CHAPTER FOUR

GeoVision Analysis: Results, Opportunities, and Impacts

Grand Prismatic Spring in Yellowstone National Park, Wyoming.
Photo credit: Jim Stimac

4 *GeoVision* Analysis: Results, Opportunities, and Impacts

As discussed in Chapter 3, the *GeoVision* analysis used detailed, quantitative models to assess geothermal deployment potential under scenarios that consider a range of technologies, market conditions, and barriers. Chapter 3 summarized the *GeoVision* modeling analytics and approach. Chapter 4 presents the modeling results, discusses key takeaways, and presents a summary of impacts to the nation from the levels of geothermal energy deployment projected in the *GeoVision* analysis. Among other findings, the results indicate that geothermal electricity-generation capacity can double based on regulatory reforms alone and that enhanced geothermal systems (EGS) have the potential to supply more than 16% of U.S. electricity generation and support the economic potential for as many as 17,500 district-heating installations by 2050. Findings also indicate that the market potential for geothermal heat-pump technologies is equivalent to supplying heating and cooling solutions to 28 million households. Achieving the levels of deployment discussed in this chapter will require actions aimed at pursuing technology innovations, reducing costs, and overcoming barriers. These actions are discussed in the *GeoVision* Roadmap (Chapter 5).

4.1 Deployment Potential—Electric Sector

The *GeoVision* analysis included modeling of geothermal technology deployment within the electricity market sector for conventional hydrothermal and EGS resources. As discussed in Section 3.2.1, the *GeoVision* analysis included assessing electric-sector opportunities under three primary scenarios: Business-as-Usual (BAU), Improved Regulatory Timeline (IRT), and Technology Improvement (TI). One key finding in the electric-sector modeling is that regulatory reforms assumed in the IRT scenario alone could double the size of installed geothermal capacity through increased access to and development of conventional hydrothermal resources. Additionally, the analysis indicates that improved exploration and drilling technologies envisioned in the TI scenario can assist across the board in the industry's ability to maximize resource capture—including up to 60 gigawatts-electric (GW_e) of electricity-generating capacity by 2050. The most promising growth potential can be realized by advancing early-stage research and development into technologies that support EGS.

4.1.1 Deployment Potential in the Business-as-Usual and Improved Regulatory Timeline Scenarios

The *GeoVision* analysis BAU scenario reflected industry trends and the anticipated future if the industry continues on the same path as 2016 conditions. Results indicate that, under the BAU scenario, installed geothermal net-summer capacity increases from 2.5 GW_e to 6 GW_e by 2050. This result is consistent with existing growth trends in the geothermal industry (Augustine et al. 2019). The BAU scenario serves as the baseline for assessing the impact of other scenarios considered in the *GeoVision* analysis and related studies (Wendt et al. 2018, Millstein et al. 2019, Young et al. 2019).

The Hoch and Vulcan geothermal power plants in California coexist amidst the existing land use.
Photo credit: Martin J. Pasqualetti

The IRT scenario assessed the effect of potential regulatory reforms that could reduce geothermal development timelines by half and triple rates of geothermal exploration and resource discovery. The deployment potentials calculated under the IRT scenario were compared to the BAU scenario to determine the effect regulatory reform alone could have on geothermal development. The results indicate that—using existing geothermal technologies—the geothermal industry could double in size relative to BAU through only regulatory reform (Figure 4-1). The total deployment resulting under the IRT scenario is nearly 13 GW_e by 2050—more than a 5-fold increase over existing installed geothermal capacity and double the installed capacity in 2050 under the BAU scenario. The IRT scenario assumed that applicable regulatory reforms are legally allowed and appropriate for the respective situation.

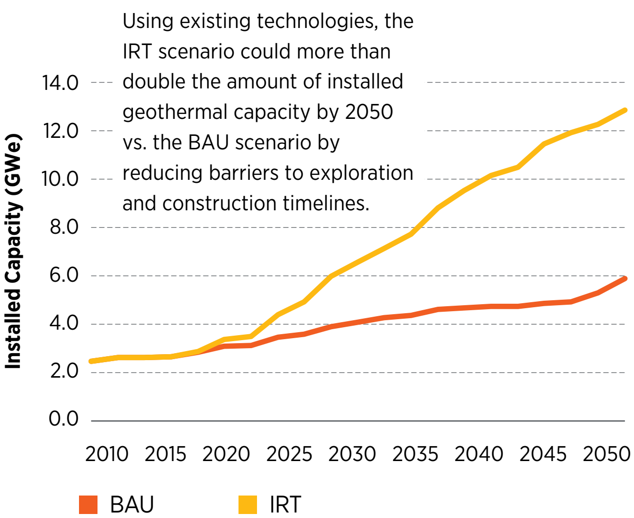


Figure 4-1. Improved Regulatory Timeline scenario results and comparison to the Business-as-Usual scenario for conventional hydrothermal resources

Figure Note: The IRT scenario projects that the geothermal industry could double in size by 2050 compared to the BAU scenario by reducing exploration barriers and construction timelines via regulatory reform. Total deployment in the IRT scenario would reach nearly 13 GW_e by 2050.

The IRT scenario assumed that EGS technologies do not advance beyond existing levels; as such, EGS resources are not commercially viable nor deployed in the Regional Energy Deployment System (ReEDS) model under the IRT scenario. As is the case in the BAU scenario, growth achieved under the IRT scenario is supported entirely by the development of conventional hydrothermal resources, the majority of which are undiscovered hydrothermal resources (Figure 4-2). Exploration that supports conventional hydrothermal resource growth in the IRT scenario results from shorter permitting timelines, which enhance developer access to resources and increase the amount of exploration that can be performed in a given time period.

> Results of the *GeoVision* analysis indicate that—using existing geothermal technologies—the geothermal industry could double in size relative to Business-as-Usual through only regulatory reform.

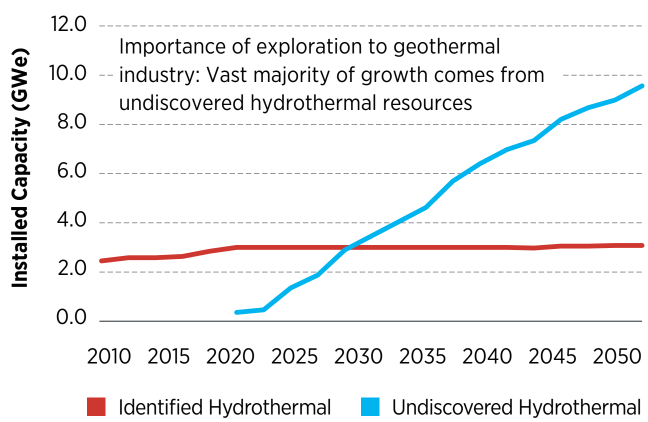


Figure 4-2. Improved Regulatory Timeline deployment results by resource type

Figure Note: Undiscovered hydrothermal resources constitute the majority of the resource capture, which supports overall growth (identified and undiscovered) to about 13 GW_e total (Augustine et al. 2019).

The increased amount and ease of conducting exploration activities under the IRT scenario is assumed to triple discovery rates for undiscovered hydrothermal resources—from 1% to 3% of the total undiscovered resources per year compared to the BAU scenario (Table 3-1). Moreover, the IRT scenario assumes the use of existing exploration technologies. To maximize growth potential across all scenarios, the industry will need to improve exploration technologies so that greater amounts of the undiscovered resource base may be discovered and developed. This result highlights the importance of exploration for facilitating geothermal industry growth and the potential for improved exploration technologies to further advance that growth. When combined with improvements in regulatory timelines, resource access, and drilling technologies, improved exploration technologies present important pathways toward achieving the full deployment potentials identified in the *GeoVision* analysis TI scenario (Section 4.1.2). Actions related to achieving such improvements are discussed in the *GeoVision* Roadmap (Chapter 5).

4.1.2 Deployment Potential in the Technology Improvement Scenario

The *GeoVision* TI scenario models the most aggressive and optimistic scenario assumptions and the resulting cost reductions that can drive geothermal deployment. The TI scenario shows particular promise for EGS resource deployment, which stands to benefit substantially from improved technology and reduced capital costs (Table 3-3). The results of the TI scenario indicate the potential for more than 60 GW_e of geothermal power generation net summer capacity, the majority of which would come from deep-EGS resources after 2030 (Figure 4-3). As explained in Section 2.2.1, net summer capacity is defined by the Energy Information Administration (EIA) as, "The maximum output, commonly expressed in MW, that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of summer peak demand (period of June 1 through September 30)."

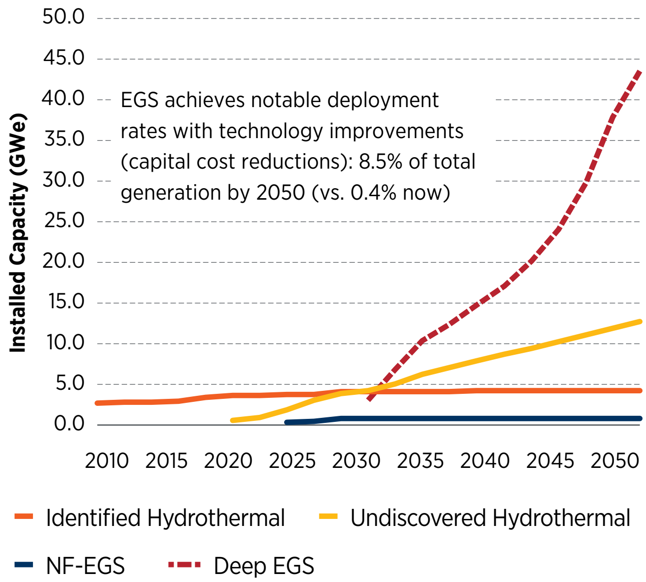


Figure 4-3. Technology Improvement scenario results by resource type

Figure Note: The TI scenario incorporates technology improvements and the resulting cost reductions that drive additional deployment. At the end of the analyzed period (2050), total geothermal deployment in the TI scenario is more than 60 GW_e, with the majority of growth supplied by deep-EGS resource development after 2030 (Augustine et al. 2019). NF-EGS is near-field EGS.

With technology improvements considered in the *GeoVision* analysis, geothermal power production could support up to 8.5% of total national generation by 2050, as compared to the 0.4% share of total national generation contributed by the existing geothermal industry today.

The levels of deep-EGS deployment shown in Figure 4-3 would require hundreds to more than 1,000 wells to be drilled annually to support EGS project developments. By comparison, the oil and gas industry has been drilling hundreds to more than 1,000 horizontally oriented and hydraulically fractured wells per month (EIA 2018).

With the technology improvements modeled in the TI scenario, geothermal power production could support up to 8.5% of total national generation by 2050, as compared to the 0.4% share of total national generation contributed as of 2017 (Augustine et al. 2019).

Figure 4-4 shows terawatt-hour generation by year within the renewable power sector for the *GeoVision* TI scenario. The results in Figure 4-4 are split into two categories: 1) baseload renewable power—which includes geothermal, hydropower, biopower, and concentrated solar power—and 2) variable-generation renewable power. In the TI scenario, geothermal energy could provide about 57% of the entire baseload renewable power-generation portfolio.[87]

87 Baseload renewable power includes geothermal, hydropower, biopower, and concentrated solar power.

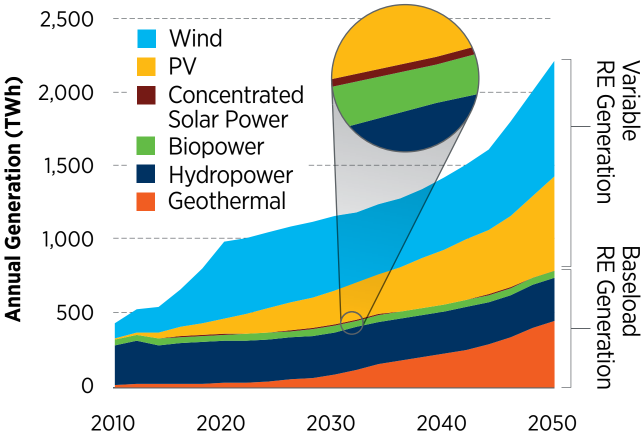


Figure 4-4. Total national generation (terawatt-hours) for the renewable energy (RE) market sector by year for the *GeoVision* Technology Improvement scenario

Figure Note: The right vertical axis divides the sector into baseload renewable power—which includes geothermal, hydropower, biopower, and concentrated solar power—and variable-generation renewable power. Geothermal power could provide about 57% of the ***baseload*** *RE generation portfolio by 2050 (or 20.4% of all RE generation). Biopower includes landfill-gas generators, co-fired biomass/co-fired coal, and biomass/dedicated biomass. PV is solar photovoltaic.*

The *GeoVision* analysis also evaluated "alternative future" combined scenarios that assess the TI scenario combined with the ReEDS Standard Scenarios.[88] This approach facilitated assessments of external factors—such as electricity demand, fuel prices, technology costs, resource and system constraints, and others—and how those factors combined with technology improvements might change geothermal deployment. One of the combined scenarios that demonstrates potential for geothermal deployment beyond that achievable under the TI scenario alone is summarized in Table 4-1. This particular combined scenario considers the TI scenario in combination with the ReEDS "High Natural Gas Prices" Standard Scenario, which uses scenario projections from the EIA's Annual Energy Outlook 2016. The combined scenario considers a possible future where both the TI scenario assumptions are true and natural-gas prices are assumed to be higher than the 2016 Annual Energy Outlook Reference case for natural-gas projections by using the 2016 Annual Energy Outlook "Low Oil and Gas Resource and Technology" case (Cole et al. 2016b, EIA 2016, Augustine et al. 2019). As noted, the combined scenario represents a possible future situation where geothermal deployment is higher than under the TI scenario alone. The full assessment of combined scenarios considered in the *GeoVision* analysis is summarized in Appendix C and detailed in Augustine et al. 2019.

Scenario	Varied Assumptions	Consistent Assumptions Across Scenarios
TI	None (Mid-case scenario)	Capital and O&M Costs: TI Construction Time, Hydrothermal: 4 years Construction Time, EGS: 5 years Financing: ReEDS Standard WACC (8%)
TI + High Natural-Gas Prices	Future with high natural-gas costs (AEO 2016)	

Table 4-1. Technology Improvement Scenario Combined with a Regional Energy Deployment System Standard Scenario

Table Notes: (1) The combined scenario described here forms the basis for a potential future that has high natural-gas costs in accordance with the AEO's Low Oil and Gas Resource and Technology case (EIA 2016). (2) WACC = weighted-average cost of capital; O&M = operations and maintenance; AEO = Annual Energy Outlook.

Using the combined scenario assumptions in Table 4-1, geothermal deployment levels reach nearly 120 GW_e by 2050 (Figure 4-5) (Augustine et al. 2019). The geothermal technology deployment potentials calculated in the combined scenario comprise less than 10% of total U.S. installed capacity, but would provide over 16% of the country's total generation due to the high capacity factor of geothermal technologies. For the combined scenario, additional deployment compared to the TI scenario alone comes primarily from deep-EGS resources. The amount of installed geothermal capacity expands due to improved

88 The Standard Scenarios are a suite of forward-looking power-sector scenarios that are used within the ReEDS capacity-expansion model (Cole et al. 2016a). The scenarios encompass Earth-system feedbacks, electricity demand growth, electricity generation, existing fleet retirements, fuel prices, the policy and regulatory environment, resource and system constraints, and technology costs. Together, the Standard Scenarios make possible the transparent and quantitative examination of how various inputs impact power-sector development. Moreover, they provide context and data to support understanding of changes in the U.S. power sector and inform stakeholder decision making about its future direction. The Standard Scenarios (Cole et al. 2016a), which are updated each year along with the Annual Technology Baseline, include technology cost and performance assumptions from the Annual Technology Baseline (Cole et al. 2016b).

economic conditions for geothermal (in this case, as higher prices for natural gas). This finding suggests that, under the conditions modeled in the *GeoVision* analysis, geothermal energy growth is limited by the conditions that drive demand for geothermal development and not by resource potential.

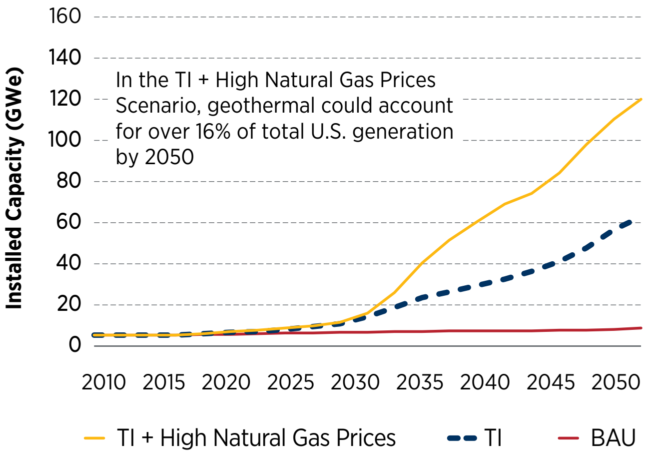


Figure 4-5. Installed geothermal capacity for Technology Improvement scenario compared to a combined scenario and Business-as-Usual

Figure Note: The combined scenario considers the TI scenario in combination with the ReEDS "High Natural Gas Prices" Standard Scenario, which uses scenario projections from the EIA's Annual Energy Outlook 2016. The combined scenario considers a possible future where both the TI scenario assumptions are true and natural-gas prices are assumed to be higher than the 2016 Annual Energy Outlook Reference case for natural-gas projections by using the 2016 Annual Energy Outlook "Low Oil and Gas Resource and Technology" case (Cole et al. 2016b, EIA 2016, Augustine et al. 2019). Appendix C provides additional detail. The combined scenario is compared to the BAU scenario and the TI scenario alone. The TI scenario alone drives greater capacity deployment starting around 2020, with greater growth starting in 2030 from deployment of more deep-EGS resources. The TI + High Natural Gas Prices combined scenario shows similar growth starting in 2030, but grows at a higher rate than the TI scenario alone through 2050. This result indicates that EGS growth is limited by demand and not supply.

4.2 Deployment Potential—Non-Electric Sector

The *GeoVision* analysis assessed opportunities for two non-electric-sector geothermal applications: geothermal direct use for district heating, and geothermal heat pumps (GHPs). Findings illustrate national opportunities for non-electric uses of geothermal energy, with the potential for more than 17,500 geothermal district-heating system installations and a more than 11-fold increase in installed GHP capacity (relative to a 2012 baseline).

Under a scenario that combined the *GeoVision* analysis Technology Improvement scenario with high natural-gas prices, geothermal deployment levels can reach nearly 120 GW_e by 2050. The deployment potentials for this scenario comprise less than 10% of total U.S. installed capacity, but would represent more than 16% of the country's total generation due to the high capacity factor of geothermal energy.

The *GeoVision* analysis used the Distributed Geothermal Market Demand (dGeo) model for the non-electric sector analysis (Section 3.1.3), and included scenarios for improved technology and—in the case of GHPs—consumer-adoption behaviors. The analysis is summarized in Sections 4.2.1 and 4.2.2 and detailed in McCabe et al. 2019 and Liu et al. 2019.

4.2.1 Deployment Potential of Geothermal Direct Use for District Heating

As noted in Chapter 2 (Figure 2-7), there is an immense array of end-use opportunities for geothermal direct-use applications, including agricultural and industrial uses where process heat is required. The *GeoVision* analysis for direct-use applications focused on district heating, which is the most widespread geothermal direct-use application (Lund and Boyd 2015) and which addresses an area of high energy demand: residential and commercial heating at a district scale. The *GeoVision* analysis did not consider district cooling.

Market-potential-based assessments for the geothermal non-electric sector using the dGeo model rely on data about the behavior of individual consumers and their willingness to adopt a technology based on payback period. As explained in Sections 3.2.2 and 3.2.3, geothermal district-heating technologies are deployed by communities whose decision to approve and adopt such installations is complicated by many factors beyond the payback period. As such, the *GeoVision* analysis considered only economic potential for geothermal district heating. As discussed in Chapter 3, economic resource potential represents the portion of total technical potential that is cost effective to recover based on technology costs and anticipated revenues.

The *GeoVision* analysis reports economic potential for geothermal district heating in relation to both the associated conventional hydrothermal and EGS resource bases (i.e., technical and resource potential) and the local demand for district heating (i.e., population density and climate). EGS resources are available over a larger geographic area and represent about 1,000 times more resource potential compared to the corresponding hydrothermal resource potential (McCabe et al. 2019) (Figure 4-6).

The *GeoVision* analysis identified national economic potential for geothermal district heating and confirms that the highest economic potential is co-located with cost-effective resource availability and concentrated heating demand. The economic potential for geothermal district-heating systems using geothermal direct-use resources is more than 17,500 installations nationwide—totaling 320 GW_{th} of heating capacity—with pronounced potential in the Northeast corridor of the United States. Figure 4-7 indicates the most favorable economic potential for geothermal district heating throughout the United States under the *GeoVision* analysis BAU scenario (top left) and under the *GeoVision* TI scenario (top right) (Table 3-5). This economic potential enables cost-competitive development of EGS resources. Both maps include conventional hydrothermal as well as EGS resources. Comparing the economic potential maps to the image of the United States at night (Figure 4-7, bottom left) illustrates the geographic alignment of the widespread EGS resource base and demand centers—discrete population centers that can benefit from geothermal district-heating systems.[89]

Potential	**Key Assumptions**	**Hydrothermal** (GW_{th})	**EGS** (GW_{th})
Market	Policy Implementation/Impacts Regulatory Limits Investor Limits Regional Competition with Energy Sources	–	–
Economic	Projected Technology Costs Projected Fuel Costs	4.6 GW_{th} TI	315 GW_{th} TI (2030)
Technical	System/Topographic Constraints Land-Use Constraints System Performance	27 GW_{th} TI	1,186 GW_{th} TI (2030)
Resource	Physical Constraints Theoretical Physical Potential Energy Content of Resource	46.5 GW_{th} (Mullane et al. 2016)	46,500 GW_{th} (Mullane et al. 2016)

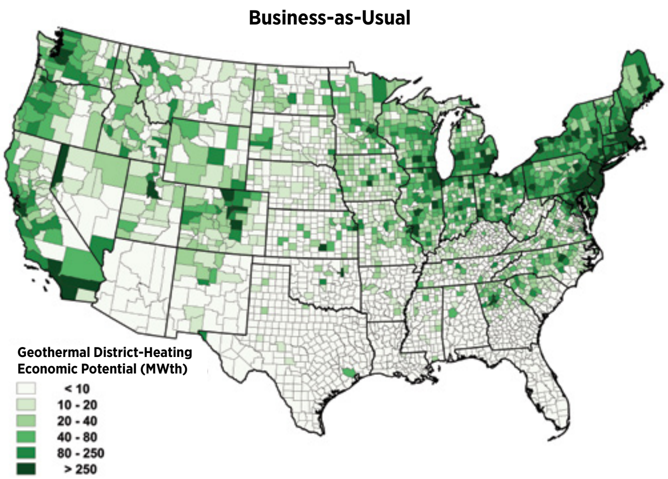
Potential

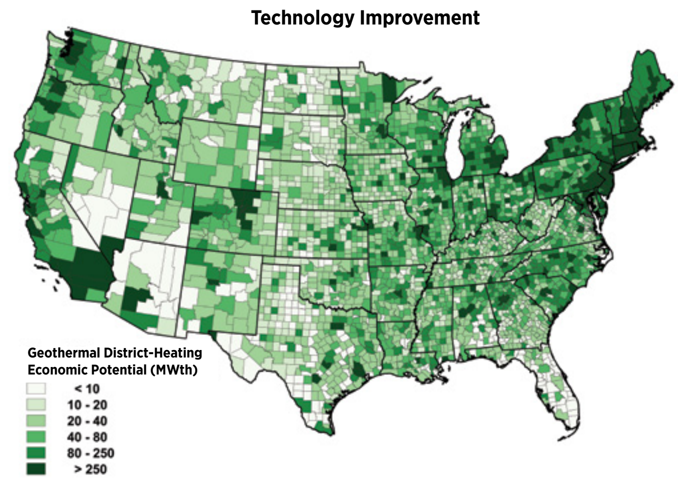
Figure 4-6. Geothermal district-heating deployment potential supported by hydrothermal and enhanced geothermal system resources as a function of resource, technical, and economic potential under the *GeoVision* analysis Technology Improvement scenario

Source: McCabe et al. 2019

Figure Note: Information about district-level consumer behavior for the U.S. geothermal direct-use/geothermal district-heating market was insufficient to enable modeling on the scale of the market potential. The GeoVision analysis assumes that EGS technologies become commercially feasible starting in 2030. "TI" in the Hydrothermal and EGS columns refers to the GeoVision analysis Technology Improvement scenario for geothermal district heating (Section 3.2.3). GW_{th} = gigawatts-thermal.

89 Population centers or groups may include building complexes such as hospitals and campuses. In locations where buildings are more dispersed, district-heating systems would be less cost effective to deploy due to piping costs.





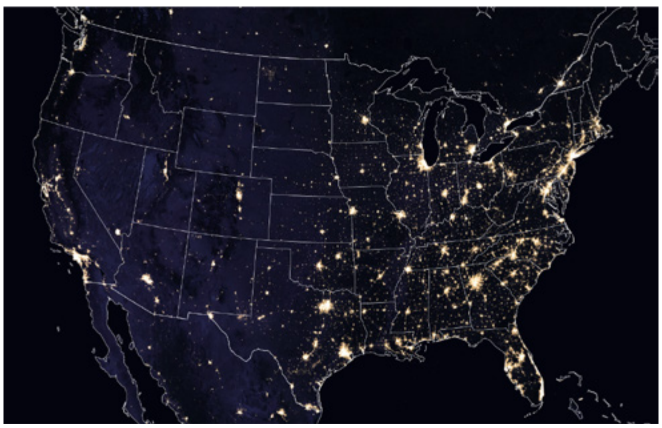


Figure 4-7. Economic potential for geothermal district heating by county in 2050 within the *GeoVision* analysis Business-as-Usual scenario (top left) and Technology Improvement scenario (top right), compared to a satellite image of United States at night, illustrating the geographic location of population centers (bottom left)

Source: McCabe et al. 2019. Satellite image created using data from the National Aeronautics and Space Administration's Earth Observatory.

Figure Note: The distribution of economic potential is closely linked geographically with major population centers. This linkage is illustrated through a comparison to nighttime satellite imagery of the United States (bottom left), which shows the brightly lit locations of population centers. Improved technology costs under the TI scenario result in greater economic potential of geothermal technologies. Deployment potential for geothermal district-heating systems exists throughout the United States, with particular potential concentrated along the Northeast Corridor. The total economic potential for geothermal district-heating systems using geothermal direct-use resources is more than 17,500 installations nationwide.

As is the case for geothermal electricity-generation applications, deployment growth for geothermal direct-use applications such as geothermal district heating will require improved technologies that lower the costs of EGS resource development.

4.2.2 Deployment Potential for Geothermal Heat Pumps

As noted in Section 3.2.2 and Table 3-4, the *GeoVision* analysis looked at two primary scenarios for the GHP market: 1) a Business-as-Usual (BAU) scenario, and 2) a Breakthrough (BT) scenario. In the BT scenario, technology improvements reduce ground heat-exchanger costs by 30%, and improve operational efficiency of GHP systems by 50%. Liu et al. 2019 provides more detail about the GHP analysis.

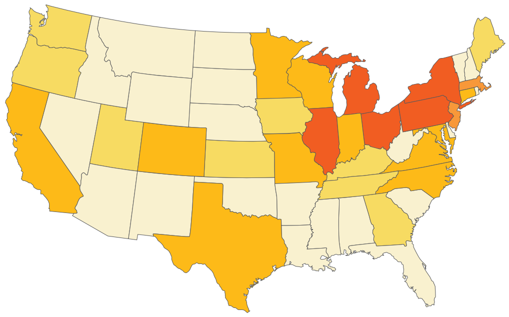
Figure 4-8 illustrates geographically the economic potential for GHP systems under the *GeoVision* analysis BAU and BT scenarios. Under both scenarios, economic potential is most concentrated in the Northeast and Midwest, with New York, Pennsylvania, Illinois, Ohio, and Michigan showing the highest potential—more than 174 gigawatts-thermal (GW_{th})[90] combined for the BT scenario.

Similar to the case for geothermal direct use, the economic potential for GHP systems is the portion of total technical potential that can be deployed where it can provide lower-cost heating and cooling alternatives for consumers. Economic potential is driven by capital costs and fuel costs and can vary with time as these factors change. Economic potential is higher than market potential because market potential is affected

90 Gigawatts-thermal is power available directly in the form of heat, as opposed to gigawatts-electric, which is power available in the form of electricity generated from the conversion of heat or other potential energy.

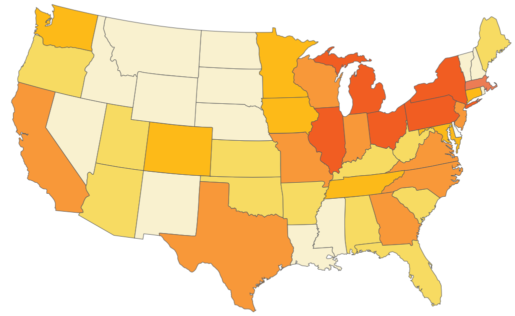
BAU Scenario

State	2050
NY	40.3
IL	28.6
PA	28.5
MI	26.7
OH	26.5
NJ	19.3
MA	19.1
CA	14.5
IN	13.8
VA	13.0



BT Scenario

State	2050
NY	44.9
PA	34.1
IL	32.7
OH	31.8
MI	30.7
CA	24.1
TX	22.5
NJ	22.4
MA	20.8
NC	18.4



GHP Potential (GWth)

< 5 | 5–10 | 10–15 | 15–25 | > 25

Figure 4-8. Economic potential for geothermal heat-pump systems by state in 2050 under the Business-as-Usual (left) and Breakthrough (right) scenarios, with the top 10 states listed separately

by conditions such as the regulatory environment, consumer understanding of the technology, and competing alternatives. GHPs are used at the individual consumer level, so market potential is affected heavily by consumer interest and understanding of the technology and its benefits. Consumer behavior also determines the speed at which full market potential is captured, determining the rate of capacity deployment at any given time. In theory, the capacity-deployment and market-potential curves will eventually meet, and consumer-adoption rates essentially determine how quickly that happens.

Figure 4-9 illustrates the economic-potential results for GHPs under the BAU and BT scenarios, as well as the related market potential and capacity deployment. The *GeoVision* analysis considered two consumer-adoption rates (Liu et al. 2019). Figure 4-9 assumes the more optimistic consumer-adoption rates, under which people are more likely to purchase a GHP system for a given payback period, and is based on adoption profiles observed within the solar photovoltaics market (Section 3.2.2 and Table 3-4).

The *GeoVision* analysis concludes that market potential for geothermal heat pumps is more than 14 times larger than existing capacity. This potential could translate to heating and cooling for about 28 million U.S. homes.

Using the more optimistic consumer-adoption rate (NREL Optimistic), the BAU and BT scenarios both show significant GHP market potential, underscoring the importance of GHP technologies to the U.S. heating and cooling market. The *GeoVision* analysis concluded that the maximum GHP **market potential** in the BT scenario—resulting from technology breakthroughs and assumptions of the "NREL Optimistic"[91] consumer-adoption rates—is more than 14 times larger than existing capacity. This result is equivalent to heating and cooling solutions for about 28 million homes, compared to the installed GHP capacity equivalent of roughly 2 million homes at the time of the *GeoVision* analysis.[92] This potential represents about 23% of the total residential heating and cooling market share by 2050. From this market potential, total actual capacity deployment in 2050 is projected to be enough to support about 18.6 million U.S. homes.

91 NREL is the National Renewable Energy Laboratory.

92 According to Lund and Boyd (2016), the installed capacity of GHPs in the United States had increased to 16.8 GW_{th} (or about 5 million cooling tons) by 2016. A GHP capacity equivalency of 1.92 million homes was determined on the basis of a calculated average size of residential GHP systems as 2.5 tons (8.75 kilowatts-thermal [kW_{th}]) per household. This average size was derived assuming an average U.S. household floor space of 1,750 square feet and an average U.S. household heating, ventilation, and air-conditioning size of 700 square feet/ton (DOE 2010, Moura et al. 2015).

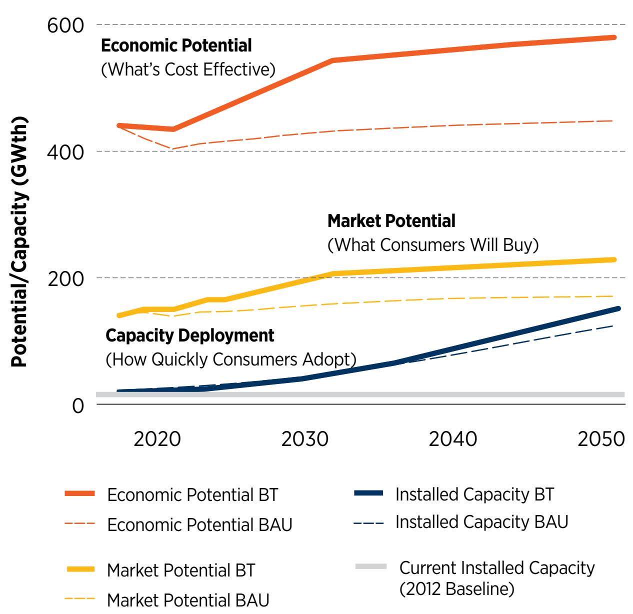


Figure 4-9. Geothermal heat-pump potential under the Business-as-Usual (denoted BAU) and Breakthrough (denoted BT) scenarios assuming the NREL Optimistic consumer-adoption rate

Figure Notes: The chart illustrates that GHP capacity deployment is lower than the economic and market potential because the speed at which deployment occurs is a function of consumer behavior. The reduced rate of increase after 2030 in the economic and market potentials is driven by changes in costs over time. Beyond 2050, the curves of capacity deployment and market potential will eventually meet, driven by consumer-adoption rates. Installed capacity as of 2012 ("2012 Baseline") was used as a baseline for comparison (Navigant 2013). NREL is the National Renewable Energy Laboratory.

The *GeoVision* analysis confirms that technology improvements are a significant factor in advancing GHP deployment. The geothermal industry could also benefit from improved financing and business structures, as well as enhanced collaboration, education, and outreach that help provide consumer knowledge. For GHPs, greater consumer understanding could lead to more and earlier adoption of the technology, converting more economic potential into market potential. Results of the full *GeoVision* analysis for GHPs are detailed in Liu et al. 2019.

4.3 The Market and Technology Nexus

The *GeoVision* analysis indicates that the market for conventional hydrothermal resources and their proven technology applications in electric-power generation have the potential to double in capacity through regulatory reform alone, relative to BAU. In the longer term, EGS resources hold the potential to supply more than 8.5% of the nation's total electric-power generation by 2050. In the *GeoVision* modeling scenario that considers improved technologies (the TI scenario), in combination with the ReEDS Standard Scenario that includes high natural-gas prices, EGS resources have the potential to provide more than 16% of the country's total generation by 2050 (Augustine et al. 2019).

For the heating and cooling sector, the *GeoVision* analysis indicates an opportunity to deploy GHP systems in 28 million homes (versus roughly 2 million residential GHP systems nationwide as of 2016). The *GeoVision* analysis also confirms that, by 2050, about 320 GW_{th} of geothermal direct-use resources are available to be economically deployed through improved technologies that enable EGS development. If deployed as geothermal district heating, these 320 GW_{th} could support as many as 17,500 geothermal district-heating installations across the United States—sufficient to satisfy the demand of about 45 million households.[93]

By identifying deployment opportunities across a range of geothermal applications and end uses that are at varied levels of maturity, the *GeoVision* analysis provides a view of the geothermal industry's nexus of markets and technologies. Figure 4-10 Illustrates the differentiation between the markets for existing, proven technologies and those that require developing technologies and primarily use EGS resources. The *GeoVision* analysis confirms significant growth opportunities for both types, along different pathways. For proven technologies, industry growth to maximum deployment will require stakeholders to collectively address barriers related to project financing, regulatory

93 The Energy Information Administration estimates that there are 118 million homes in the U.S. residential sector (Energy Information Administration 2015). Using this value plus data from the *GeoVision* analysis related to existing GHP market share and installed capacity indicates that 1 GW_{th} can supply heat to about 140,000 homes on average. This value was used to determine the impact of 320 GW_{th} of direct-use capacity on U.S. homes.

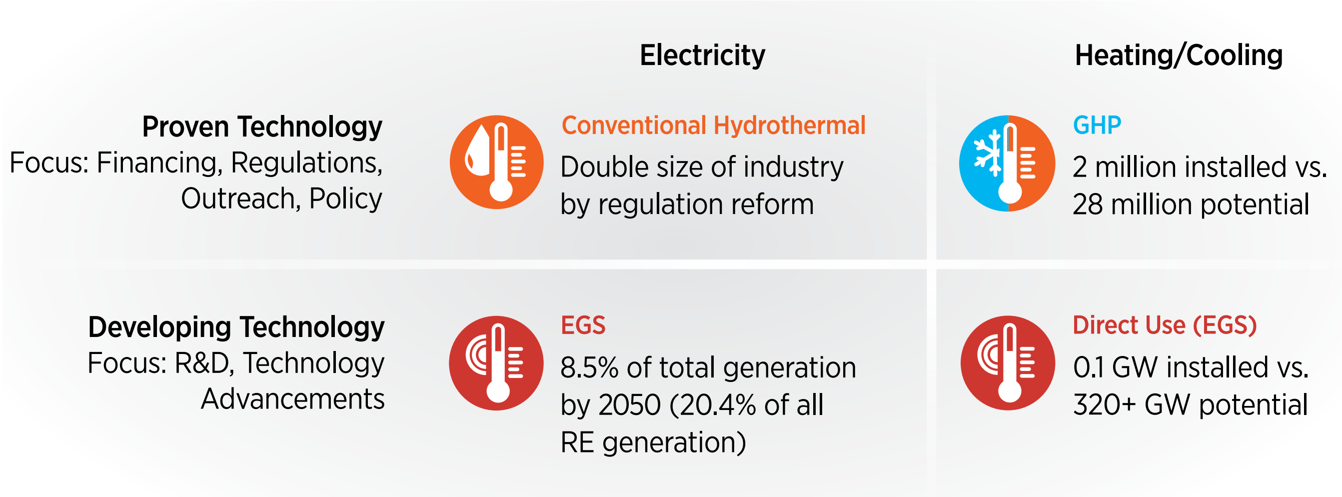


Figure 4-10. The *GeoVision* analysis market-technology nexus

Figure Note: The primary geothermal market sectors are electricity and heating and cooling. The electric sector is served by proven and cost-effective conventional hydrothermal resource technologies and by developing EGS technologies. The heating and cooling sector is served by proven GHP technologies and direct-use applications such as geothermal district heating supported by both conventional hydrothermal resources—and, eventually, EGS technologies. Proven technologies face greater development and implementation obstacles in the areas of financing, regulatory timelines, outreach, and market structures, whereas developing technologies require a focus on research and development to support technology advancements. Installed and potential values under GHP and direct use refer to market potential and economic potential, respectively. As discussed in this chapter, deployment of geothermal district heating based on market potential could not be modeled in the GeoVision analysis.

timelines, outreach and education, and market structures. For *unproven* and *developing* geothermal technologies, deployment growth will be advanced most effectively through research, development, and technology advancement. Actions to advance pathways for both proven and unproven technologies are discussed in the *GeoVision* Roadmap (Chapter 5).

4.4 Impacts of the *GeoVision* Analysis Findings

The *GeoVision* analysis included an assessment of impacts resulting from increased geothermal deployment—jobs and economic development in the domestic geothermal sector as well as water use and air emissions. Most of the impacts were examined at a national scale, with job impacts also evaluated regionally. Sections 4.4.1–4.4.3 summarize the impacts modeling and results, which are based on modeled deployment potentials for the electric and non-electric sectors as described in Sections 4.1–4.3. Impacts were evaluated independently for each sector using the results from the deployment modeling scenarios. Unless otherwise indicated, impacts are expressed as the difference between existing conditions and the various *GeoVision* analysis scenarios. Details of the impacts assessment are in Millstein et al. 2019.

Impacts assessments for power generation in the electric sector correspond to the deployment potential analysis of the Business-as-Usual, Improved Regulatory Timeline, and Technology Improvement scenarios. For the electric sector, impacts were calculated as the difference in specific outcomes (e.g., water consumption) between the BAU scenario and each of the other two scenarios (IRT and TI). For GHPs in the non-electric sector, impacts were calculated as the difference between a 2012 installed-capacity baseline with no additional GHPs (Liu et al. 2019) and the two technology scenarios—BAU and BT—in combination with two market-adoption rates: Navigant Low and NREL Optimistic (Table 3-4).[94]

94 The 2012 Baseline was chosen within the dGeo model framework to allow for assessment of the benefits of the growth in the GHP sector under both the Navigant and NREL adoption rates. This was accomplished by quantifying the benefits vs. the level of GHP deployment at the beginning of the dGeo model run. This initial level of GHP deployment is the "2012 Baseline." NREL is the National Renewable Energy Laboratory.

Modeling impacts for geothermal direct-use applications in district heating differed from electric-sector and GHP modeling due to the nature of the technology. In geothermal district heating, underground heat reservoirs are tapped to provide heating for many—sometimes thousands of—buildings. As such, geothermal district-heating systems have community impacts as well as individual impacts that would likely be substantive if such systems were deployed on a national scale. However, limited data and experience constrain understanding of U.S. market potential for geothermal district heating. As such, full market-potential expansion scenarios could not be modeled for geothermal district-heating systems in the *GeoVision* analysis. Instead, the impacts of a limited number of representative systems were quantified, and those results were used to qualitatively describe the impacts that could be realized from expansion based on economic-potential levels. Projected impacts for district-heating systems are discussed in McCabe et al. 2019 and Millstein et al. 2019.

A flow test on a 7,000-foot geothermal well at Naval Air Station Fallon, Nevada. *Photo credit: Andrew Tiedeman*

4.4.1 Jobs and Economic Development

The *GeoVision* analysis included assessing geothermal industry employment and economic impacts associated with increased deployment. However, specific job numbers are not reported here because the analysis data are gross numbers only and do not evaluate economy-wide net impacts. The assessment used the National Renewable Energy Laboratory's Jobs and Economic Development Impact model, commonly known as JEDI.[95] Details can be found in Millstein et al. 2019.

The majority of jobs in the geothermal electric-power sector depend on the exploration, construction, and deployment of new geothermal installations. As indicated, the employment impacts presented in this chapter represent gross job increases resulting from newly installed capacity in the geothermal electric sector, as opposed to net job impacts in the national economy.[96] Employment impacts are expressed in terms of cumulative expenditures (Table 4-2).[97] For the scenarios studied in the *GeoVision* analysis, job increases in the geothermal electric sector are driven primarily by widespread EGS resource potential that could support electricity demand in large population centers.

Job growth in the geothermal electric sector initially reflects industry growth enabled by improvements in regulatory timelines and technologies. The *GeoVision* analysis indicates that around 2030, technology improvements could reduce EGS costs and enable rapid growth in EGS resource deployment. If results of the TI scenario are achieved, EGS deployments would be responsible for the majority of jobs created and increased rates of job growth toward the end of the analyzed period in 2050.

95 Information on the JEDI model is available on the National Renewable Energy Laboratory's website at https://www.nrel.gov/analysis/jedi/.

96 The *GeoVision* analysis assessed gross job impacts from geothermal deployment compared with BAU scenarios. These gross job impacts represent total jobs needed to fulfill increased geothermal deployment, which may displace other energy generation technologies. The net impacts of this displacement were not calculated in the *GeoVision* analysis; thus, the gross job impacts reported in the *GeoVision* analysis do not represent the impact of geothermal jobs on employment within those other sectors. Assessing such impacts was beyond the scope of the *GeoVision* analysis (Millstein et al. 2019).

97 Cumulative expenditures include capital and O&M spending over the analyzed timeframe that is required to support deployment potential modeled in the *GeoVision* analysis.

Table 4-2 contains cumulative expenditures (millions of dollars) on geothermal electric-sector deployment from 2015 to 2050 by state, in the states where geothermal deploys under the TI scenario (Millstein et al. 2019).

State	Cumulative Expenditures (millions of $)	State	Cumulative Expenditures (millions of $)
CA	79,851	CO	3,008
WV	27,030	MT	976
OR	26,495	TX	222
ID	21,838	WY	208
NV	17,310	PA	110
UT	14,914	VA	51
AZ	13,754	MS	30
NM	13,339	LA	17
Total (millions of $) 219,152			

Table 4-2. Cumulative Expenditures on Geothermal Electricity-Generation Capacity Deployment by State in Millions of Dollars (2015–2050) in the TI Scenario

Table Note: Table contains the states in which geothermal deploys in the TI scenario. Cumulative expenditures include capital and operations and maintenance spending required over the analyzed timeframe to support deployment potential modeled in the GeoVision analysis. Expenditures depend on how the model (ReEDS) builds out generation and transmission at a bulk-grid scale. Expenditures in states such as West Virginia, Oregon, and Arizona are driven upward by a complex function of EGS availability, other generation retirements, and demand, levelized by the least-cost generation option. Expenditures shown are absolute values and not relative to the BAU scenario.

The *GeoVision* analysis indicates that, at a local level, geothermal power plants can provide more than double the long-term jobs per powered household when compared to other utility-scale power-generation technologies considered in the *GeoVision* analysis (Figure 4-11) (Millstein et al. 2019, Young et al. 2019). Long-term geothermal jobs are generally operations and maintenance positions filled mainly by local workers (Figure 4-12). As such, wages generated by these jobs are also more likely to be spent locally. Operations and maintenance spending includes royalties, which are unique to geothermal power plants, as well as property taxes, land-lease payments, and other spending.

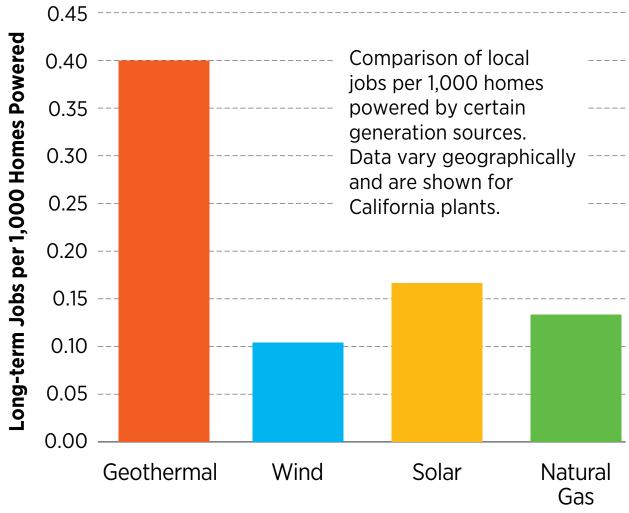


Figure 4-11. Comparison of long-term jobs per 1,000 homes powered, by energy-generation technology

Figure Note: Geothermal can provide more than double the long-term jobs per powered household compared to other electricity-generation technologies considered. As indicated, data shown are for California power plants.

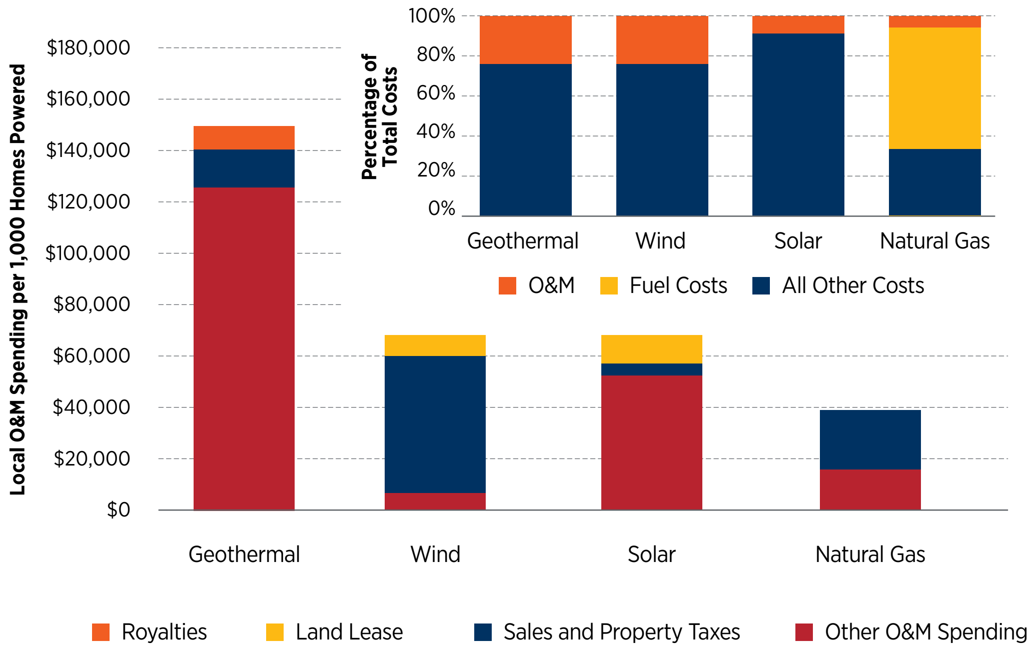


Figure 4-12. Comparison of local operations and maintenance spending per 1,000 homes powered, by energy-generation technology

Figure Note: Data vary geographically and are shown for California power plants.

GHP expenditures can help provide insight on GHP economic impacts and where those impacts might occur. Figure 4-13 illustrates the geographic distributions of gross GHP expenditures in 2030 and 2050 for the BT scenario. Most of the expenditures in 2030 are in Texas and the eastern half of the country. This result is geographically complementary with electric-sector deployment, which occurs mainly in the western United States (Table 4-2). As such, combined electric-sector and GHP economic impacts would be more geographically diverse when compared to each sector individually. GHP expenditures grow from $2.9 billion annually in 2030 to $4.3 billion annually in 2050. From 2030 to 2050, the expenditure increases occur mainly in six states: New Jersey, New York, California, Massachusetts, Michigan, and North Carolina (ranked in order of highest to lowest change).

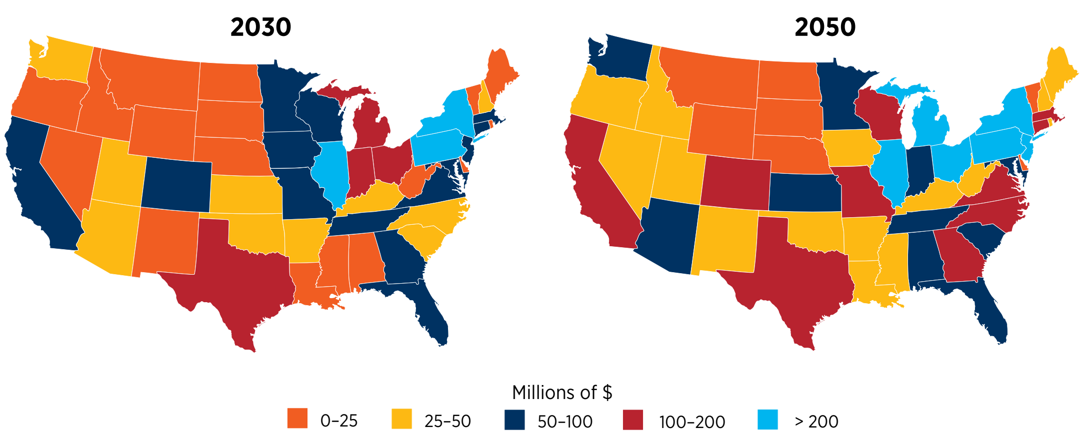


Figure 4-13. Geothermal heat-pump expenditures (in millions of USD) for 2030 (left) and 2050 (right) by state under the Breakthrough scenario

Source: Millstein et al. 2019

Achieving deployment levels identified in the *GeoVision* analysis can increase employment, wages, and economic output in the geothermal electric and non-electric GHP sectors. The analysis also demonstrates that combining geographic trends of development in the geothermal electric and GHP sectors can result in benefits in many U.S. states, particularly the West and Mid-Atlantic regions (Millstein et al. 2019).

4.4.2 Water Use

For the *GeoVision* analysis, water-use impacts were calculated for the electric sector only. This evaluation included two categories of water impacts: 1) water **withdrawal**, which is water removed or diverted from a water source for use, and 2) water **consumption**, which is water evaporated, transpired, or incorporated into products or crops or otherwise removed from the immediate water environment. Water consumption represents a net loss from the local source. For electricity generation, withdrawal is typically water used for cooling and then returned to the source at a slightly elevated temperature, whereas consumption is usually water used for evaporative cooling and not returned directly to the source.

Modeling for water-use impacts focused exclusively on operational water-use requirements, which can vary based on the type of fuel, power plant, and cooling system. Water-use impacts calculated for the *GeoVision* analysis were based on the ReEDS modeling results and extracted directly from the ReEDS model. ReEDS includes water availability in modeling capacity deployment and will restrict deployment of a technology if water resources are not available. Millstein et al. 2019 includes a detailed explanation of the modeling methodology and assumptions for water-use impacts.

Under the *GeoVision* TI scenario, geothermal power generation would represent 8.5% of total national generation in 2050, but only 1.1% of power-sector water withdrawals. Figure 4-14 shows water withdrawals for the TI scenario (Millstein et al. 2019). Because the water-withdrawal percentages for geothermal and other renewable technologies are minor in relative terms, they do not register visibly at full scale in the figure.

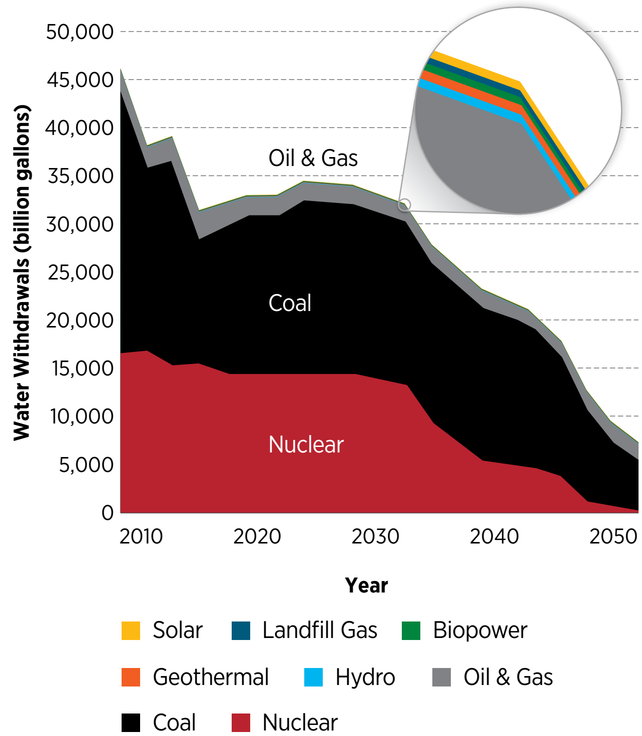


Figure 4-14. Power-sector water-withdrawal impacts in billions of gallons

Source: Millstein et al. 2019

Figure Note: Chart illustrates water-withdrawal impacts from geothermal generation as modeled under the TI scenario. Geothermal, solar, landfill gas, biopower, and hydropower have minimal impact on water withdrawals for the total electric sector; data for these technologies are reflected in the figure but are too small to be seen at full scale. The inset magnifies these data to make them visible.

Under the *GeoVision* analysis Technology Improvement scenario, geothermal energy could represent 8.5% of total national electricity generation while being accountable for only 1.1% of power-sector water withdrawals. The majority of this growth could be supported using non-freshwater sources.

The *GeoVision* analysis indicates that geothermal power generation under the TI scenario impacts water consumption relative to BAU, representing 7.6% of total power-sector water consumption by 2050, as compared to 8.5% of total generation (Figure 4-15). This percentage of water consumption by geothermal power generation represents a cumulative increase from present day to 2050 of about 230 billion gallons systemwide over the BAU scenario—a small percentage (0.5%) relative to total electric-system-wide consumption (46 trillion gallons cumulatively) over that same time period. Annual water consumption in 2050 in the BAU scenario is about 1.01 trillion gallons, compared with 1.05 trillion gallons under the TI scenario (4% higher). Results are driven by modeling assumptions related to subsurface water loss and the assumed binary, air-cooled configuration for EGS plants (Millstein et al. 2019).

Geothermal technology deployment in the BAU, IRT, and TI scenarios was not restricted on the basis of water quality (i.e., sources being freshwater or non-freshwater). The *GeoVision* analysis evaluated the sensitivity of geothermal growth to restrictions on water sourcing. An alternate sensitivity scenario considered limiting geothermal water use to non-freshwater sources (e.g., brackish groundwater or municipal wastewater). Under the non-freshwater-consumption sensitivity analysis, geothermal deployment could still increase to nearly the same levels as in the freshwater scenario, maintaining about 90% of total projected deployment. The sensitivity analysis results indicate the potential to support almost all of the geothermal energy growth using only non-freshwater resources. This means that geothermal deployment growth could be supported even where access to freshwater is limited. Achieving the deployment results of the *GeoVision* analysis is not expected to materially impact the water needs of the wider electric system.

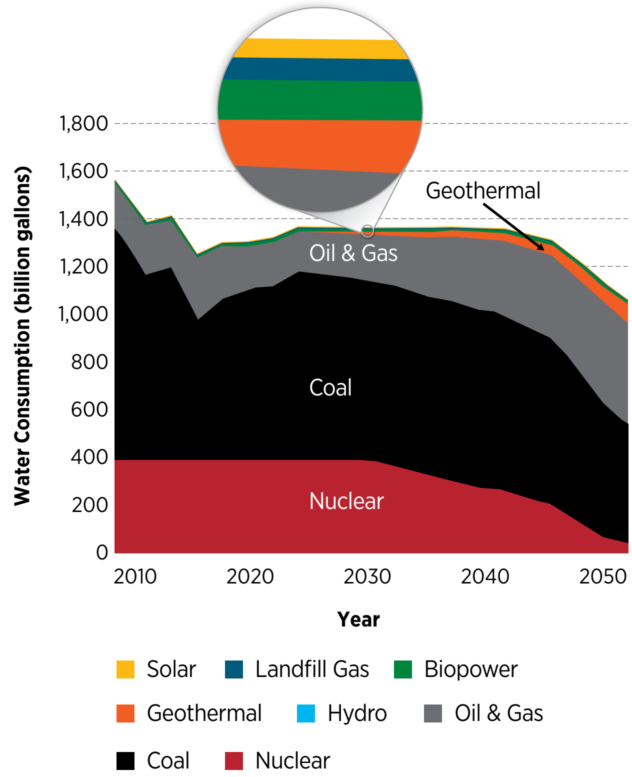


Figure 4-15. Water-consumption impacts from the geothermal power sector (in billions of gallons) under the Technology Improvement scenario

Source: Millstein et al. 2019

Figure Note: Water consumption increases with increasing geothermal power generation, accounting for 7.6% of total power-sector water consumption by 2050 and 8.5% of total generation. Comparatively, however, geothermal accounts for a fraction of the water consumption of coal, natural gas, and nuclear power generation. Solar, landfill gas, biopower, and hydropower are included in systemwide data but represent consumption values that are too low to see at full scale in the figure. The inset magnifies these data to make them visible.

4.4.3 Air Emissions

The *GeoVision* analysis assessed the impact of increased geothermal deployment on air emissions, including greenhouse gas (GHG) emissions, measured as carbon-dioxide equivalents (CO_2e),[98] as well as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$).[99] Results of the analysis indicate opportunities for reduced emissions and improved U.S. air quality resulting from greater geothermal deployment in both the electric and non-electric sectors.

Figure 4-16 illustrates annual life cycle greenhouse gas emissions and annual displaced life cycle greenhouse gas emissions in the entire electric sector under the BAU, IRT, and TI scenarios. In the entire electric sector, geothermal deployment under the TI scenario—particularly from EGS resources—reduces total sector CO_2e emissions by a *cumulative* 516 million metric tons (MMT) from 2015 to 2050, on a life cycle basis relative to a BAU scenario. By the end of the analyzed period (2050), the GHG emissions avoided annually are roughly equal to the annual GHG emissions of 6.4 million cars.[100]

98 Carbon-dioxide equivalents are a summation of the GHG effects of contributing gases (e.g., methane) measured on a carbon-dioxide equivalency basis.

99 $PM_{2.5}$ refers to fine inhalable particulates that are 2.5 microns or less in diameter.

100 Car-emission equivalent calculations assume that a typical U.S. passenger vehicle emits about 4.7 metric tons of CO_2 per year, based on fuel economy of about 21.6 miles per gallon and 11,400 miles of travel per year (Environmental Protection Agency 2014).

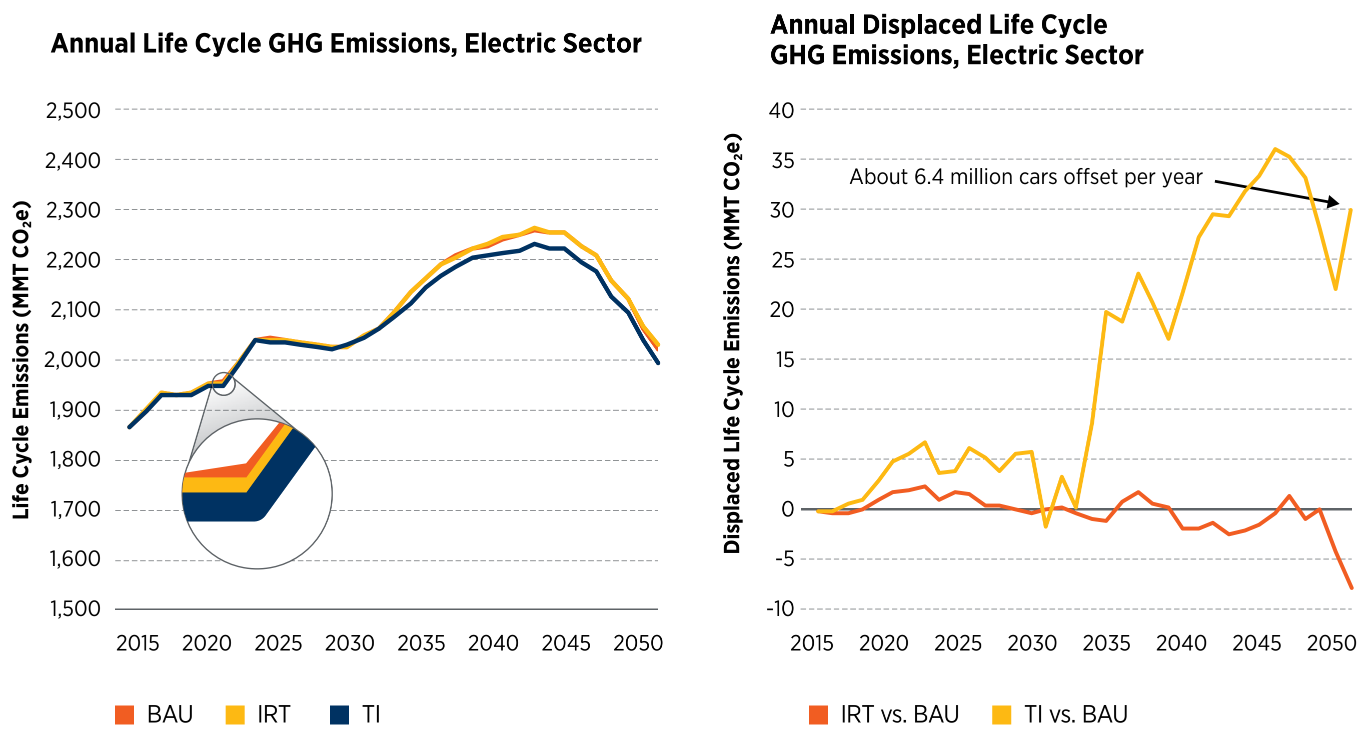


Figure 4-16. Annual life cycle greenhouse gas emissions (left) and annual displaced life cycle greenhouse gas emissions (right) in the entire electric sector under the Improved Regulatory Timeline, Technology Improvement, and Business-as-Usual scenarios

Source: Millstein et al. 2019

Figure Note: For the TI scenario, geothermal deployment in the electric sector results in a cumulative total reduction of 516 MMT of CO_2e from 2015 to 2050, on a life cycle basis relative to a BAU scenario. By the end of the analyzed period, the annual avoided emissions are equivalent to the emissions from about 6.4 million cars. "MMT CO_2e" is million metric tons of CO_2e. Negative impacts (i.e., minor increases in emissions resulting in negative displacement) derive from increases in systemwide emissions, not from geothermal power plants specifically.

Figure 4-17 illustrates annual life cycle greenhouse gas emissions and annual displaced life cycle greenhouse gas emissions in the heating and cooling sector under the BAU and BT scenarios, relative to the 2012 baseline. In the heating and cooling sector, deployment of GHPs in the BT scenario results in as much as ~90 MMT of displaced annual GHG emissions by 2050 relative to the 2012 GHP baseline—the equivalent emissions of about 20 million cars. Given the nature of GHP deployment, GHG emissions reductions from the technology are distributed relatively evenly throughout the contiguous United States, with somewhat higher amounts in the Mid-Atlantic, Midwest, and Great Lakes regions (Millstein et al. 2019).

Assuming the most aggressive technology improvements modeled for both the electric and non-electric sectors, the overall results of the *GeoVision* analysis of air-emissions impacts indicate that—by 2050—geothermal deployment could avoid annual GHG emissions equivalent to removing a total of about 26 million cars from U.S. roads relative to the 2012 baseline. As noted, geothermal deployment in the U.S. electric sector, as modeled in the TI scenario, yields *cumulative* life cycle GHG emissions reductions of 516 MMT of CO_2e through 2050 relative to BAU, whereas GHP deployment in the heating and cooling sector yields *cumulative* life cycle GHG emissions reductions of 1,281 MMT of CO_2e through 2050 relative to the 2012 baseline. Across both the electric and heating and cooling sectors under the most aggressive

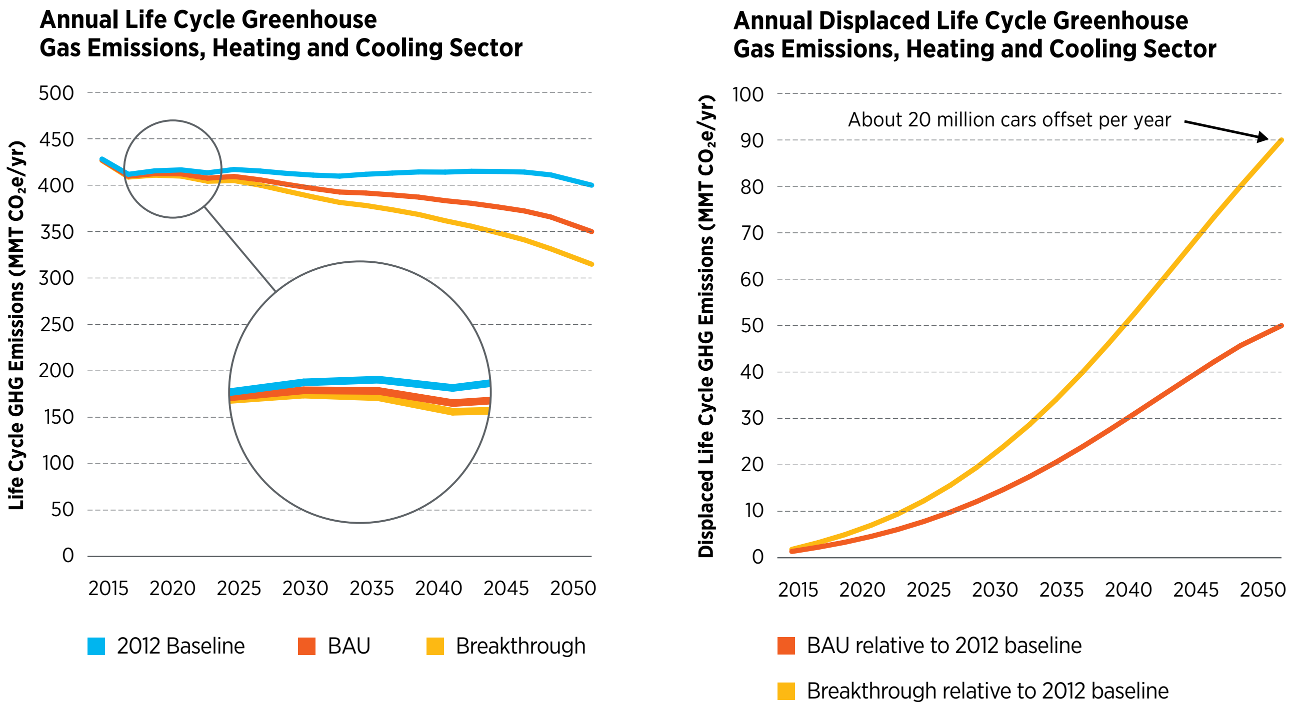


Figure 4-17. Annual life cycle emissions (left) and annual displaced life cycle greenhouse gas emissions (right) in the entire heating and cooling sector under the Breakthrough and Business-as-Usual scenarios, relative to the 2012 GHP baseline

Source: Millstein et al. 2019

technology improvement and growth scenarios, the rate of annual GHG emissions reductions increases through 2050, reaching a combined *annual* reduction of 117 MMT CO_2e by 2050 (Millstein et al. 2019).

By 2050, geothermal deployment in the nation's electric and non-electric sectors could reduce greenhouse gas emissions equivalent to removing 26 million cars from U.S. roads annually.

Results in the *GeoVision* analysis for SO_2, NO_X, and $PM_{2.5}$ emissions also demonstrate improvements in air quality resulting from increased deployment of geothermal technologies. Figure 4-18 illustrates total electric-sector emissions for SO_2, NO_x, and $PM_{2.5}$ and net air-quality impacts (in thousands of metric tons) resulting from the *GeoVision* scenarios compared to the BAU scenario. As with GHG emissions, improvements in SO_2 and NO_x are especially notable for the TI scenario in the electric sector. As illustrated in Figure 4-18, the TI scenario results in greater reductions in SO_2, NO_x, and $PM_{2.5}$ emissions than the IRT scenario. Achieving the TI scenario reduces cumulative emissions of SO_2, NO_x, and $PM_{2.5}$ by 279,000, 417,000, and 54,000 metric tons, respectively, relative to the BAU scenario. These reductions represent about 1% of total emissions in each category and are concentrated in the time period between 2030 and 2050. Reductions of emissions of SO_2, NO_x, and $PM_{2.5}$ are seen in all modeled regions of the country, but are highest in Texas and the southwestern region of the United States. If the nation achieves the large-scale deployment of EGS resources identified in the *GeoVision* analysis TI scenario, then these air-quality benefits are expected to increase around 2030.

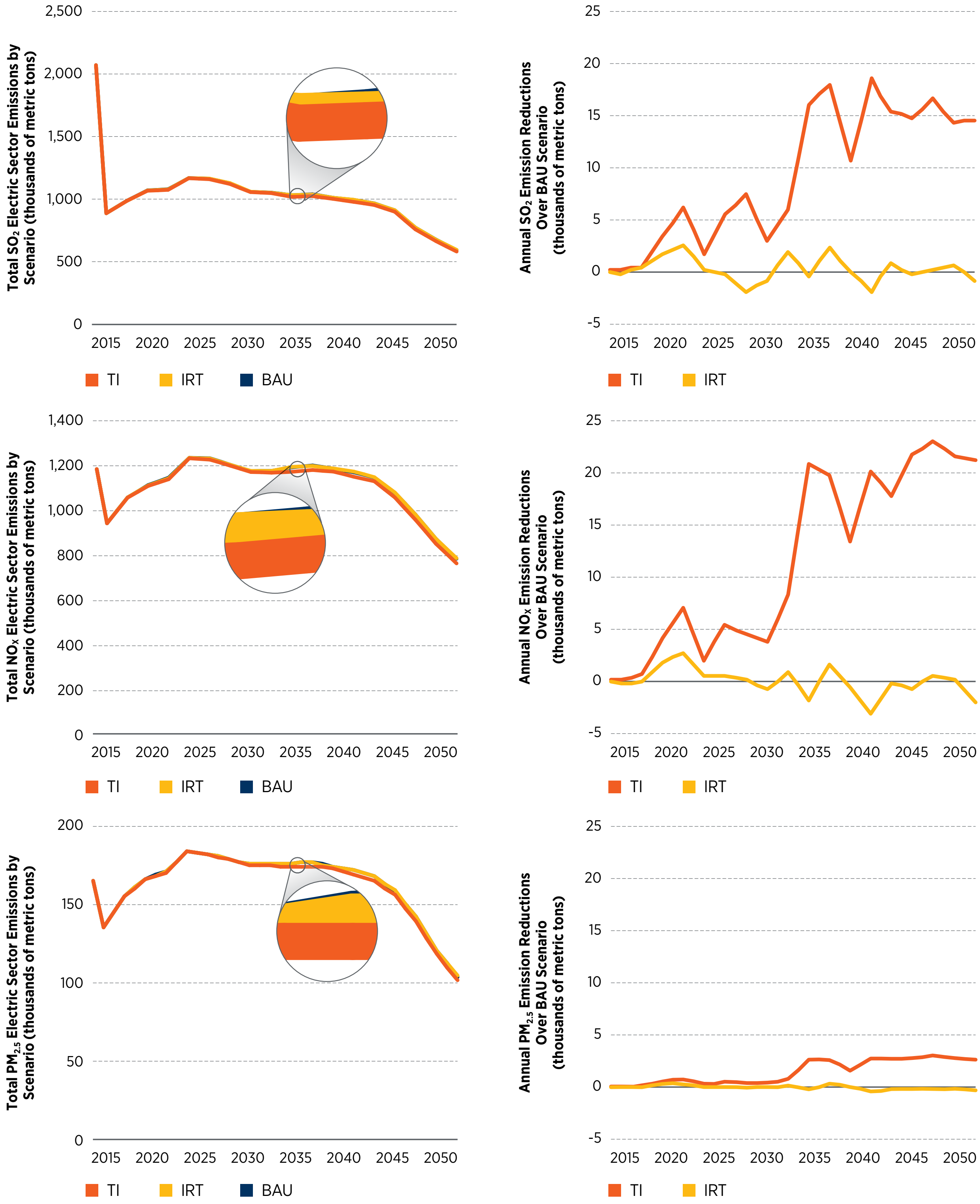


Figure 4-18. Air-quality impacts (SO_2, NO_x, and $PM_{2.5}$ emissions) for the entire electric sector, illustrating total (left) electric-sector emissions and annual (right) emissions reductions impacts from the *GeoVision* scenarios on electric-sector emissions (in thousands of metric tons)

Source: Millstein et al. 2019

Figure Note: Emissions reductions (right) are reported in thousands of metric tons of NO_x, SO_2, or $PM_{2.5}$ emissions removed from the electric sector and attributable to geothermal deployment. The highest emissions reductions in the electric sector result from the TI scenario. Reductions begin in about 2030, when large-scale deployment of EGS resources occurs. Negative impacts (i.e., minor increases in emissions) derive from increases in systemwide emissions, not from geothermal power plants specifically.

In the heating and cooling sector, the decrease in on-site fuel use that results from achieving the BT scenario reduces cumulative emissions (from 2015 to 2050) of SO_2, NO_x, and $PM_{2.5}$ by 232,000, 711,000, and 57,000 metric tons, respectively, relative to the 2012 baseline. These emission reductions are equivalent to double to triple the total single-year SO_2 and NO_x emissions from all residential combustion sources and one-fifth of a single year of $PM_{2.5}$ residential emissions (Environmental Protection Agency 2016). Figure 4-19 illustrates the total GHP heating and cooling sector emissions for SO_2, NO_x, and $PM_{2.5}$ and net air-quality impacts (in thousands of metric tons) resulting from the *GeoVision* BAU and BT scenarios, compared to the 2012 GHP baseline. The emission reductions increase gradually over time. In the case of GHPs, significant benefits are found even in the BAU scenario, with the additional deployment in the BT scenario providing further benefits.

Further details about air-emissions impacts, including a description of methodologies and models, are provided in Millstein et al. 2019.

An evaporative cooling tower at Socrates Geothermal Power Plant (The Geysers, California). *Photo credit: Geothermal Resources Council*

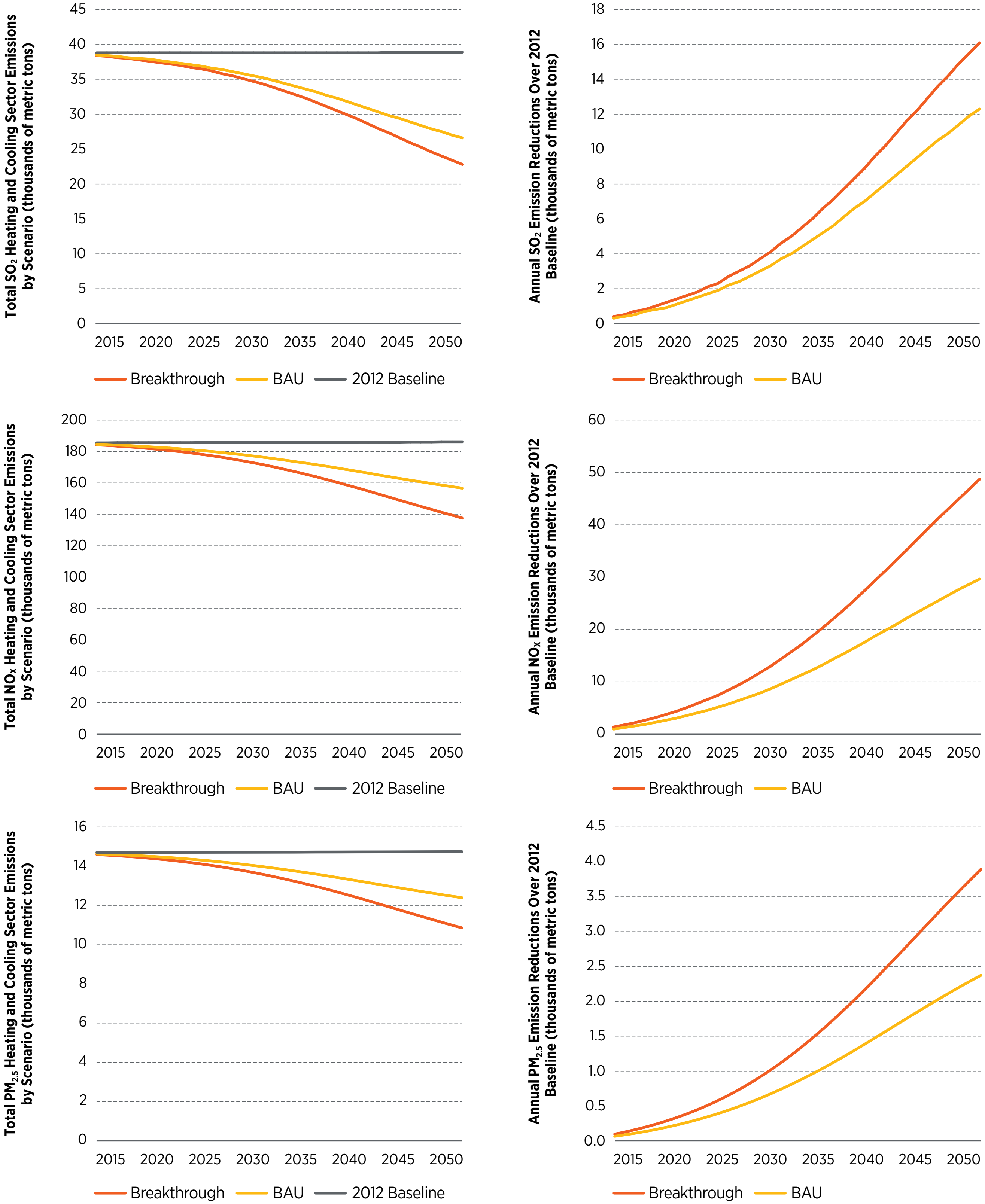


Figure 4-19. Air-quality impacts for the heating and cooling sector, illustrating total sector emissions of SO_2, NO_X, and $PM_{2.5}$ and annual emissions reductions impacts (in thousands of metric tons) from the *GeoVision* scenarios on heating and cooling sector emissions

Source: Millstein et al. 2019

Figure Note: Air-quality impacts reflect reductions (right) in cumulative NO_X, SO_2, or $PM_{2.5}$ emissions resulting from reduced on-site fuel use under the BAU and BT scenarios. These emissions reductions track GHP capacity deployment values and increase gradually over time. "2012 Baseline" refers to the 2012 installed GHP baseline used in the analysis.