figure 3-3 in the main *GeoVision* report present these empirically derived market-adoption curves in detail.

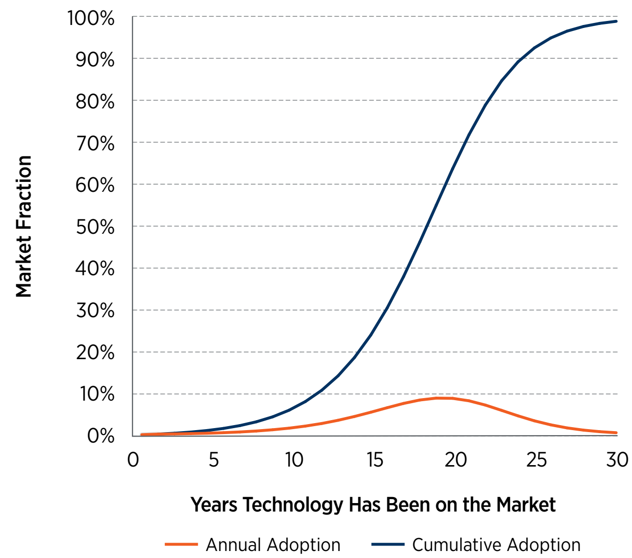


Figure C-30. Annual and cumulative adoption rates simulated using the diffusion-of-innovations framework (for illustrative purposes only)

Source: Gleason et al. 2017

C.4.6 Geothermal Heat-Pump Deployment

The final component of the dGeo modeling framework is the simulation GHP technology deployment into the market. dGeo simulates deployment using the "diffusion of innovations" framework, also known as Bass diffusion (Bass 1969, Rogers 2003). Under this framework, cumulative diffusion of a novel technology into a market is assumed to follow a logistic "S"-shaped trajectory (Figure C-30). Technology deployment initially follows slow growth, accelerates as mass-market uptake begins, and then decelerates as the market for the technology reaches saturation. In short, Bass diffusion defines the pattern by which technologies are adopted by a market over time, and it is used by dGeo to influence the rate of GHP adoption given current and past conditions.

For GHP, dGeo models technology deployment following the methodology described in section 5.2 of Sigrin et al. 2016. In brief, dGeo initializes each agent in the model to reflect the historical state-level deployment of GHP (derived from Schoonover and Lawrence 2013). At each model time step, the model determines the amount of new incremental technology adoption as a function of the existing deployment, current market potential (i.e., maximum market share), and location on the Bass diffusion trajectory. These calculations are applied independently to the sub-population of buildings represented by each agent; in aggregate, the population-level deployment across all agent sub-populations exhibits the characteristic Bass diffusion trajectory.

C.4.7 Additional Model Results

The main part of the *GeoVision* analysis report includes results on the economic potential of GHPs for the BAU and BT scenarios, as well as a summary of nationwide GHP economic potential, market potential, and installed capacity as a function of time. The following additional model results put these results in context of heating and cooling sector market share and geographic distribution of deployment.

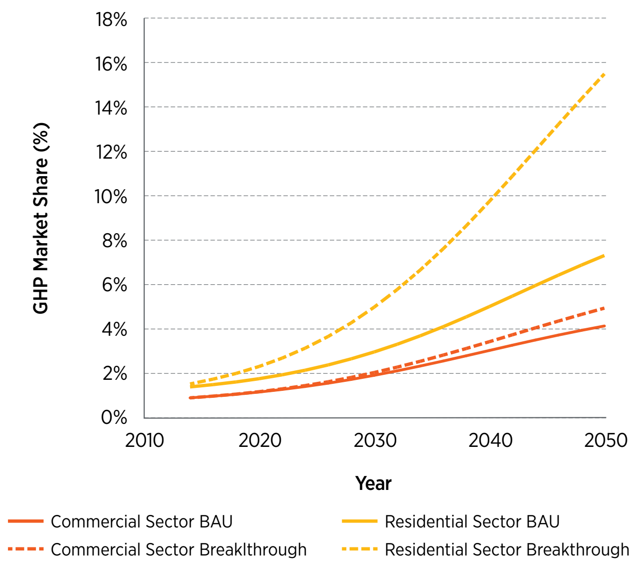


Figure C-31. Projected market share of geothermal heat pumps in commercial and residential sectors from 2014 through 2050

Source: Liu et al. 2019

Figure C-31 illustrates that 4%–5% of commercial buildings are projected to be conditioned by GHPs by 2050. For the residential sector, with the AEO Reference case energy prices, GHPs can realize about 7% market share in the BAU scenario with conservative customer adoption. Residential market share could increase to more than 15% in the BT scenario and more optimistic customer adoption.

Figure C-32 shows the geographical distribution of the normalized installed GHP capacities in 2050. Under BAU (Figure C-32, top), most counties with high installed capacity (more than 20 kW_{th} installed GHP capacity per square km) are in the Northeast, especially New England. The large heating demands and high heating-fuel costs make GHPs more cost effective for space heating in this region. Under the BT (Figure C-32, bottom) scenario, most counties in the Northeast and South Atlantic have high installed GHP capacity.

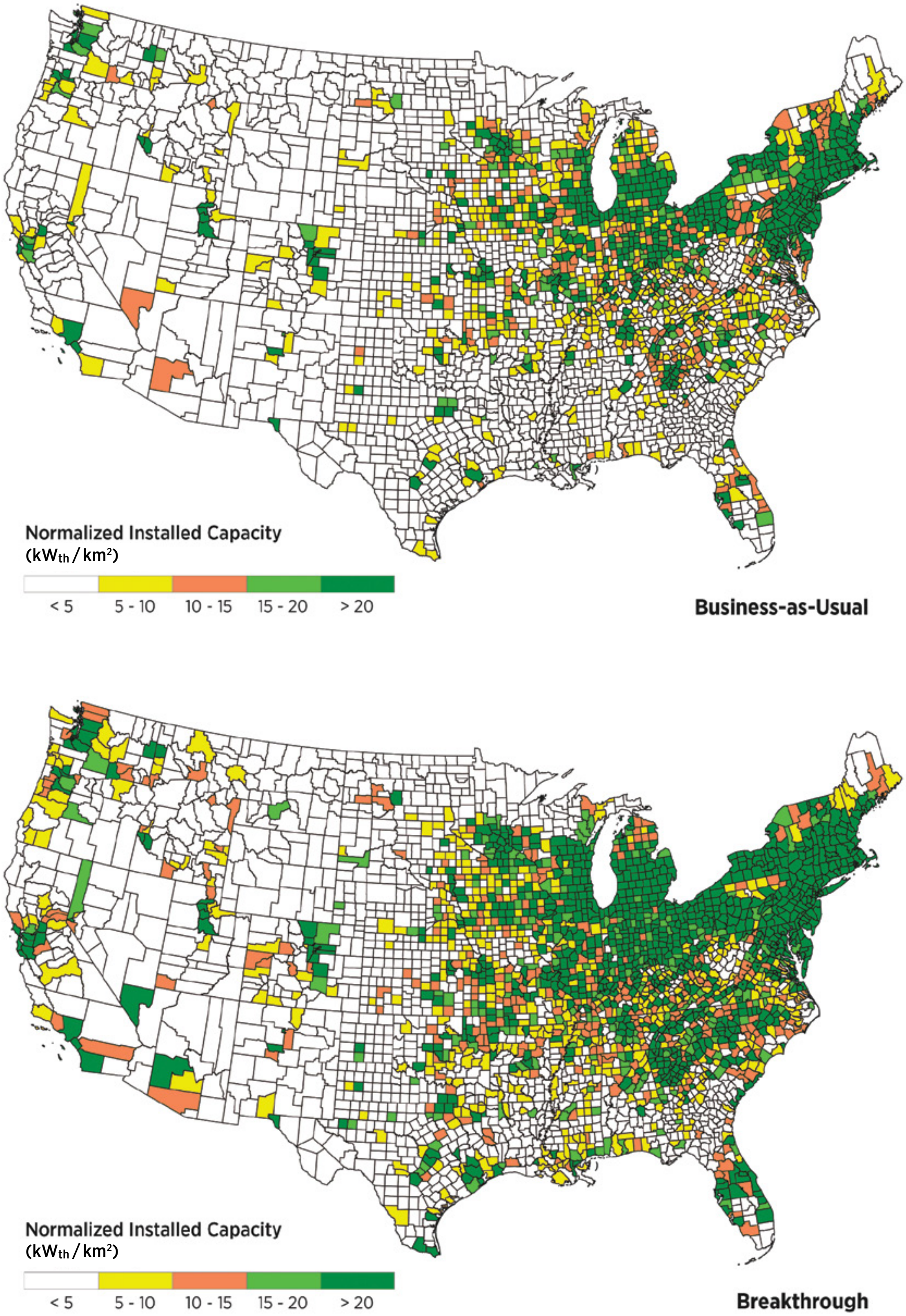


Figure C-32. Installed geothermal heat-pump capacities in 2050: under the Business-as-Usual (top) and Breakthrough (bottom) scenarios

Source: Liu et al. 2019

Appendix D: Contributors

The U.S. Department of Energy (DOE) acknowledges the authors, reviewers, and various contributors listed in this appendix, all of whom contributed to this project since its inception in early 2015. More than 115 individuals representing more than 65 organizations provided technical knowledge, draft text, or review comments.

The DOE Geothermal Technologies Office (GTO) managed the overall *GeoVision* analysis process, ensuring participation of individuals representing a broad range of geothermal stakeholder sectors including, but not limited to, trade organizations, equipment manufacturers, project developers, independent power producers, technical consultants, non-governmental and environmental organizations, electric utilities, state organizations, national laboratories, and federal agencies.

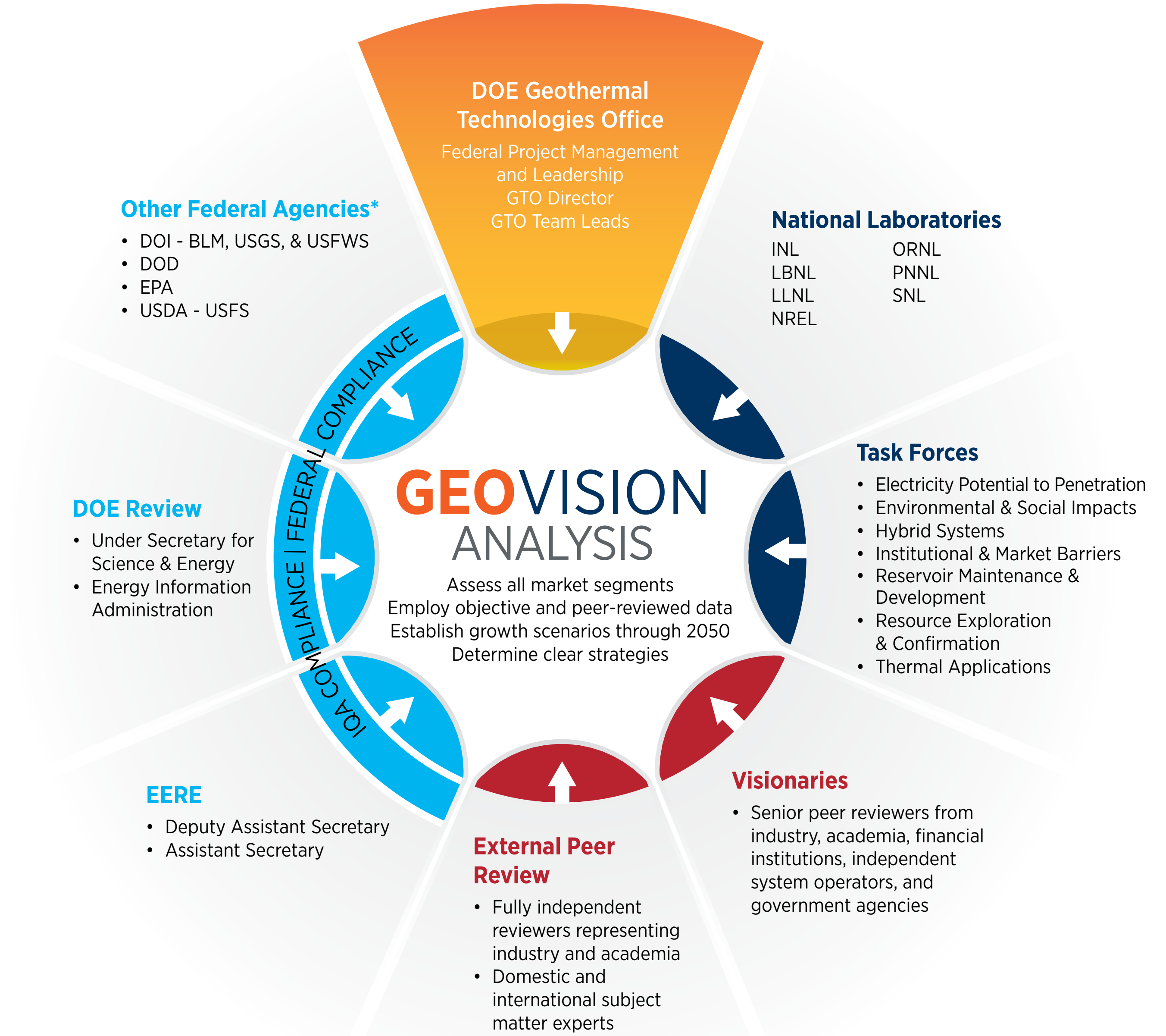
The *GeoVision* analysis relied on the collection, modeling, and analysis of robust datasets through DOE national laboratory partners. Expert input was provided through active participation in seven technical task forces (Section D.3) that focused on:

1. Electricity Potential to Penetration
2. Environmental and Social Impacts
3. Hybrid Systems
4. Institutional and Market Barriers
5. Reservoir Maintenance and Development
6. Resource Exploration and Confirmation
7. Thermal Applications

The technical task forces comprised national laboratory partners coupled with GTO task management and were responsible for producing the foundational work products and basis for the *GeoVision* analysis (see ***GeoVision* Analysis Supporting Task Force Reports** in the References). GTO provided a governance and leadership role in integrating the technical task force work products, guiding the formation of the *GeoVision* analysis objectives, and leading the external and interagency review process. The work of the task forces was also iteratively and transparently reviewed through a group of 20 senior peer reviewers ("Visionaries").

Following preparation of the draft report and findings, additional review was provided by an external review group of 34 experts who had not previously been involved in preparation of the analysis, findings, or the report. Contributions and support from reviewers were incorporated throughout the development of this report. Collectively, participants in the *GeoVision* analysis process were instrumental in documenting the state of the industry and identifying future opportunities for growth, as well as pinpointing challenges that need to be addressed for the geothermal industry to continue to evolve and contribute value to the nation.

Various offices within DOE provided counsel and review throughout the effort. The DOE's Office of Energy Efficiency and Renewable Energy (of which GTO is a part) was a principal internal advisor. DOE's U.S. Energy Information Administration, Office of Fossil Energy, and Western Area Power Administration provided review and input. DOE also coordinated review with other federal agencies, such as the White House Office of Management and Budget, Department of the Interior (U.S. Geological Survey, Bureau of Land Management, and U.S. Fish and Wildlife Service), Department of Agriculture (U.S. Forest Service), Department of Defense (U.S. Navy), and the U.S. Environmental Protection Agency. The final version of this document was prepared by DOE. The framework for the *GeoVision* analysis collaboration—including compliance with the Office of Management and Budget's Information Quality Act, or IQA—is illustrated in Figure D-1.



*Other Federal Agencies: Department of Interior, Bureau of Land Management, United States Geological Survey, United States Fish and Wildlife Service, Department of Defense, Environmental Protection Agency, United States Department of Agriculture, and United States Forest Service

Note: National laboratories are defined in Appendix A.

Figure D-1. Framework of the interaction of parties involved in the formation and execution of the *GeoVision* analysis

The following sections acknowledge specific contributors to the *GeoVision* project management and coordination (Section D.1); report authorship, editing, content development (Section D.2); task force contributors (Section D.3); and senior peer and external reviewers (Section D.4). Where applicable, main advisors and lead contributors are indicated by parentheses after the contributor's name. GTO offers sincere thanks to all participants, who were instrumental in the development of the *GeoVision* analysis and the resulting report.

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D.4 *GeoVision* Analysis Report Review

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