The Future of Geothermal in Pennsylvania

Leveraging the Commonwealth's Legacy of Energy Leadership

February 2025

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PennState

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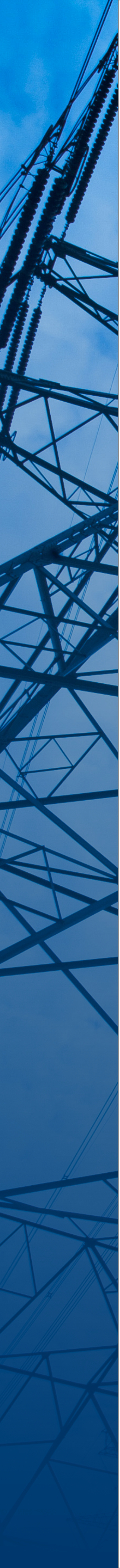

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Acknowledgments

Special thanks to Jon Benesch, Mike Canich, John Wang, and Ozgur Yildirim for their help in collecting, organizing, and compiling subsurface data, and for their contributions to advancing our understanding of Pennsylvania's subsurface geothermal energy potential. Thanks also to the Pennsylvania Department of Conservation and Natural Resources Bureau of Geological Survey for their guidance in understanding sources of subsurface data. Thanks also to Sean Walter, Yuvasri Raghavan, and Sabrina Hochberg with ZS Associates for their contributions to the industrial process heat-demand analysis. And the National Renewable Energy Lab for their initial county-by-county thermal demand analysis. Special thanks to Brigid Khuri for providing early and ongoing assistance in understanding Pennsylvania property rights. Thanks to Brian Regli for his early vision, infectious enthusiasm, and ongoing support.

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Definitions

The terms below are used frequently throughout this report. There are no universally agreed upon terminologies or definitions to describe geothermal technologies, particularly with emerging concepts and applications, so the authors have adopted prevailing terms consistent with those defined in *The Future of Geothermal in Texas: The Coming Century of Growth and Prosperity in the Lone Star State (2023)*. Here they are presented in categories to help show the relationships between terms.

Conventional Hydrothermal Systems (CHS) - Also known as traditional geothermal systems or hydrothermal geothermal systems, this geothermal resource is often accessible close to the surface and at times has surface manifestations, such as hot springs, volcanic rock formations, geysers, or steam vents, among others. CHS have a combination of sufficient permeability in the subsurface, sufficient heat transfer into the system, and the natural presence of circulating water which produces an exploitable geothermal resource. Heat flow is convection dominant, i.e., conduction and advection contribute to the movement of heat. Most of the world's developed geothermal capacity is currently produced from CHS resources.

Next-Generation Geothermal - An umbrella term for any geothermal extraction technology that harvests subsurface energy outside the geography of Conventional Hydrothermal Systems (CHS). In most cases, next generation geothermal technologies rely on advances from the oil and gas industry which enable the expanded geographic potential or to more effectively tap into existing conventional resources.

Sedimentary Geothermal System (SGS) - A type of conduction-dominated geothermal resource found in sedimentary rock formations (with some convection cells in complex settings). These sedimentary rocks, including sandstone, shale, and limestone, often contain water within their pores that can be harvested for geothermal energy production. Most sedimentary basins are closed systems, unless they have experienced uplift, in which case surface springs may highlight geothermal potential.

Conventional Geothermal - A geothermal extraction method that requires a hydrothermal system and doesn't use hydraulic fracturing to artificially engineer a subsurface reservoir. Horizontal drilling may be used, but only to improve access to otherwise naturally occurring reservoirs and naturally occurring fluid.

Engineered/Enhanced Geothermal Systems (EGS) - A geothermal technology that uses hydraulic fracturing to engineer a subsurface reservoir by creating or enhancing existing fractures in rock. Fluids are then circulated through the fracture network, where they heat up, and are brought to the surface to generate electricity or for direct use. These systems can be deployed in various rock types and are considered scalable.

- **Traditional Engineered Geothermal Systems (Traditional EGS)** - Systems that use hydraulic fracturing to engineer or enhance a subsurface reservoir to produce geothermal heat or electricity, but do not use advanced directional drilling or multi-stage fracturing techniques. These systems are typically developed by drilling vertical or deviated wells, and can be deployed in various rock types, but the development of these systems has historically focused on basement rock formations.
- **Next-Generation Engineered Geothermal Systems (Next-Gen EGS)** - Not to be confused with the umbrella "Next-Generation Geothermal" concept, this is a subtype of EGS which still uses hydraulic fracturing to engineer or enhance a subsurface reservoir while also incorporating advanced drilling and/or fracking techniques, including but not limited to, horizontal drilling and multi-stage fracturing. These systems can be deployed in a variety of rock types.

Super Hot Rock (SHR) - A term given to geothermal technologies that aim to exploit hot rock resources above approximately 703°F (373°C), the supercritical point of water. In volcanic regions of the world, SHR may be encountered relatively close to the surface; in other regions, SHR may require drilling to as much as 6 miles (about 10 kilometers) or more, therefore, they are sometimes referred to as "Deep Geothermal."

Advanced Geothermal Systems (AGS) - Occasionally referred to as Closed Loop Geothermal Systems (CLGS), this is a geothermal technology (with many configurations) that allows the circulation of fluid in the subsurface without fluid leaving the wellbore. Fluid is pumped from the surface, picks up heat from the surrounding formation (primarily through conduction), and flows back to the surface, where the heat is harvested for direct-use or power applications. These systems can be deployed in various rock types, can use engineered fluids like supercritical CO_2 to improve efficiency, and are considered scalable.

Ground Source (Geothermal) Heat Pumps (GSHP) - These pumps harvest the ambient temperature in the top one to two meters of the subsurface, where the ground remains at a relatively constant temperature of 55°F (13°C). GSHPs have traditionally been used to heat and cool buildings but are increasingly used in higher-temperature industrial and commercial applications.

Direct-Use Geothermal Systems - Unlike using geothermal heat to generate electricity, Direct-Use Geothermal Systems use the heat contained in geothermal fluids to enable various heating and cooling applications. These systems can be shallow or deep.

- **Shallow Direct-Use** applications typically use Ground Source Heat Pumps to harvest the constant temperature of the shallow subsurface for a variety of low-temperature applications, including heating and cooling buildings.
- With **Deep Direct-Use,** wells are drilled to reach higher subsurface temperatures, which can be used for various applications, including industrial and commercial direct heating or for numerous industrial and manufacturing processes. Deep direct-use applications may still use heat pumps but do so at much higher temperatures. Wells can target deep aquifers or man-made places filled with water, like mines.

Thermal Energy Networks (TEN) –When direct-use geothermal energy is supplied to a large area, clusters of buildings, or in a district from a central location, it is called a Thermal Energy Network. This is also referred to as District Heating.

Geothermal Energy Storage (GES) Systems - A technology that stores mechanical and/or thermal energy in any of a variety of settings. Underground Thermal Energy Storage (UTES) uses the subsurface for energy storage. Aquifer Thermal Energy Storage (ATES) injects hot water into porous underground aquifers and retrieves it when needed. Borehole Thermal Energy Storage (BTES) uses a network of boreholes drilled into the ground and filled with heat exchangers to store thermal energy. Mine Thermal Energy Storage (MTES), popular in Europe, utilizes abandoned mines filled with water as heat storage reservoirs.

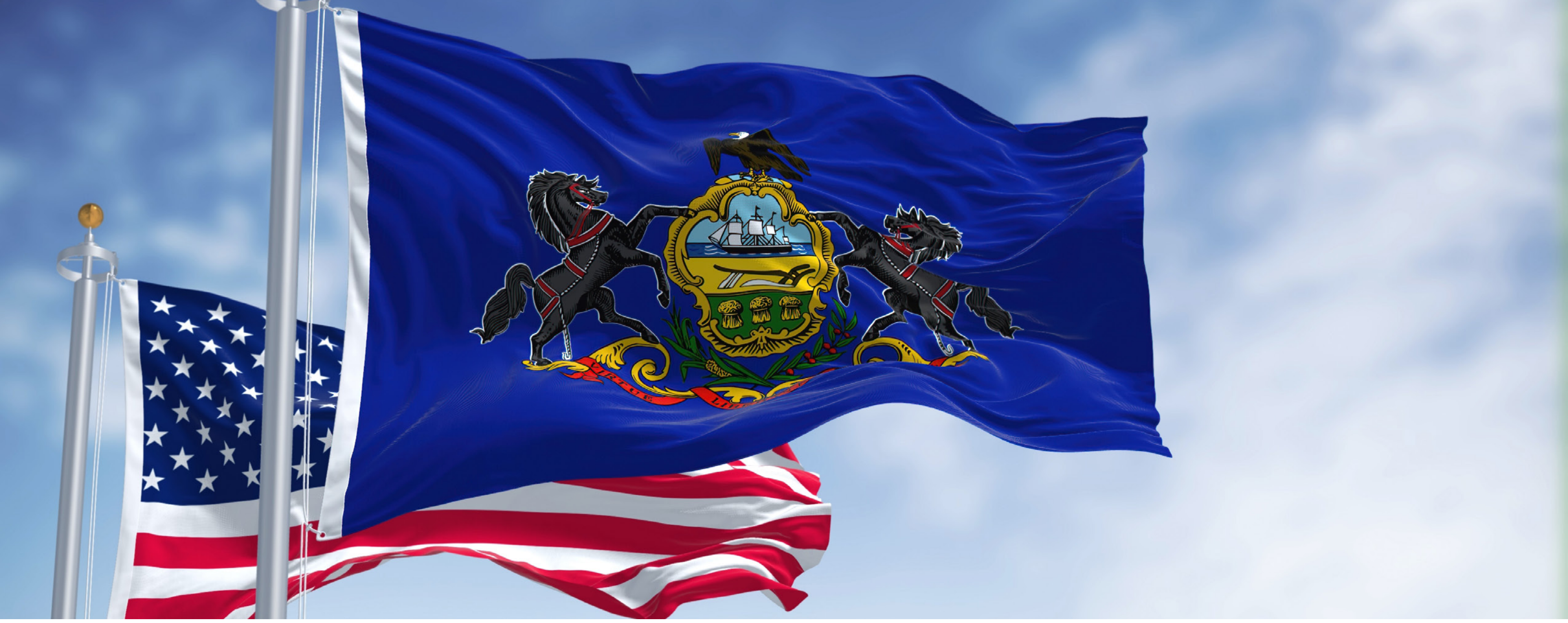
Hybrid Geothermal Systems or Multi-System Hybrids - A geothermal application that couples two different technologies such as solar and geothermal, direct air capture and geothermal, hydrogen and geothermal, energy storage and geothermal, and others. These systems can be deployed in a variety of rock types and may or may not be scalable, depending on the system combination.

Oil and Gas Well Reuse (Well Reuse) - A geothermal application in which geothermal energy is produced from existing oil and gas wells. There are two possibilities. First, an existing hydrocarbon well could be repurposed to produce geothermal energy only, known as conversion. Second, an existing well could produce hydrocarbons and heat simultaneously, known as co-production.

Working Fluid - A term given to the fluid used to harvest geothermal heat from the subsurface and deliver it to the surface in geothermal applications. Working fluids can be, and have been historically, water or brine. Next-generation geothermal concepts seek to use novel, non-water "engineered working fluids" with lower boiling points than water to increase system efficiencies and performance, particularly in lower-temperature geothermal resources. Examples of engineered working luids that are currently in research and development include supercritical carbon dioxide (sCO_2), combinations of organic fluids, or combinations of both sCO_2 and organic fluids. Binary cycle power plants also use engineered working fluids to drive the turbines in their second stage.

Geothermal Anywhere - A colloquial term used to refer to scalable geothermal concepts, such as EGS, AGS, or SHR, that could enable the development and production of geothermal energy anywhere in the world.

Scalable Geothermal - A term given to any geothermal resource that has few, if any, geographical limitations on its ability to scale globally (as opposed to locally or regionally) or to any geothermal technology that, once proven through field trials, could feasibly be deployed anywhere in the world. Advanced Geothermal Systems (AGS), Engineered Geothermal Systems (EGS), and some Hybrid Geothermal System concepts are considered to be scalable geothermal technologies. Conventional Hydrothermal Systems (CHS) are not considered scalable geothermal resources under this definition.



Executive Summary

Pennsylvania can help write the next chapter for American subsurface energy: leveraging abundant, secure and always-on geothermal energy. The Commonwealth's subsurface stores thousands of times more energy in the form of heat than it consumes annually. The resources and workforce of its existing oil and gas industry can be deployed to generate geothermal energy throughout Pennsylvania.

Pennsylvania has been at the leading edge of American energy production since the 1700s, when coal mines were dug across the Monongahela River from Pittsburgh. The nation's first oil well was drilled in 1859 in Titusville, in the northwest corner of the Commonwealth. For the last twenty years, the Keystone State has led the shale boom, making Pennsylvania one of the world's top natural gas producers. Now, with the skills, knowledge, and resources, Pennsylvania is well positioned to become a leader in the next energy revolution to emerge in the U.S.: abundant, secure, and always-on next-generation geothermal energy.

To produce geothermal energy, fluids are circulated underground to capture some of Earth's ubiquitous subsurface heat, then brought back to the surface. There, the heat can be used for thermal energy or to make electricity. Traditionally, geothermal energy production has only been possible in volcanic regions—areas where the right mixture of heat, water, and rock permeability lies close to the surface. These unique conditions, called "hydrothermal resources," are often associated with surface features like hot springs and geysers. They are extremely limited geographically. However, it is hot everywhere underground. Technological advances in drilling and subsurface engineering over the past two decades have made it possible to tap into that geothermal energy almost anywhere, including Pennsylvania.

The New Geothermal Opportunity

Because of the robust oil and gas industry in Pennsylvania—and a corps of geologists and researchers—subsurface temperatures in the Commonwealth have been recorded and modeled for years. That data shows that there is 1000-fold (or more) energy available in the form of heat underground than Pennsylvanians consume each year. And there are opportunities to use it, in some form, all across the Commonwealth's 46,000-plus square miles.

If Pennsylvania were to develop and grow this abundant local energy source, the impact would be swift and

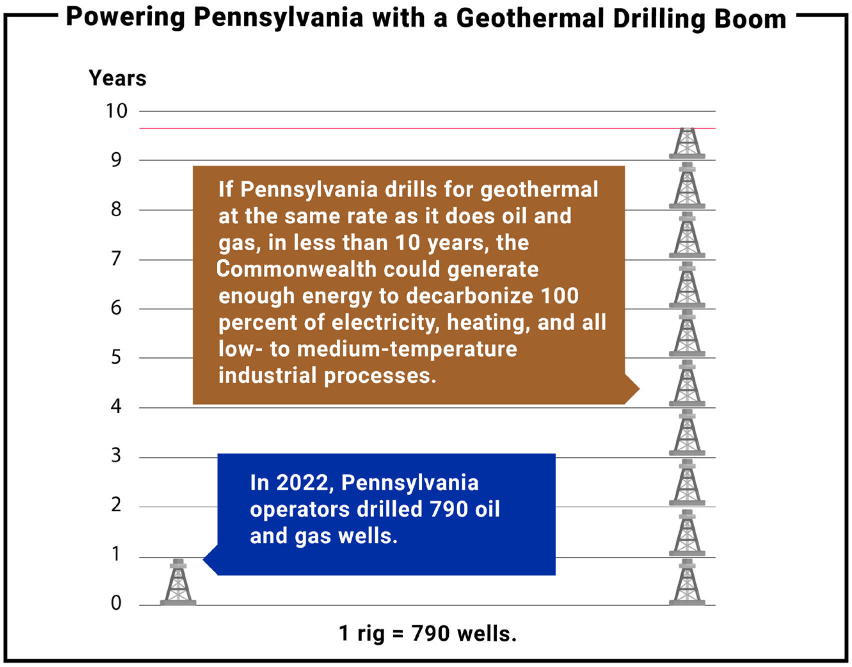


Figure ES.1: The potential for geothermal energy in Pennsylvania.

significant. Take the current energy industry: using its existing resources and workforce to drill for geothermal at the same rate it currently drills for oil and gas, in one year, the Commonwealth could generate enough geothermal energy to meet all thermal demands for its commercial heating and low-temperature industrial processes. Geothermal could also help some of the region's largest energy users—the industrial and agriculture sectors—reduce emissions while maintaining large numbers of jobs in the drilling sector.

Working with new and emerging technologies, geothermal could generate enough energy to meet 100 percent of Pennsylvania's electricity, and heating, and low- to medium-temperature industrial process needs in as few as 10 years.

What are these new technologies? In Engineered Geothermal Systems, or EGS, engineers create a hydrothermal reservoir far underground by drilling wells into hot rock and connecting the wells via hydraulic fracturing. Then, to gather the heat, fluid is circulated through the fractured rock and brought back to the surface. For Advanced Geothermal Systems (AGS), drillers bore lengthy wells deep into hot rock, but instead of using hydraulic fracturing to create a reservoir, fluids are simply circulated within a closed loop of pipes, absorbing the heat and bringing it back to the surface.

Engineers have also developed geothermal direct-use systems to use heat energy just below a source or a region. These include improved Ground Source Heat Pumps (GSHP) to harvest the constant temperature of the shallow subsurface, as well as deeper direct-use wells drilled to reach higher temperatures. In some areas, developers are supplying direct-use geothermal to a large area, clusters of buildings, or a full district from a central location. This is called district heating or a Thermal Energy Network (TEN).

In many cases, the hotter the subsurface rock, the more effective and economical geothermal energy can be. This is especially true if the goal is to produce electricity. But—importantly for Pennsylvania— super hot rocks are not actually necessary to effectively put geothermal to work. Many uses only need high-enough temperatures. In fact, worldwide, temperatures below 150°C are perfectly sufficient for 30 percent of heat for manufacturing processes, and all building heating and cooling. Much of the thermal demand in agriculture also uses lower temperatures, from 0°C to 99°C. (See Figure ES.2.) There is a robust manufacturing sector and agriculture industry in Pennsylvania—and the Commonwealth's subsurface characteristics are especially well-suited to provide them with geothermal energy at the temperatures they need.

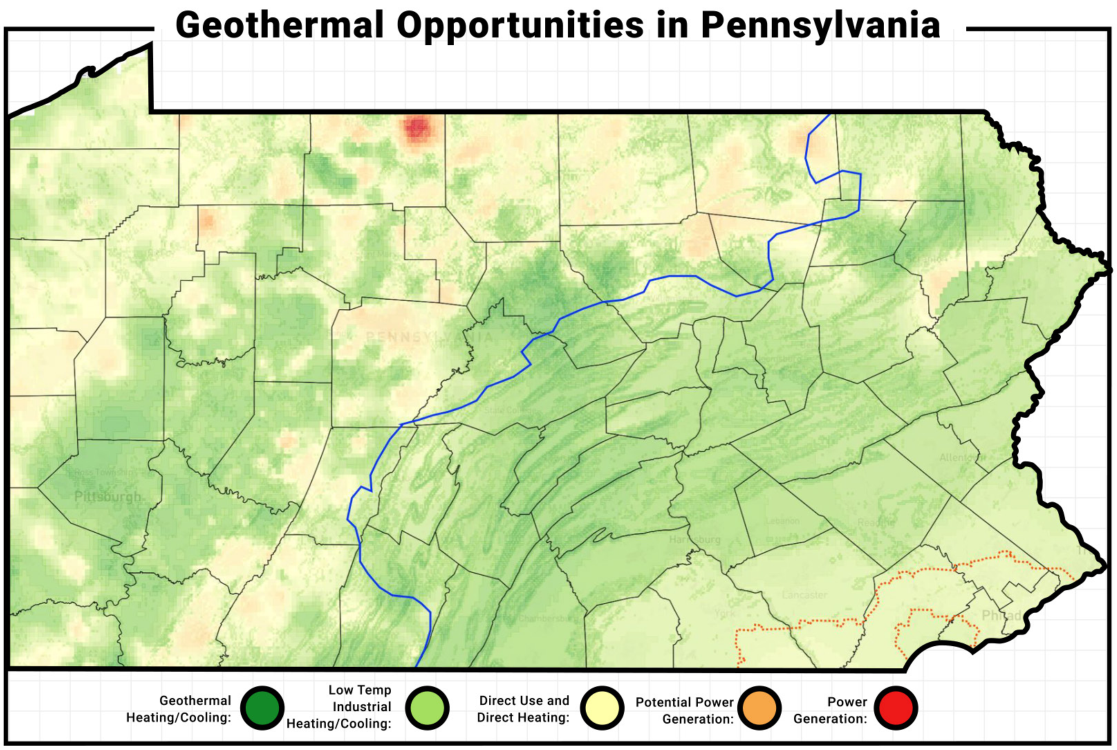


Figure ES.2: Dark green portions of the map are likely limited to using ground-source heat pumps in buildings to provide heating and cooling. Light green and yellow areas are suitable for heat pumps but also present opportunities to use geothermal directly for district heating and to provide heat for industrial processes. Locations in orange and red may be suitable for electricity generation. The area to the right of the blue line shows the parts of the state lacking sufficient direct measurements and requiring the use of geological models to estimate temperatures. Regional geological modeling indicates the areas near Philadelphia within the red dotted line are likely hotter at shallower depths than the surrounding areas, though exploratory wells are needed to verify modeled favorability. Source: GeoMap

Measurements and models of subsurface temperature in Pennsylvania indicate that its agriculture sector is an ideal candidate for geothermal direct-use in places such as York, Lancaster, and Chester counties. (See chapters 2 and 3.) As for manufacturing, the distribution of Pennsylvania's subsurface heat indicates promising opportunities for industrial geothermal direct-use in the petroleum and coal sector in Philadelphia, Delaware, McKean, Butler, and Warren counties, and the pharmaceutical sector in Montgomery County. Add to all of this, there are "hot spots" in the Commonwealth where geothermal technology could cost-competitively generate electricity via EGS or AGS.

Pennsylvania has robust potential for geothermal energy development. Realizing it will require putting the right legal, regulatory, and policy framework into place, building on its already strong foundation.

Legal, Regulatory, and Policy Support

A key question to ask when developing geothermal as an energy source is: Who owns the resources associated with geothermal energy? The heat, the water, the pores in the earth? No Pennsylvania court has addressed all of these questions, but case law and statutes offer guidance; in general, they seem to support the conclusion that heat and pore space are owned by the surface owner of real property, and they can be deeded or conveyed to another user. (See Chapter 4.) This is all good news: Because ownership of resources associated with geothermal energy can be derived from existing Pennsylvania law, geothermal projects in the Commonwealth should be able to move forward without waiting for further clarification or change in state law on the issue of property rights.

Pennsylvania also has existing regulations, programs,

POLICIES TO PROMOTE GEOTHERMAL ENERGY

Provide Industry with Regulatory Certainty and Eliminate Red Tape

- Clarify regulatory authority
- Permitting reform and improved siting
- Define “geothermal resources”
- Hold legislative hearings
- Pursue Class V primacy

Encourage the Adoption of Ground Source Heat Pumps (GSHP) for Building Heating and Cooling

- Amend Act 129 to incentivize GSHPs
- Adopt PUC incentives
- Educate about GSHP tax credits

Create and Expand Targeted Incentives for Direct-Use Geothermal Applications for the Industrial and Agricultural Sectors

- PTC/ITC for clean geothermal heat
- Expand AEIA for industrial process heat
- Fund exploratory geothermal projects
- Ensure incentive effectiveness

Catalyze the Creation of Thermal Energy Networks to Serve Residential, Commercial, Academic, and Public Buildings

- Allow utilities to own and operate TENs
- Create TEN incentives
- Expand TEN ownership pathways

Advance Comprehensive State and Regional Power Market Policies that Promote Clean, Firm, Flexible Power

- Revitalize Pennsylvania’s Renewable Portfolio Standard
- Adopt carbon reduction targets and cap-and-invest
- Capacity market reform to encourage clean baseload
- Incentivize abundant, flexible energy sources

Educate Stakeholders and Create Geothermal Development Strategies

- Pennsylvania “Geothermal Future Plan”
- Incorporate geothermal into state energy planning
- Expand TA programs into geothermal
- Improve online information sources

Figure ES.3

and policies that can support geothermal energy in other ways, including a renewable energy loan program and an Alternative Energy Portfolio Standard. By modifying existing policies and initiatives and adopting a suite of new ones, policymakers could spur much greater geothermal adoption in the Commonwealth and influence the pace and scale of deployment for both mature and next-generation geothermal applications. This report recommends 23 targeted ideas across six areas of focus:

1. Provide industry with regulatory certainty and eliminate red tape;
2. Encourage the adoption of ground source heat pumps for building heating and cooling;
3. Create and expand targeted incentives for direct-use geothermal applications for the industrial and agricultural sectors;
4. Catalyze the creation of thermal energy networks to serve residential, commercial, academic, and public buildings;
5. Advance comprehensive state and regional power market policies that promote clean, firm, flexible power;
6. Educate stakeholders and create geothermal development strategies.

These policies could bring to the Commonwealth a myriad of economic, workforce, energy security, and environmental benefits.

Environmental Impacts and Stakeholder Engagement

Geothermal energy development is likely to lead to better environmental outcomes across multiple measures than other forms of both conventional and renewable energy. The types of geothermal likely to be deployed in Pennsylvania could decrease pressure on land use and wildlife habitats, reduce air pollution, and lower emissions while providing jobs for oil field services professionals. Geothermal adoption could further reduce land-use impacts by repurposing the Commonwealth's many abandoned oil and gas wells to tap into geothermal energy. In other words, upcycling sites that have already been disturbed.

Like all energy sources, geothermal development can also come with local environmental impacts that require careful management. Well drilling for geothermal resources largely involves the same techniques used in the oil and gas industry, and so presents some similar issues, including wastewater management,

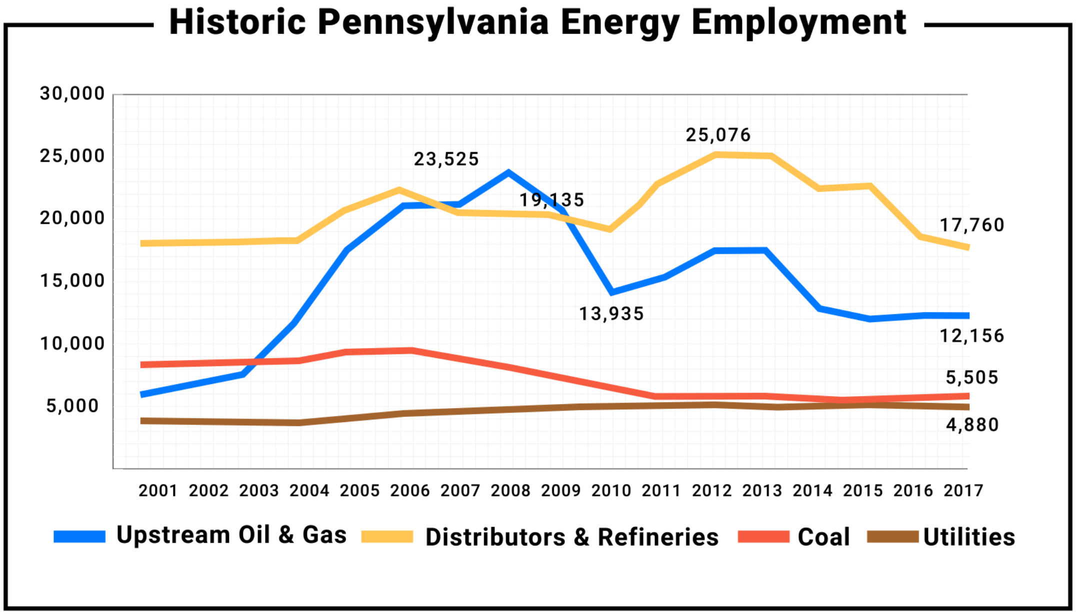


Figure ES.3: Number of workers; excludes transportation fuel retailing. Source: Bureau of Labor Statistics (BLS), Quarterly Census of Employment and Wages water use, traffic, and noise. These issues are all quite manageable, but they will require careful oversight and mitigation during geothermal project assessment and development in Pennsylvania.

To ensure effective deployment, developers should engage with a range of stakeholders affected by and central to geothermal energy development in the Commonwealth. Private landowners may stand to gain the most from geothermal development, and arrangements for royalties will be a principal element of obtaining their participation and support. As well, talking to communities that may be impacted by geothermal development in the commonwealth will be necessary to address concerns and bolster public support. Engaging with natural gas and electricity providers and distributors will also be key to help ensure there is interest and infrastructure to support using geothermal energy for local heating, cooling, and power.

There are also myriad groups—including labor unions and environmental groups—who could benefit from and help advocate for geothermal in Pennsylvania. For example, there are nearly 40,000 Pennsylvania workers directly involved in drilling, producing, refining, and transporting oil, gas, and coal, who could immediately benefit from jobs created by the development of next-generation geothermal. Geologists, drillers, engineers, and landmen can develop next-generation geothermal wells with minimal retraining. Utility workers and pipefitters can install and repair thermal energy networks in the same rights-of-way, and with similar tools and techniques, as those used for natural gas. Process engineers can design, develop, and maintain direct-use systems.

With robust engagement with these and other stakeholders, a range of Pennsylvanians will reap the benefits of and be key players in promoting geothermal energy development in the Commonwealth.

Conclusion

As the demand for energy grows over the coming years, ground-source heat pumps and next-generation geothermal are poised to become key sources of abundant energy. The Commonwealth is well-suited to be at the forefront of the emerging geothermal boom. Building on its history as an energy pioneer and an energy-producing powerhouse, with thoughtful approaches and the right policies and incentives for this burgeoning ecosystem, Pennsylvania can help write the next chapter for American subsurface energy while bringing new jobs to its energy sector and economic and environmental benefits to every corner of the Commonwealth.

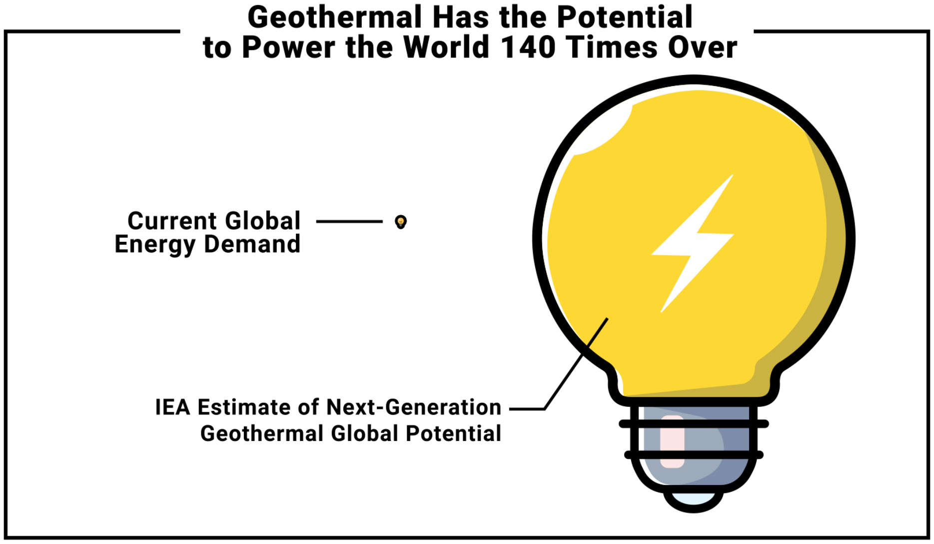


Figure ES.5: Information from IEA's Future of Geothermal Report which uses data produced by Project InnerSpace to develop global estimates for next-generation geothermal energy. https://www.iea.org/reports/the-future-of-geothermal-energy/executive-summary.

Part I

Geothermal Basics

Chapter 1

An Introduction to Next-Generation Geothermal

Reporting Division, Project InnerSpace

> ***Geothermal energy is an abundant, reliable resource for electricity, heating, and cooling. New technologies like Engineered and Advanced Geothermal Systems expand its use beyond traditional geographic limits. By leveraging expertise from the oil and gas industry, geothermal is becoming increasingly scalable and sustainable, with a small environmental footprint, high capacity factors, and significant potential to complement other renewable energy sources.***

OVERVIEW

Geothermal is a naturally occurring, ubiquitous, and abundant energy source emanating from the core of the Earth. At about 4,000 miles from the planet's crust, that center is roughly as hot as the surface of the sun, over 10,800°F (see Figure 1.1). Geothermal heat is present across the entire planet, both on dry land and on the ocean floor, with enough potential energy to power the whole world thousands of times over.

Geothermal energy works by extracting heat via hot fluids naturally present in the subsurface, or by introducing fluid and circulating it through hot rock. Geothermal resources have been exploited for centuries for things like cooking, bathing, and washing. Its use expanded in the 19th century to include industrial processes, the heating and cooling of buildings, and electricity generation.

(While the term "geothermal" is often casually used to refer to both subsurface natural resources—hot rock, steam, fluids—and the means and methods used to *extract* and *exploit* geothermal energy, this report uses more explicit terminology to draw distinctions between the two.)

APPLICATIONS FOR GEOTHERMAL ENERGY

Today, the opportunities to use geothermal energy—an always-on resource—have expanded. In addition to electricity generation, heating and cooling of homes and buildings, and industrial process heat, there are new and emerging applications. For instance, a geothermal energy system can act as an earthen battery, and the production process can help extract critical minerals, such as lithium.

Geothermal Electricity Generation

Geothermal has been used to generate electricity for more than a century, with the first documented instance in Lardarello, Italy, in 1904.[1] Today geothermal provides only 0.5% of global electricity,[2] although adoption is much higher in (primarily) volcanic regions where geothermal resources—called Conventional Hydrothermal Systems—are uniquely close to the surface. For example, Conventional Hydrothermal Systems account for 46 percent of electricity in Kenya, 33 percent in Nicaragua, and 30 percent in Iceland.[3]

Now new technologies are enabling orders of magnitude more geothermal electricity generation all over the world (see "The Evolution of Geothermal," later in this chapter). Next-generation geothermal technologies allow us to engineer underground conditions and manufacture the unique features that naturally exist in hydrothermal geothermal systems. The engineering of these systems can take many forms, such as deeper drilling, using techniques that create additional pore space for fluid flow, or introducing fluids into subsurface areas where they may not naturally be present.

A report published in December 2024 by the International Energy Agency (IEA) shows that "the potential for geothermal is now truly global" and that next-generation geothermal systems have technical potential "to meet global electricity demand 140-times over." The IEA analysis also found that by 2035, geothermal could be highly competitive with solar photovoltaic and wind paired with battery storage.

Generally, the hotter the geothermal resource, the more efficient a geothermal power plant will be at producing

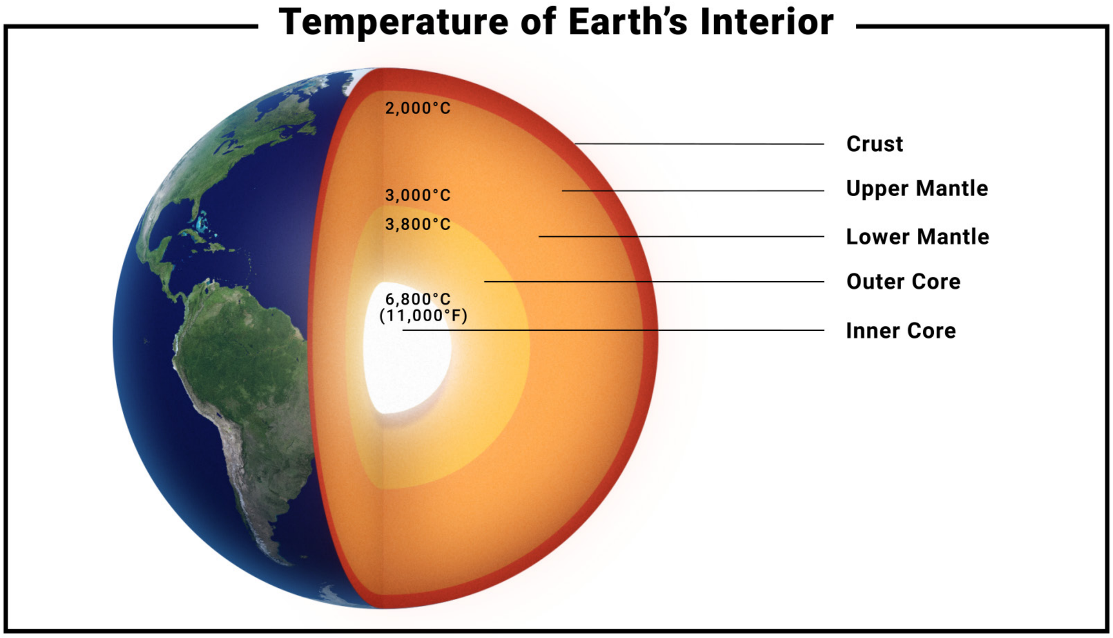


Figure 1.1 The core of the earth exceeds the temperature of the surface of the sun. Because the crust of Earth is an excellent insulator, enough heat is trapped beneath us to power the world hundreds of times over.

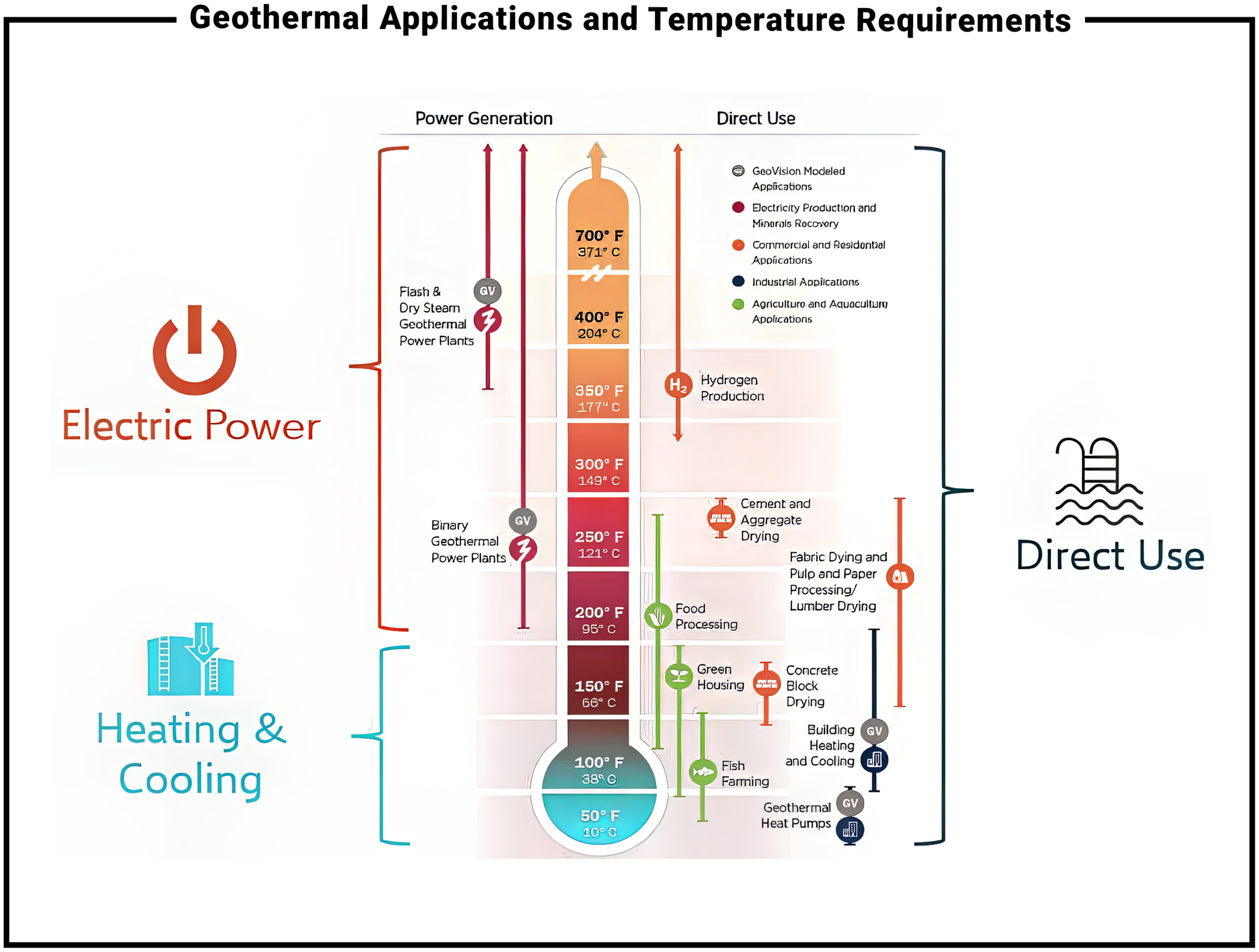


Figure 1.2: Source: *Porse, S. (2021, August 2-6). Geothermal Energy Overview and Opportunities for Collaboration [Conference presentation]. Energy Exchange, Georgia World Congress Center, Atlanta, GA, United States.*

electricity. The more efficient, the lower the cost of producing the energy. As shown in Figure 1.2, geothermal electricity generation is possible with fluid temperatures as low as 200°F (approximately 95°C) using "binary" cycle power plants (in other words, two fluid cycles). However, these lower-temperature power plants are thermally inefficient, with much of the potential energy lost in the process of converting heated fluid into electricity and from the "parasitic load" (the energy required to operate the system).[4] Flash and dry steam electric turbines (see Figure 1.3) can be used when fluid temperature rises above 350°F (approximately 180°C).[5] Some higher temperature installations have started utilizing novel binary-type configurations.

Direct Heat Use: Geothermal Heating, Cooling, and Industrial Process Heat

Globally, heat energy makes up about half of all energy consumption and contributes to about 40 percent of energy-related emissions.[6] This is a significant enough point to frame another way: abundant geothermal can address almost half of the world's energy demand. Until recently, this has been an almost entirely overlooked opportunity.

Approximately three-quarters of all heat used by humans, from building heating and cooling to industrial processes, is produced by directly burning oil, gas, and coal.[7] The rest is produced from other sources, like burning biomass, or via the electrification of heat—meaning electricity produced using solar, wind, or other fuels, and then converted back into heat. (Think of, say, electric strip heaters.)

Geothermal Heating and Cooling for the Built Environment

Heating and cooling buildings represents about half of all energy consumption in the U.S. residential[8] and commercial[9] sectors. That figure is higher in the residential sector in Europe.[10] Established geothermal technologies already exist that can help meet this demand: Ground-Source Heat Pumps (GSHPs or Geothermal Heat Pumps) and Geothermal District Heating.

Most buildings are typically kept at temperatures between 68 and 73°F, requiring heat in colder weather and cooling in warmer weather. While the outside air may climb to higher than 100°F in the summer or plummet to lower than 30°F in the winter, the shallow ground remains at a relatively constant 55°F (13°C) year-round.[11] GSHPs function by taking advantage of the temperature difference between the desired indoor temperature and that constant temperature of the earth, redistributing the thermal energy to cool buildings in the summer and heat in the winter. (See Figure 1.4.) An analysis by Oak Ridge National Lab in 2024 found that widespread installation of GSHPs could save as as much as 593 terrawatt hours of generation annually (about 15% of total US generation).

Going bigger, there's Geothermal District Heating, which can be developed to address heating and cooling via community-scale networks—much like water, natural gas, and electricity utilities. Geothermal District Heating Systems, sometimes referred to as thermal energy networks (TENs) or GeoExchange systems, provide groups of interconnected buildings with some of the most energy-efficient heating and cooling available today.[12] (See Figure 1.5.)

This can be done using a few deep wells that tap into hotter subsurface rock, or with dozens of shallower, cooler wells (drilled 10-500 feet deep) that are paired with industrial-scale GSHPs. Swarthmore College recently installed such a system throughout its campus.[13]

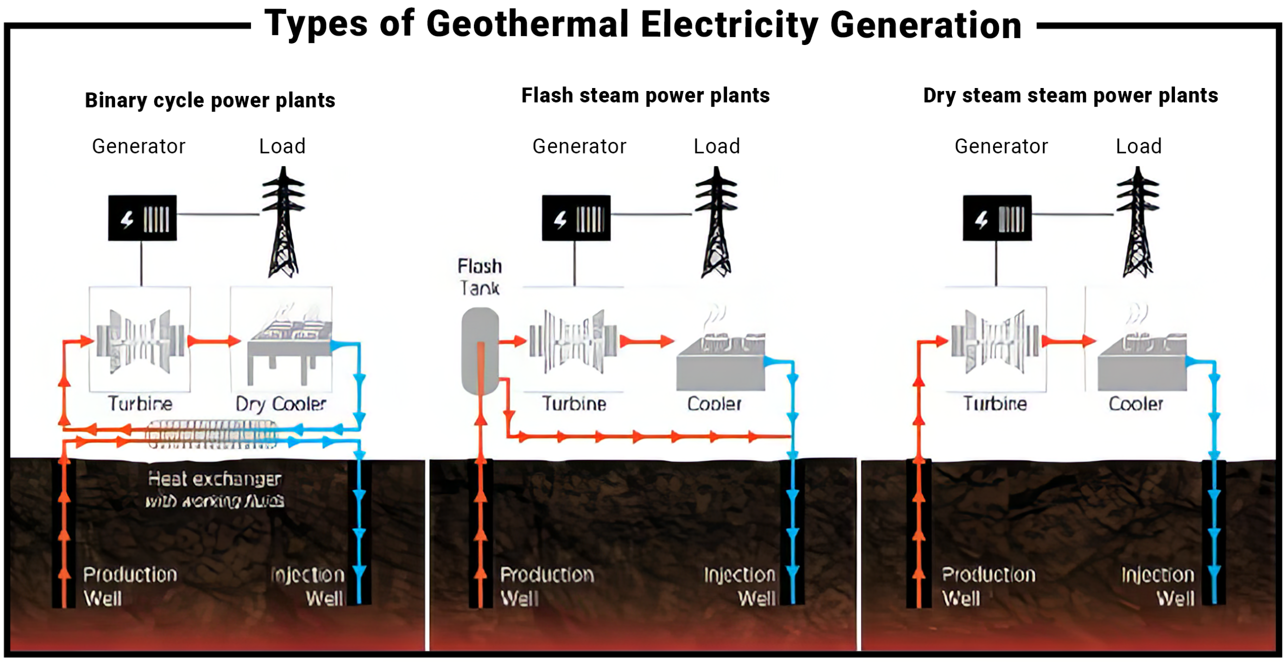
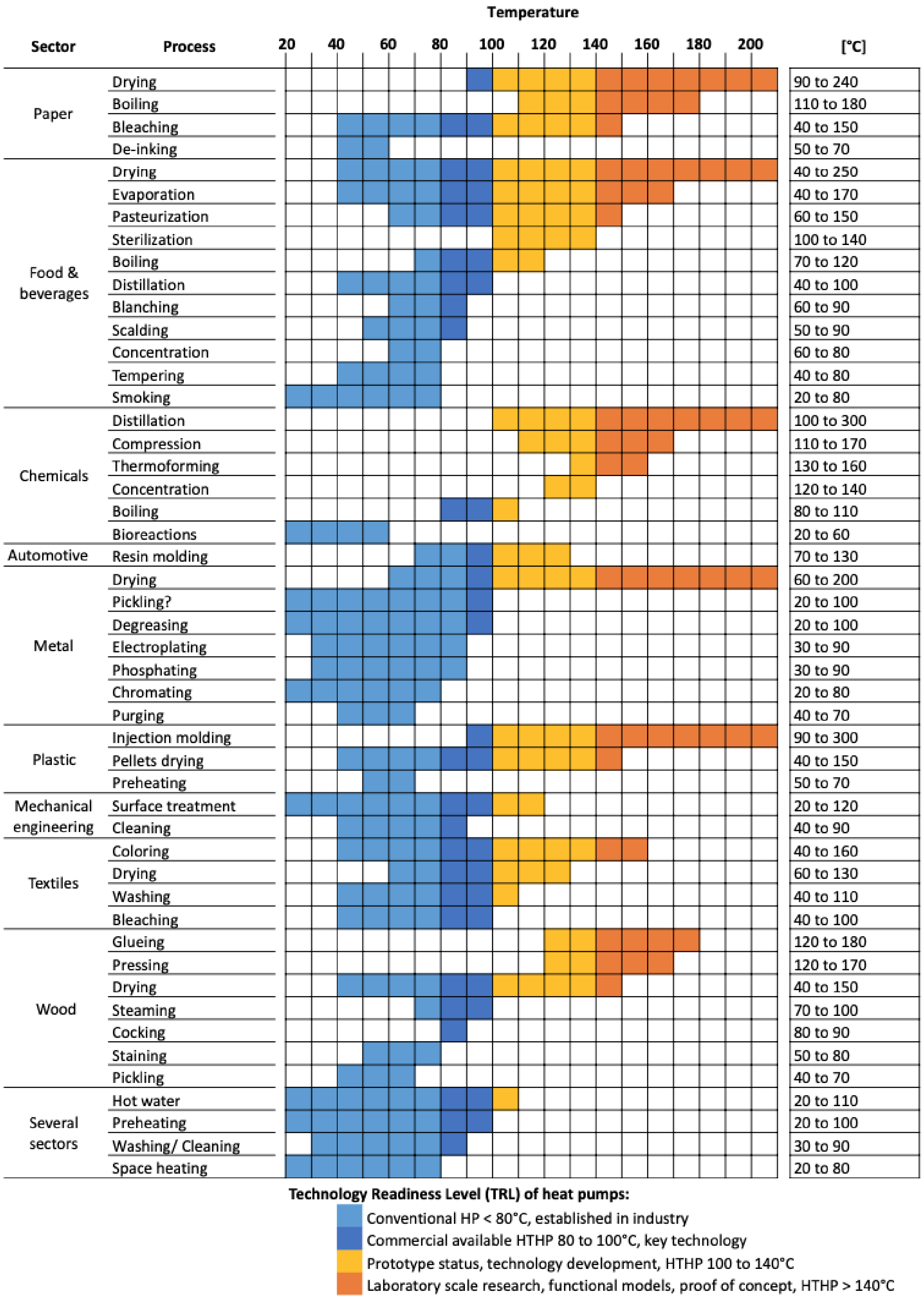


Figure 1.3: Source: Adapted from *U.S. Department of Energy (2019).* Geovision: Harnessing the Heat Beneath Our Feet. https://www.energy.gov/eere/geothermal/geovision

Industrial Process Temperatures and Heat Pump Technologies



Temperature

Sector	Process	20		40		60		80		100		120		140		160		180		200	[°C]
Paper	Drying								■	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	90 to 240
	Boiling										🟨	🟨	🟨	🟧	🟧	🟧	🟧				110 to 180
	Bleaching			🟦	🟦	🟦	🟦	■	■	🟨	🟨	🟨	🟨	🟧							40 to 150
	De-inking			🟦	🟦																50 to 70
Food & beverages	Drying			🟦	🟦	🟦	🟦	■	■	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	40 to 250
	Evaporation			🟦	🟦	🟦	🟦	■	■	🟨	🟨	🟨	🟨	🟧	🟧	🟧					40 to 170
	Pasteurization					🟦	🟦	■	■	🟨	🟨	🟨	🟨	🟧							60 to 150
	Sterilization									🟨	🟨	🟨	🟨								100 to 140
	Boiling						🟦	■	■	🟨	🟨										70 to 120
	Distillation			🟦	🟦	🟦	🟦	■	■												40 to 100
	Blanching					🟦	🟦	■													60 to 90
	Scalding				🟦	🟦	🟦	■													50 to 90
	Concentration					🟦	🟦														60 to 80
	Tempering			🟦	🟦	🟦	🟦														40 to 80
	Smoking	🟦	🟦	🟦	🟦	🟦	🟦														20 to 80
Chemicals	Distillation									🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	100 to 300
	Compression										🟨	🟨	🟨	🟧	🟧	🟧					110 to 170
	Thermoforming												🟨	🟧	🟧						130 to 160
	Concentration											🟨	🟨								120 to 140
	Boiling							■	■	🟨											80 to 110
	Bioreactions	🟦	🟦	🟦	🟦																20 to 60
Automotive	Resin molding						🟦	🟦	■	🟨	🟨	🟨									70 to 130
Metal	Drying					🟦	🟦	🟦	■	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	60 to 200
	Pickling?	🟦	🟦	🟦	🟦	🟦	🟦	🟦	■												20 to 100
	Degreasing	🟦	🟦	🟦	🟦	🟦	🟦	🟦	■												20 to 100
	Electroplating		🟦	🟦	🟦	🟦	🟦	🟦													30 to 90
	Phosphating		🟦	🟦	🟦	🟦	🟦	🟦													30 to 90
	Chromating	🟦	🟦	🟦	🟦	🟦	🟦														20 to 80
	Purging			🟦	🟦	🟦															40 to 70
Plastic	Injection molding								■	🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟧	🟧	90 to 300
	Pellets drying			🟦	🟦	🟦	🟦	■	■	🟨	🟨	🟨	🟨	🟧							40 to 150
	Preheating				🟦	🟦															50 to 70
Mechanical engineering	Surface treatment	🟦	🟦	🟦	🟦	🟦	🟦	■	■	🟨	🟨										20 to 120
	Cleaning			🟦	🟦	🟦	🟦	■													40 to 90
Textiles	Coloring			🟦	🟦	🟦	🟦	■	■	🟨	🟨	🟨	🟨	🟧	🟧						40 to 160
	Drying					🟦	🟦	■	■	🟨	🟨	🟨									60 to 130
	Washing			🟦	🟦	🟦	🟦	■	■	🟨											40 to 110
	Bleaching			🟦	🟦	🟦	🟦	■	■												40 to 100
Wood	Glueing											🟨	🟨	🟧	🟧	🟧	🟧				120 to 180
	Pressing											🟨	🟨	🟧	🟧	🟧					120 to 170
	Drying			🟦	🟦	🟦	🟦	■	■	🟨	🟨	🟨	🟨	🟧							40 to 150
	Steaming						🟦	■	■												70 to 100
	Cocking							■													80 to 90
	Staining				🟦	🟦	🟦														50 to 80
	Pickling			🟦	🟦	🟦															40 to 70
Several sectors	Hot water	🟦	🟦	🟦	🟦	🟦	🟦	■	■	🟨											20 to 110
	Preheating	🟦	🟦	🟦	🟦	🟦	🟦	■	■												20 to 100
	Washing/ Cleaning		🟦	🟦	🟦	🟦	🟦	■													30 to 90
	Space heating	🟦	🟦	🟦	🟦	🟦	🟦														20 to 80

Technology Readiness Level (TRL) of heat pumps:

🟦 Conventional HP < 80°C, established in industry
■ Commercial available HTHP 80 to 100°C, key technology
🟨 Prototype status, technology development, HTHP 100 to 140°C
🟧 Laboratory scale research, functional models, proof of concept, HTHP > 140°C

Table 1.1: Image shows technology readiness levels as of 2018. All heat pump technologies, especially high temperature industrial heat pumps above 100°C, have seen efficiency improvements in the intervening years. Source: Adapted from Arpagaus, C., Bless, F., Uhlmann, M., Schiffmann, J., & Bertsch, S. S. (2018). High-temperature heat pumps: Market overview, state of the art, research status, refrigerants, and application potentials. Energy, 152, 985-1010.

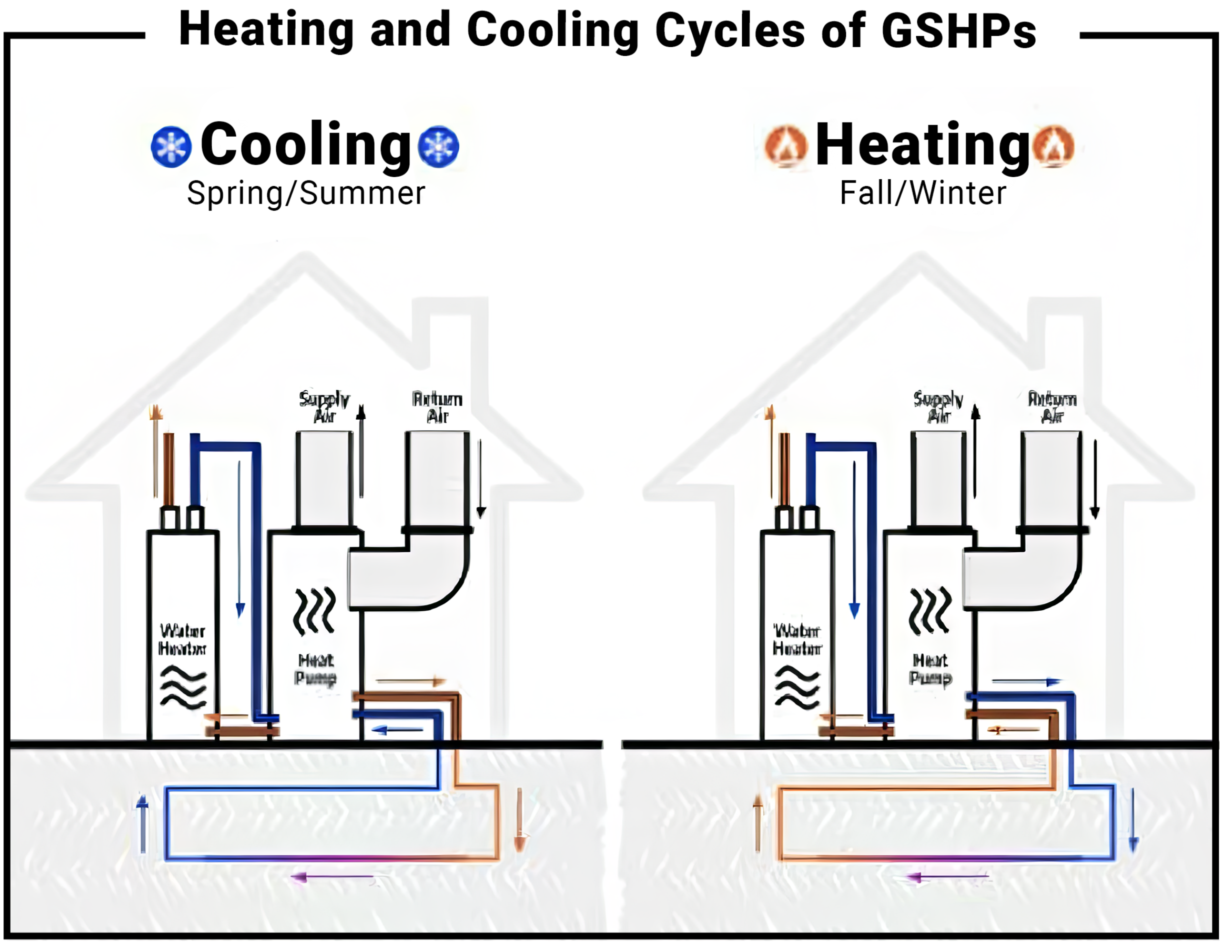


Figure 1.4: Source: Beard, J. C., & Jones, B. A. (Eds.). (2023). The future of geothermal in Texas: The coming century of growth and prosperity in the Lone Star State. Energy Institute, University of Texas at Austin. https://doi.org/10.26153/tsw/44084. Adapted from U.S. Department of Energy - DOE. (2019). GeoVision: https://www.energy.gov/eere/geothermal/geovision

Industrial Process Heat

Heat is used to make everything from pens to paper, pasteurized milk to pharmaceuticals. Four of the most critical materials in the modern world—fertilizer, cement, steel, and plastics—all require significant amounts of heat to produce. In the industrial sector, thermal consumes over half of total energy use and contributes the majority of the sector's emissions.[14]

All building heating and cooling (HVAC) and 30 percent of heat used for manufacturing processes worldwide use temperatures below 300°F (150°C).[15] In many parts of the world, geothermally derived heat at this temperature is cost competitive currently with coal, biomass, and solar/wind. Getting a little warmer, the IEA report mentioned earlier also estimates that next-generation geothermal could economically satisfy 35 percent of all global industrial thermal demand for processes requiring temperatures below 390°F (~200°C). This could save about 750 megatons (Mt) of CO_2 emissions (equivalent to the annual emissions of Canada, the world's 12th largest emitter).

Geothermal Energy Storage

The modern electricity grid is a delicate, vital system that requires constant monitoring to balance electricity production against electricity demands. With more electrons flowing onto the grid from intermittent energy sources like wind and solar—which are only available

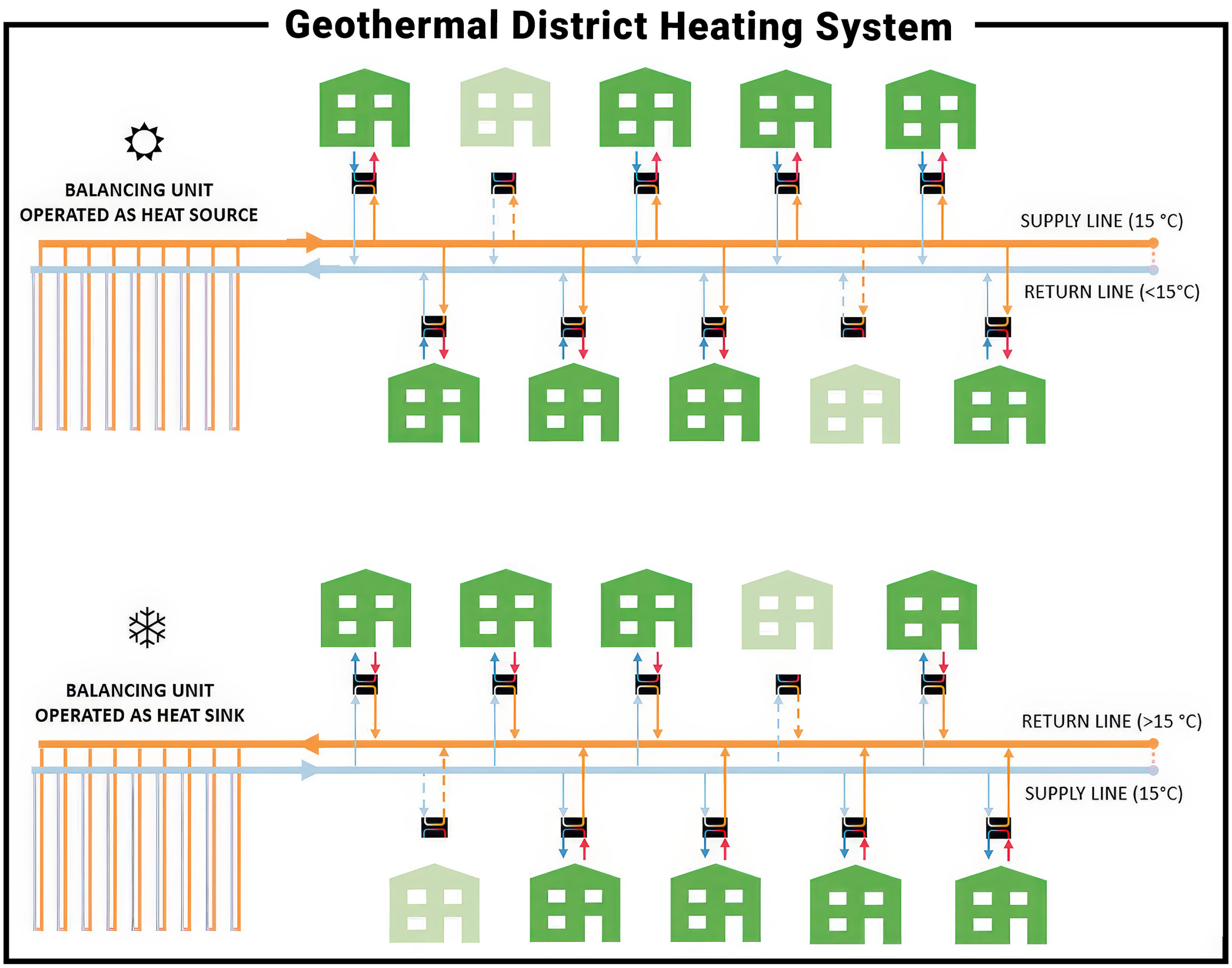


Figure 1.5: García-Céspedes, J.; Herms, I.; Arnó, G.; de Felipe, J.J. Fifth Generation District Heating and Cooling Networks Based on Shallow Geothermal Energy: A review and Possible Solutions for Mediterranean Europe. Energies 2023, 16, 147. https://doi.org/10.3390/en16010147

when the sun shines or the wind blows—concerns about having power when power is needed have brought the need for storage to the forefront.[16] Today, hydroelectric storage provides most global energy storage capacity,[17] and recent years have seen a significant expansion in the deployment of batteries for energy storage. A new approach, called Underground Thermal Energy Storage (UTES), also known as Geothermal Energy Storage (GES), may offer an additional option.

GES systems capture and store waste heat or excess electricity by pumping fluids into natural and/or artificial subsurface storage spaces, from aquifers to boreholes to mines. GES can be primarily mechanical—with hydraulic fracturing techniques storing pressurized fluid in subsurface reservoirs—or mechanical and thermal, with both pressure and heat combined to return more energy than was required to pump the fluid underground.

Critical Minerals Extraction

Fluids, also called brines, are often produced from geothermal systems. These brines are rich in dissolved minerals, including lithium, which can be harvested to meet the growing demand for lithium-ion batteries in electric vehicles and electric-grid storage solutions. This dual-purpose approach—providing abundant energy and a domestic lithium source—could lower lithium extraction's environmental impact compared to traditional mining. At one of the nation's Conventional

Hydrothermal Geothermal sites in Southern California's Salton Sea, the brines are highly saline with high concentrations of minerals. Historically, salt and minerals were purely a nuisance, and significant work was required to keep pipes from scaling or developing mineral deposits that restrict fluid flow. Today, Direct Lithium Extraction (DLE) offers the possibility that these critical minerals can instead be extracted and sold, providing power plant operators with an additional revenue stream. The California legislature estimated the Salton Sea contains enough battery-grade lithium to "satisfy more than one-third of the worldwide demand."[18]

BENEFITS OF GEOTHERMAL

In addition to the variety of applications, geothermal has considerable advantages over other renewables. First, it is a 24-7-365, nearly always on source, unlike other renewables. As depicted in Figure 1.6, geothermal enjoys capacity factors far above intermittent wind and solar, as high as 90 percent.[19] As shown in Figure 1.7, on a per gigawatt basis, geothermal energy also has lower land use requirements than coal and virtually all other clean energy sources (only 15 percent the footprint of solar), allowing for the conservation of natural landscapes and animal habitats.

Compared to coal-fired power plants of similar size, geothermal power plants can reduce the release of acid-rain-causing sulfur compounds by up to 97 percent and carbon dioxide by up to 99 percent.[20] On a per kilowatt basis, geothermal has the same lifecycle greenhouse gas emissions as solar photovoltaic.[21]

Additionally, the well-developed supply chain and skilled workforce of the oil and gas industry means next-generation geothermal already has the resources necessary to enable a "green drilling" geothermal revolution. Because Next-Generation Geothermal relies on technology developed by oil and gas during the shale revolution, the industry can directly transfer its exploration, drilling, and engineering skills to this renewable resource.

Taken all together—significantly higher capacity factor, minuscule footprint, low emissions, an existing skilled workforce—the benefits of geothermal stack up.

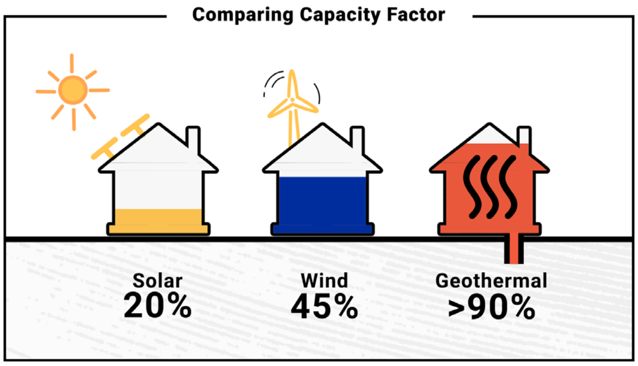


Figure 1.6: Capacity factor is the percentage of time that a plant is generating electricity. Source: Adapted from EIA, 2014.

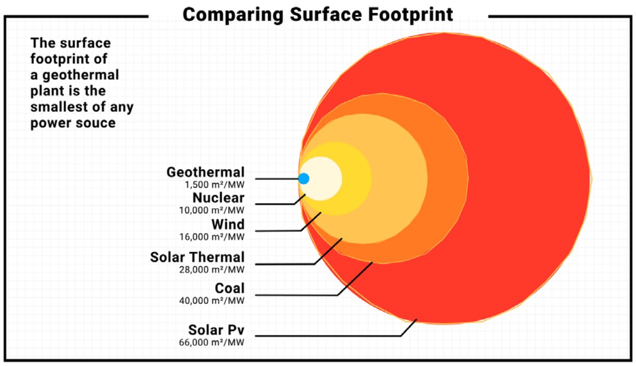


Figure 1.7: The project surface footprint, acre for acre for one gigawatt of generating capacity, is smallest with geothermal compared to other clean sources and coal. Source: Adapted from Lovering et al., 2022 and NREL.

THE EVOLUTION OF GEOTHERMAL: FROM CONSTRAINTS TO POSSIBILITIES

Historically, geothermal energy use relied on Conventional Hydrothermal Systems. As mentioned, these are geographically limited. They require specific subsurface conditions—sufficient heat, water, and rock permeability— typically found in tectonically active regions such as Iceland and the western United States.[22] Only when all three of these factors overlapped was there an exploitable geothermal resource. Even then, finding such a resource typically required a fourth natural phenomenon: an obvious surface manifestation

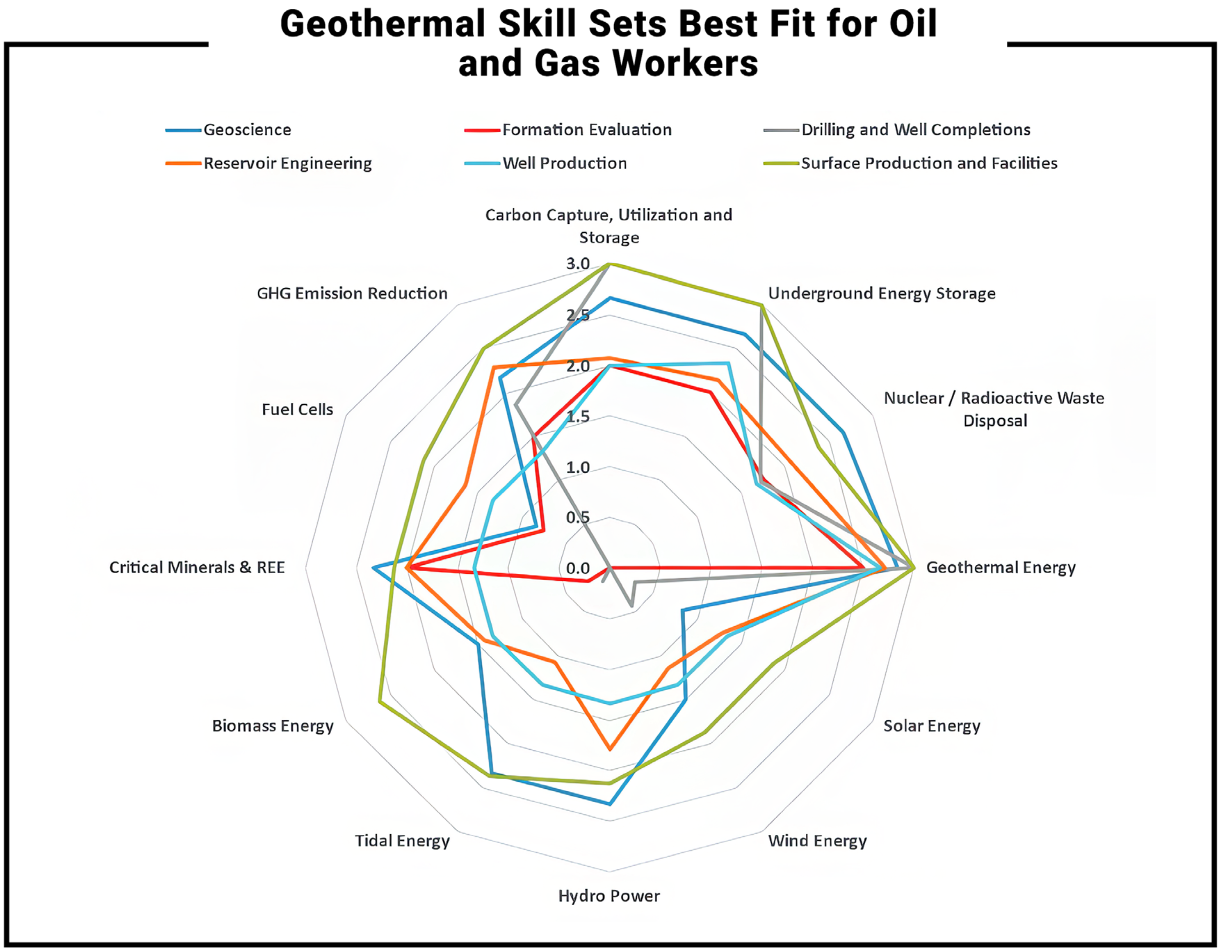


Figure 1.8: As shown, geothermal ranks highest when considering the potential impact of transferring oil and gas skills into other energy transition and low-carbon technologies. Source: Tayyib, D., Ekeoma, P. I., Offor, C. P., Adetula, O., Okoroafor, J., Egbe, T. I., and E. R. Okoroafor. "Oil and Gas Skills for Low-Carbon Energy Technologies." Paper presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, October 2023. doi: https://doi.org/10.2118/214815-MS

like a geyser or hot spring.[23] This has severely restricted geothermal's broader global use, as few locations meet these natural requirements.

But next-generation technologies, such as Engineered Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS), are advancing the future of geothermal energy beyond such geographical limitations. These systems bypass the need for natural permeability by engineering reservoirs or utilizing closed-loop methods. Using technologies pioneered and commercialized by the oil and gas industry during the shale revolution—horizontal directional drilling and hydraulic fracturing—next-generation geothermal developers can mine the near-limitless subsurface heat virtually anywhere they can reach it economically. These approaches make geothermal globally scalable and viable in a wide range of locations, leading the IEA to declare, "The potential for geothermal is now truly global."

As shown in Figure 1.9, there is more potential thermal energy in the Earth's crust than in all fossil fuels and natural nuclear fissile material combined. The challenge, then, becomes identifying the areas and technologies that can, most efficiently and economically, tap into that potential energy.

Figure 1.10 summarizes the latest geothermal extraction technologies. The sections below describe those technologies in greater detail. (Also see Table 1.1.)

Engineered Geothermal Systems (EGS)

This kind of system uses both horizontal drilling and hydraulic fracturing to create artificial permeability, allowing for the use of geothermal energy far beyond the regions with naturally occurring hydrothermal. EGS extracts heat by introducing fluids into the subsurface, breaking open fissures in relatively impermeable rock, and circulating fluid between one or more wells. The more fractures, the greater the surface area for the flowing fluid to conduct heat from rock.

While conceived as early as the 1970s,[24] the scalability of EGS has only been made possible because of cost reductions and technological advances in drilling and fracturing techniques commercialized by the oil and gas industry over the past few decades.

However, unlike hydraulically fractured oil and gas wells—which are only intended for one-way extraction of oil and gas—EGS systems are designed to reuse fluids, continuously flowing the same liquid through hot rock in a convective loop.

EGS generally targets shallow hot rock formations with few natural fractures and limited natural permeability in order to minimize uncontrolled fluid loss. Well depths can vary depending on where sufficient temperature and appropriate stress conditions are found.[25]

Fracturing methods are subject to some uncertainty; even the most accurate engineering model cannot perfectly predict how a subsurface rock will crack or how fluids will flow. Nonetheless, as of this writing, EGS is seeing rapid technological advances, including at the U.S. Department of Energy's Frontier Observatory for Research in Geothermal Energy (FORGE) and from EGS startups such as Houston, Texas-based Fervo, and its Project Red demonstration. Along with advances in tech, EGS is also scaling to industrial-size projects. Fervo recently secured a 400 MW Power Purchase Agreement (PPA) to construct a first-of-a-kind EGS power plant in Utah targeting approximately 350ºF (175ºC) hot rock.[26]

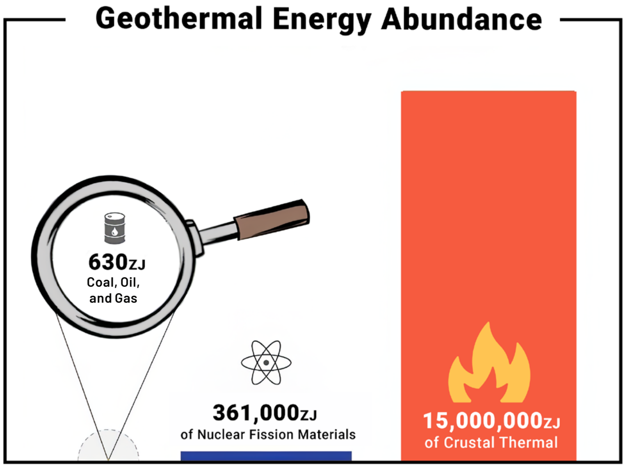


Figure 1.9: Comparison of total heat energy in Earth's crust, compared to fissionable materials and fossil fuels. Note that total fossil fuels, when compared with crustal thermal energy, is the equivalent of less than one pixel at the bottom of the graphic, shown magnified to illustrate scale. Measurements in zettajoules ("zj"). Source: Beard, J. C. and Jones, B. A. (Eds.). (2023). The future of geothermal in Texas: The coming century of growth and prosperity in the Lone Star State. Energy Institute, University of Texas at Austin. https://doi.org/10.26153/tsw/44084. Adapted from Dourado, 2021.

Advanced Geothermal Systems (AGS) or Closed-Loop

Like EGS, AGS eliminates the need for permeable subsurface rock. Instead, AGS creates and uses sealed networks of pipes and wellbores closed off from the subsurface, with fluids circulating entirely within the system in a closed loop.

Today, many closed-loop geothermal well designs are in development, including single well, U-shaped well "doublets" with injection and production wells, and subsurface radiator designs. All of them use only their own drilled pathways; none require a conventional hydrothermal resource or hydraulic fracturing to create fluid pathways.

All geothermal energy extraction relies on conduction, the heat transfer from hot rock to fluid (see "Geothermal Geology and Heat Flow" box for more). Thus, unlike EGS, which benefits from the substantial surface area created by hydraulic fracturing, closed-loop systems have only the walls of their wells to conduct heat. As such, closed-loop systems must drill deeper, hotter, or longer well systems than EGS, to conduct similar amounts of heat energy. Because closed-loop systems do not exchange fluids with the subsurface, they can more easily use engineered, non-water working fluids, such as supercritical carbon dioxide (sCO_2).

AGS can be developed in virtually any geological condition with sufficient subsurface heat. While AGS guarantees a more definitive pathway for fluid flow in the subsurface relative to fracked EGS wells, drilling sufficiently long and deep AGS wells can be challenging and expensive.

Super Hot Rock (SHR)

SHR is a type of next-generation geothermal targeting extremely deep, high-pressure rocks above approximately 703°F (373°C), the temperature at which water goes supercritical. SHR has the potential to revolutionize power production globally with superheated, supercritical geothermal steam capable of highly efficient heat transfer from the subsurface. Theoretically, SHR can employ either EGS or AGS well technologies, but no commercial SHR geothermal project has yet been developed because advances are needed in drilling technologies, rates, and costs to enable the economically competitive development of this next-generation concept.[27]

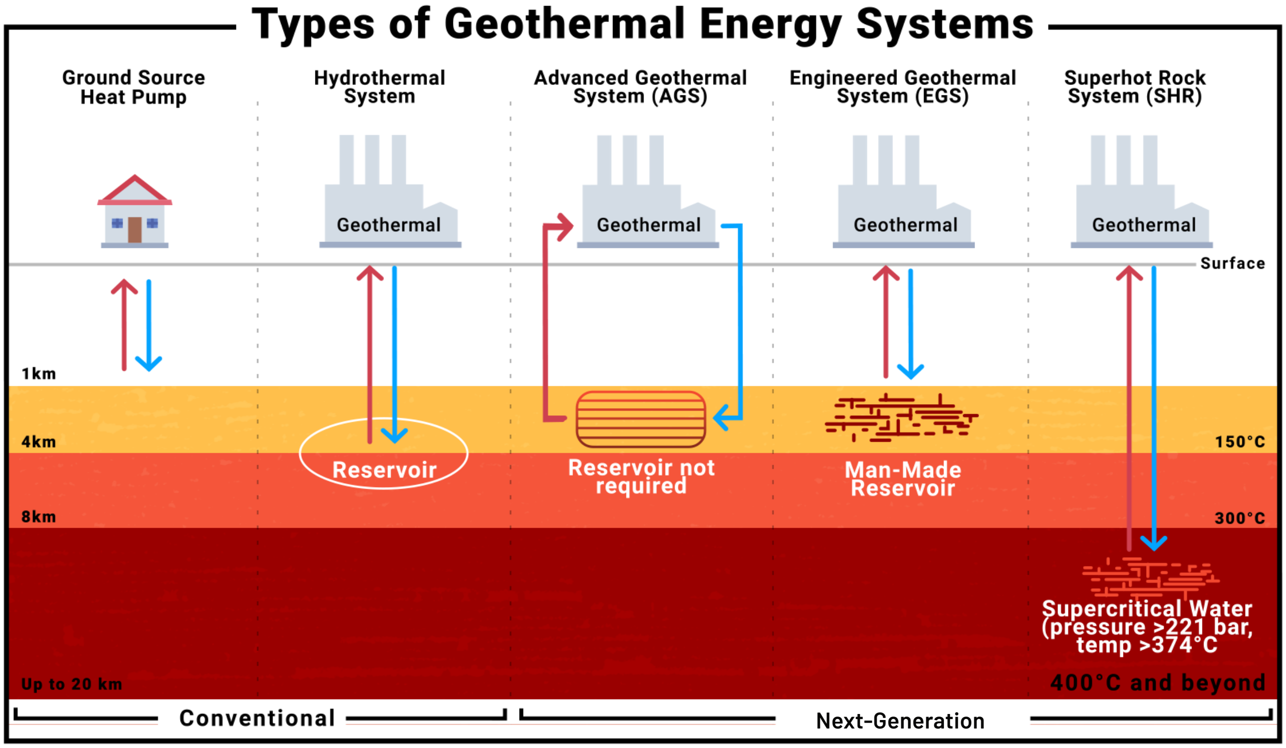


Figure 1.10: Except for Ground Source Heat Pump, images depict geothermal electricity generation. GSHP shows building heating; the arrows would reverse for building cooling. Source: Adapted from S&P Global Commodity Insights. (2024) Next-generation technologies set the scene for accelerated geothermal growth. https://www.spglobal.com/commodity-insights/en/news-research/latest-news/energy-transition/011124-infographic-next-generation-technologies-set-the-scene-for-accelerated-geothermal-growth-energy-transition

GEOTHERMAL GEOLOGY AND HEAT FLOW

The movement of heat from Earth's hot interior to the surface—what geologists call "heat flow"—is controlled by the geology of the planet. Heat from the core and mantle, and the decay of naturally occurring radioactive deposits in the Earth's crust, combine and emanate toward the surface of the planet.

Conduction, Advection, Convection, and Radiation

Heat flow in the earth results from physical processes that contribute, to varying degrees, to the available heat in a geothermal resource:

Conduction: The transfer of energy between objects in physical contact through molecular vibrations without the movement of matter. Conduction is efficient in some materials, like metals, and inefficient in others. Rock is a relatively poor conductor, but conduction is nonetheless considerable in the interior of the Earth.

Advection: The transfer of heat is due to the movement of liquids from one location to another. In geology, advection occurs in the movement of magma and groundwater, where the fluid carries heat as it moves through cracks, fractures, and porous rock formations. Advection is different from conductive heat transfer, which relies solely on direct contact between particles to transfer heat.

Convection: A cycle of heat transfer involving conduction and advection that occurs when matter is heated, becomes less dense, rises, cools, increases in density, and sinks. Convection typically creates circulating loops of rising and sinking material. The Earth's mantle is almost entirely solid but behaves as a highly viscous fluid, thus allowing for convective heat transfer. The mantle's movement is extremely slow relative to human life but becomes significant over geologic periods.

Radiation: Energy that moves from one place to another as waves or particles. Certain areas in the Earth's crust have higher concentrations of elements with natural radiation, like uranium-238, uranium-235, thorium-232, and potassium-40.

Geology and Energy Extraction

The geological processes listed above interact to contribute to geothermal energy extraction under three common geological settings:

Convection-dominated:

Geologically Open Geothermal Systems: In these, water circulates freely (e.g., the U.S. Great Basin). These systems are typically targeted for power generation and open-loop heat.

Conduction-dominated:

Geologically Closed Systems, with Limited Porosity/Permeability: Water doesn't flow naturally in these systems, and geothermal energy extraction requires engineered "enhancements" (e.g., hydraulic fracturing).

Geologically Closed Systems, with Natural Porosity/Permeability: These systems have natural pore spaces to a certain depth, allowing some fluid flow. This is beneficial when considering storage for heating and cooling.

Comparison of Existing and Emerging Geothermal Technologies and Concepts

	Geographies, Applications, and Technologies:		
	Conventional Hydrothermal Geothermal	**District Heating**	**Ground Source Heat Pumps (GSHP)**
Basic Concept	Relies on natural hydrothermal systems with hot water and porous rock	Provides heating through interconnected building networks, using centralized geothermal systems	Uses shallow ground temperature stability to heat and cool buildings
Working Fluid	Naturally occurring fluids	Water or steam circulated through centralized pipes to buildings	Typically, water or antifreeze or refrigerant in a closed-loop system
Reservoir Type	Open to natural hydrothermal reservoir	Central reservoir supplying district buildings with hot water or steam	Closed-loop system buried at shallow depth
Geological Requirement	Natural hot aquifers in porous rock formations	Typically, sedimentary aquifers but can be utilised near conventional geothermal systems such as Iceland	No special geology; suitable for almost any location
Temperature Range	150°C - 350°C	Generally, around 80-100°C	All ranges
Drilling Depth	Shallow or deep, depending on hydrothermal location	Shallow to medium depth, depending on temperature requirements	Very shallow, typically 10-500 feet for residential to deeper for industrial heat pumps
Scalability	Limited to those few regions with natural hydrothermal conditions	Scalable anywhere concentrated clusters of buildings can share interconnected hot water or steam	Highly scalable; can be installed almost anywhere
Environmental Impact	Lower impact but dependent on natural resource conditions	Low impact; minimal drilling required and low emissions	Minimal impact; closed system without subsurface interaction
Examples of Use	Traditional geothermal power plants, direct-use heating in regions with hydrothermal conditions	Geothermal district heating in Iceland, Paris, and some U.S. cities	Commonly used for residential and commercial building heating and cooling but increasing in use for industrial heat when combined with industrial heat pumps
Primary Advantage	Established technology in areas with existing hydrothermal resources	Efficient and cost-effective heating for multiple buildings in urban or suburban networks	Proven, simple, reliable system for year-round building climate control and a key technology for data centre cooling
Challenges	Limited to specific geographical areas with natural conditions	High initial setup cost, complex infrastructure needed to connect multiple buildings	Higher upfront cost relative to conventional HVAC

Table 1.2

	New Geographies, Applications, and Technologies:		
	Super Hot Rock (SHR)	**Sedimentary Geothermal Systems (SGS)**	**Engineered Geothermal Systems (EGS)**
Basic Concept	Exploits extremely high temperatures at great depths	Utilizes sedimentary rock formations that may contain hot water in pores; can involve low-porosity rocks	Uses hydraulic fracturing to create artificial permeability for heat extraction
Working Fluid	Water, potentially reaching supercritical state	Typically, water from aquifers in sedimentary rocks; may require pumped circulation	Re-circulates same fluid (water or otherwise) through fractures in hot rock
Reservoir Type	Open, targeting superheated rock	Open, with naturally porous and permeable rock acting as the reservoir for fluid flow	Open to reservoir with engineered fractures
Geological Requirement	High temperatures (above 373°C)	Sedimentary rock formations with some porosity and permeability for water flow	Requires heat and engineered permeability; benefits from high rock surface area for heat transfer
Temperature Range	373°C+ (targeting supercritical steam)	Can vary from low ~20°C to >200°C	Typically, 150°C - 300°C
Drilling Depth	Significant depth (potentially 10+ kilometers)	Variable depth range from 500m to 8000m	Typically, <3000m as high pressure and high drilling costs beyond that
Scalability	Potentially scalable with improved deep drilling technology	Scalable, 73% of continental land mass contains sedimentary basins	Scalable with advances in hydraulic fracturing and drilling but potentially limited to areas where hot dry rock is <3000m and does not contain natural fractures which will increase uncertainty and potential fluid losses
Environmental Impact	High-impact drilling; needs tech improvements for feasibility	Typically, lower environmental impact	Possible induced seismicity, depending on geology; significant water use despite reuse of working fluid
Examples of Use	Experimental; no large-scale deployment yet	Residential and Industrial heat applications: Southampton, UK, Paris	DOE's FORGE project, Fervo's Project Red in Utah
Primary Advantage	High efficiency in power generation due to superheated steam	Cost-effective and scalable, particularly in well-explored basins. Stacked aquifer systems mean these basins could supply tiered geothermal, ranging from low-temp direct use to higher-temp electricity generation—and geothermal energy storage	Unlocks geothermal potential in non-ideal rock formations with artificial permeability
Challenges	High-cost drilling; significant R&D required	Limited to areas with sufficient sedimentary rock in basins with moderate temperatures	Subsurface unpredictability in fracturing; possible seismic risks; high initial costs; high water use

	New Geographies, Applications, and Technologies:		
	Advanced Geothermal Systems (AGS)	**Geothermal Cooling**	**Thermal Storage**
Basic Concept	Closed-loop system with no fluid exchange with subsurface	Uses ground or subsurface temperatures to provide cooling in buildings or industrial processes	Stores thermal energy in subsurface reservoirs for later use in heating, cooling, or power generation
Working Fluid	Circulates fluid (water, supercritical CO_2, or otherwise) entirely within sealed, engineered system	Water or refrigerant circulated to transfer cool temperatures to buildings	Water or other heat-transfer fluid for thermal storage, optimal recovery in pressurized reservoirs
Reservoir Type	Closed to reservoir; uses sealed pipes and engineered pathways	Closed or open loop with pipes in shallow ground, utilizing ground cooling	Closed underground reservoirs or aquifers for energy storage, utilizing natural or engineered pathways
Geological Requirement	No permeability needed; functions anywhere with heat availability	Generally, no special requirements; suitable for most shallow grounds with stable temperatures	Requires subsurface space with adequate pressure retention for heat and energy storage
Temperature Range	Variable; typically requires hotter rock > 100°C to achieve competitive heat extraction	Utilizes both the shallow natural ground temperature (~55°F/13°C) for cooling purposes and the deeper with absorption cooling technology	Flexible; can be adapted for seasonal thermal storage or for high-temperature dispatch
Drilling Depth	Potentially deeper to access high heat, as system is inherently limited in the surface area available for conductive heat transfer	Both shallow, typically 10-500 feet, as cooling requires lower temperatures, and deeper >100°C with absorption cooling technology	Depth varies; can be shallow for seasonal storage or deep for high-temperature storage
Scalability	Scalable as system is independent of subsurface permeability	Scalable for residential, commercial, and industrial applications	Scalable; suitable for integration with renewable sources for energy balancing
Environmental Impact	Low impact; closed system with no interaction with surrounding rock fluids	Minimal impact; closed-loop systems ensure no ground contamination	Low environmental impact; relies on pressure management for safe thermal storage
Examples of Use	Various closed-loop designs in development, technologies such as Everloop and Greenfires Greenloop	ADNOC, in collaboration with the National Central Cooling Company PJSC (Tabreed), has initiated operations at G2COOL in Masdar City, Abu Dhabi	Underground Thermal Energy Storage (UTES), Borehole Thermal Energy Storage (BTES), Aquifer Thermal Energy Storage (ATES)
Primary Advantage	No fluid exchange with subsurface; suitable for areas lacking natural aquifers	Cost-effective cooling in regions with high air conditioning demand, reduces HVAC costs, could be used to optimise Data Center Cooling	Provides energy storage to balance renewable power and support grid stability
Challenges	Expensive drilling costs; reduced heat transfer area compared to EGS; requires wells to touch more rock for heat exchange	Installation and initial costs; suitable ground area needed for installation	Requires specific geological settings for pressure control; drilling costs can be high

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Part II

Geothermal Resources and Applications in Pennsylvania

Chapter 2

Where to Develop Geothermal? Assessing Pennsylvania's Potential via Depth, Temperature, and Rock-Attribute Maps

H. Doran, V. Matt & T. McFadyen

> ***Pennsylvania has vast geothermal potential, especially for use in industrial processes and residential heating and cooling. There is also potential for geothermal electricity generation in key spots across the state. While reliable data exists for the north and west, further exploration is needed elsewhere. With the right investments, Pennsylvania can become a leader in geothermal energy.***

INTRODUCTION

With its deep experience extracting coal, oil, and natural gas from the ground, Pennsylvania has the know-how and workforce necessary to tap into the next frontier in subsurface energy: geothermal. The Commonwealth can become a hub of geothermal innovation and supply chain development that could be exported to other states, regions, and countries, ensuring that the Commonwealth's position as an energy leader is strong for decades to come.

The ground in Pennsylvania stores thousands of times more energy in the form of subsurface heat than the people of the Commonwealth consume annually. The challenge is identifying where that geothermal heat can be economically extracted and utilized.

This chapter provides analyses and maps of Pennsylvania's subsurface geology and geothermal potential, starting with an overview and then delving into technical, specialized information. Consistent with past analyses of Pennsylvania's geothermal resources,[1] this study finds that actual and modeled subsurface temperatures point towards opportunities in (1) the direct use of geothermal for low-temperature industrial processes,[2] (2) the use of geothermal heat pumps and district heating for heating and cooling of buildings, and (3) geothermal electricity generation in some "hots pots" in the Commonwealth.

Theoretically, if Pennsylvania's energy industry employed its resources and workforce to drill for geothermal at the same rate it drilled for other sources (790 oil and gas wells in 2022), within a year, geothermal could produce enough energy for all of the Commonwealth's commercial heating and low-temperature (<120°C) industrial processes. At a sustained drilling rate and with emerging technology, Pennsylvania could, in as few as 10 years, drill enough geothermal wells to meet 100 percent of the Commonwealth's electricity and heating needs as well as eliminate emissions from more energy-intensive industrial processes (see calculations in Table 2.A.1 of the Appendix).

Using the same data as a recent IEA analysis, the Commonwealth has a potential 55.28 gigawatts of geothermal electricity that could be extractable for less than $300/MWh at depths of less than 18,000ft (5500m).[3] That's enough energy to meet Pennsylvania's current electricity demand 3.5 times over.

This chapter delineates the locations and depths required for geothermal wells to most easily deliver on this potential. To be sure, the maps and analyses in this chapter are meant to highlight areas with potential for geothermal resource utilization. Additional site-specific analyses, including economic, engineering, and fluid production rate analyses, are required to identify drill-ready prospects and potential uses. Additionally, in the future, technological advances will allow Pennsylvania to develop even more of its subsurface geothermal resources, including in locations and at depths that are neither possible nor cost-effective today.

Online Data Exploration with GeoMap

*Much of the data presented in this analysis is available online through **GeoMap**, an interactive, open-source, and free platform on which individual users can explore and manipulate a variety of geothermal maps and relevant data, including temperature, depth, sources of energy demand, power plants, and more.*

OVERVIEW OF PENNSYLVANIA'S SUBSURFACE

The U.S. Energy Information Administration estimates that in 2022, Pennsylvanians' primary energy consumption hit 3,737 trillion British thermal units (Btu).[4] Pennsylvania's upper 6.2 miles (10 km) of subsurface likely holds 18,000 times that much energy. [5]

The following section serves as a guide for those who are not geothermal experts, offering summary temperature-depth maps of Pennsylvania's geothermal heat resources and a brief review of subsurface rock characteristics. Subsequent sections of this chapter provide more technical, specialized analyses geared more towards experts.

Subsurface Temperature

Drilling is a significant contributor to the overall cost of developing a geothermal project and, thus, to its economic viability.[6] Whether based on directly measured or modeled data, understanding the depths required to reach a given subsurface temperature helps to illuminate subsurface geothermal potential and the different applications that may be feasible at a given site.

Temperature at 1 Kilometer

Figure 2.2 shows those portions of Pennsylvania that are 95°F or below at a depth of 3,281 feet underground (below 35°C at 1 km). Figure 2.3 maps locations that have temperatures above 95°F at 3,281 feet deep. As explained later in this section, the areas in Figure 2.2 are likely limited to using geothermal for climate control of residential and commercial buildings. The hotter locations in Figure 2.3 start to lend themselves to an increasingly broad range of direct geothermal uses, such as greenhouse heating and low-temperature industrial processes. At the 1 kilometer depth, Pennsylvania's subsurface temperatures appear to peak at 152°F (67°C) in McKeon County near the New York border.[7]

A Caveat About Data

Analysis of Pennsylvania's subsurface temperature is based on two very different types of data sources: **direct temperature measurements** and **geological models**. As shown in Figure 2.1, direct measurements are mostly available in the Commonwealth's north and west where significant oil and gas activity has created ample subsurface data. In the rest of the Commonwealth, analysis of subsurface temperatures relies on regional geological computer models to estimate temperatures. This chapter primarily focuses on the directly measurable areas in the north and west, which have verifiable observational data. Future exploration in the rest of the Commonwealth, including drilling exploration wells, would greatly benefit Pennsylvania and broaden geothermal opportunities.

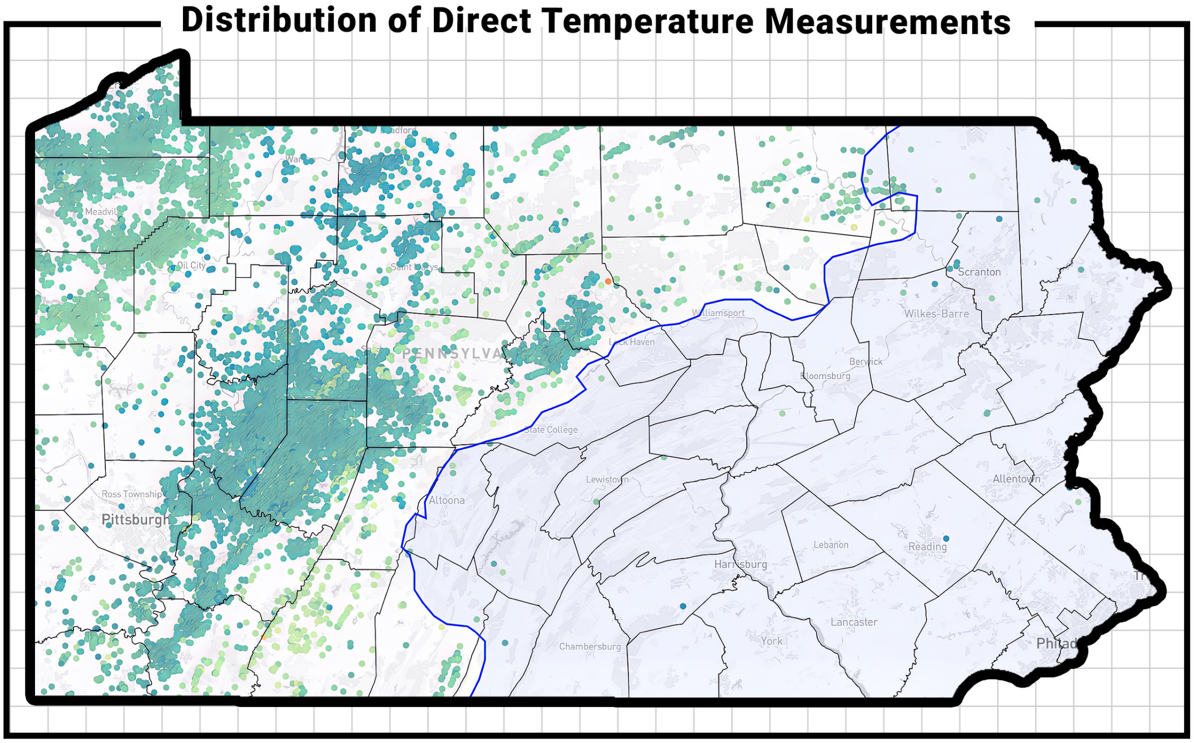

Distribution of Direct Temperature Measurements

Figure 2.1: Dots represent well locations where subsurface temperatures were directly measured. The area shaded in blue shows the parts of the Commonwealth that lack sufficient direct measurements and require the use of geological models to estimate temperature. Source: GeoMap

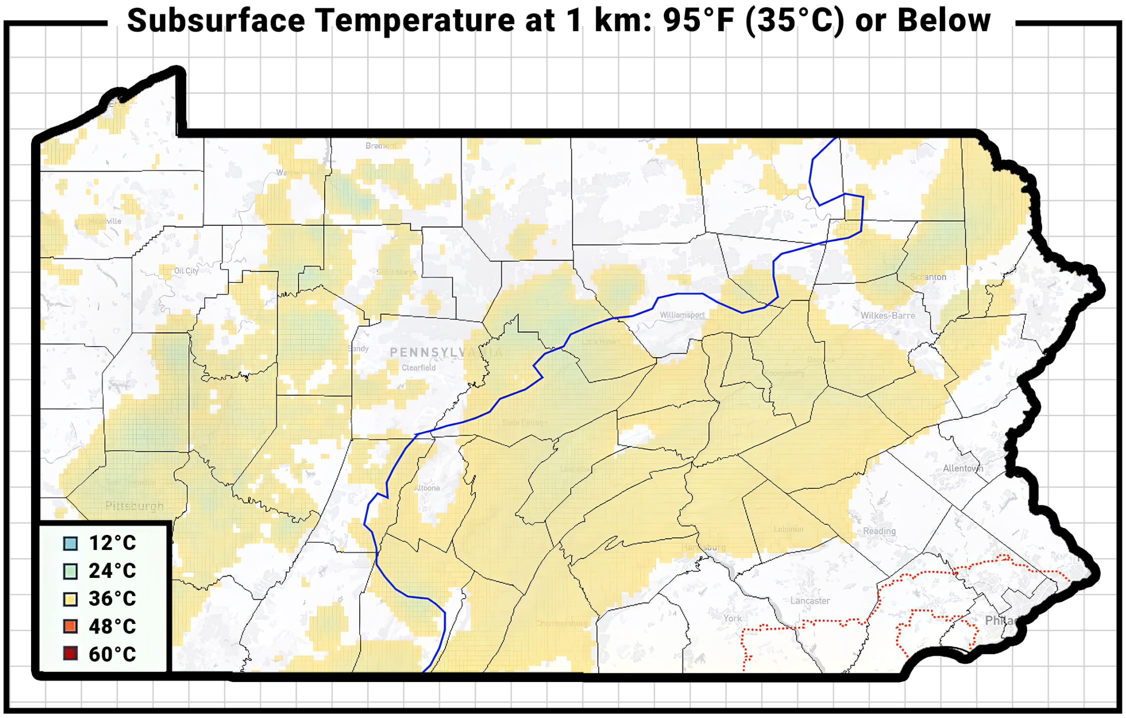

Subsurface Temperature at 1 km: 95°F (35°C) or Below

Figure 2.2: Based on available corrected temperature data. The legend provides reference colors on a sliding scale of gradients. The parts of Pennsylvania east of the blue line lack sufficient direct measurements and require the use of geological models to estimate temperature. The red dotted line around Philadelphia shows areas which geological modeling indicates are likely hotter at shallower depths than surrounding areas. Source: GeoMap

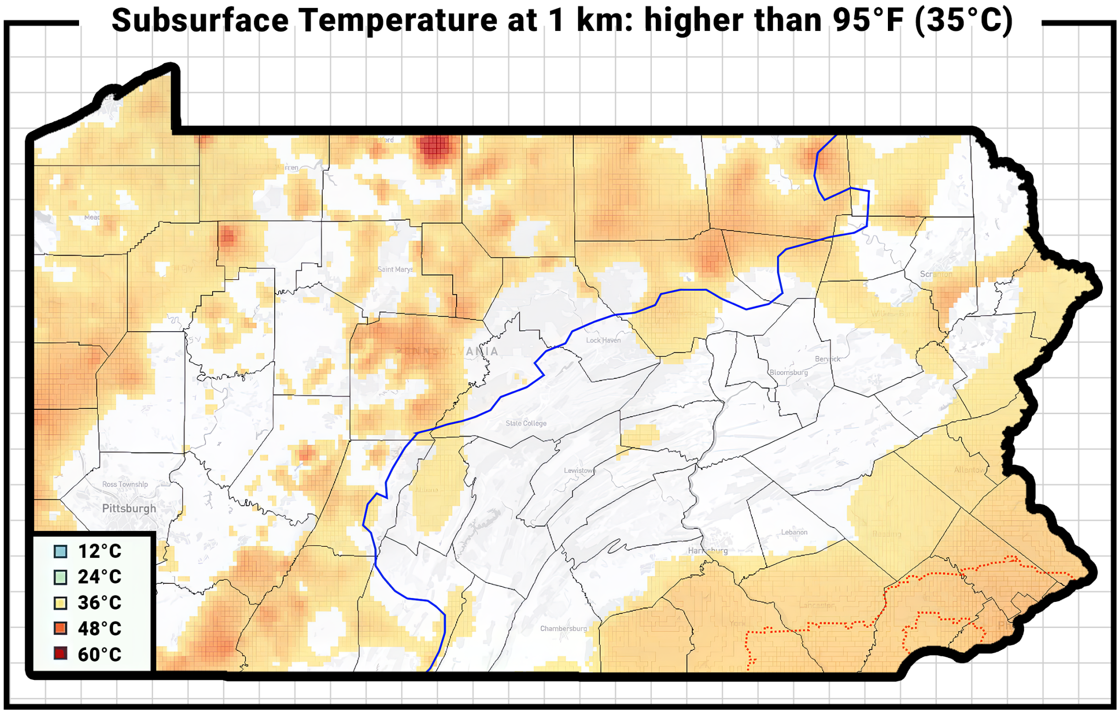

Subsurface Temperature at 1 km: higher than 95°F (35°C)

Figure 2.3: Based on available corrected temperature data. The legend provides reference colors on a sliding scale of gradients. Blue and red dotted lines have the same meaning as in Figure 2.2. Source: GeoMap

Depth to a Given Temperature

Subsurface temperatures generally increase the deeper you go. In other words, the farther a well is drilled, the hotter the rock, and the more options there are for geothermal applications. Figure 2.4 shows the depths needed to reach 212°F (100°C) in Pennsylvania. Electricity generation becomes possible at this temperature using technologies such as low-efficiency Organic Rankine Cycle (ORC) turbines. However, geothermal at this temperature is more thermally efficient (less energy is wasted) when used directly for industrial purposes (see *Chapter 3: Geothermal Direct-Use Opportunities*).

At a temperature of 300°F (150°C), you can efficiently generate electricity. As indicated in Figure 2.5, available temperature measurements show two locations in Pennsylvania that can reach 300°F at depths of less than 10,000 feet (3 km): the northeast corner of McKean County and the northwest corner of Forest County. This is shallower than some Marcellus shale gas wells. Many additional locations across the Commonwealth reach 300°F at depths of approximately 13,000 feet (3.9 km). These might be beyond the sedimentary rocks and into the older basement rock (see box on next page). These depths, too, are easily reached using existing oil and gas technology.

Note: While Figure 2.3 used red to show hotter, more favorable areas at 1km, Figures 2.4. and 2.5 now use red to display areas requiring greater depth to reach the specified temperatures. Green areas are shallower, more favorable locations (see legends).

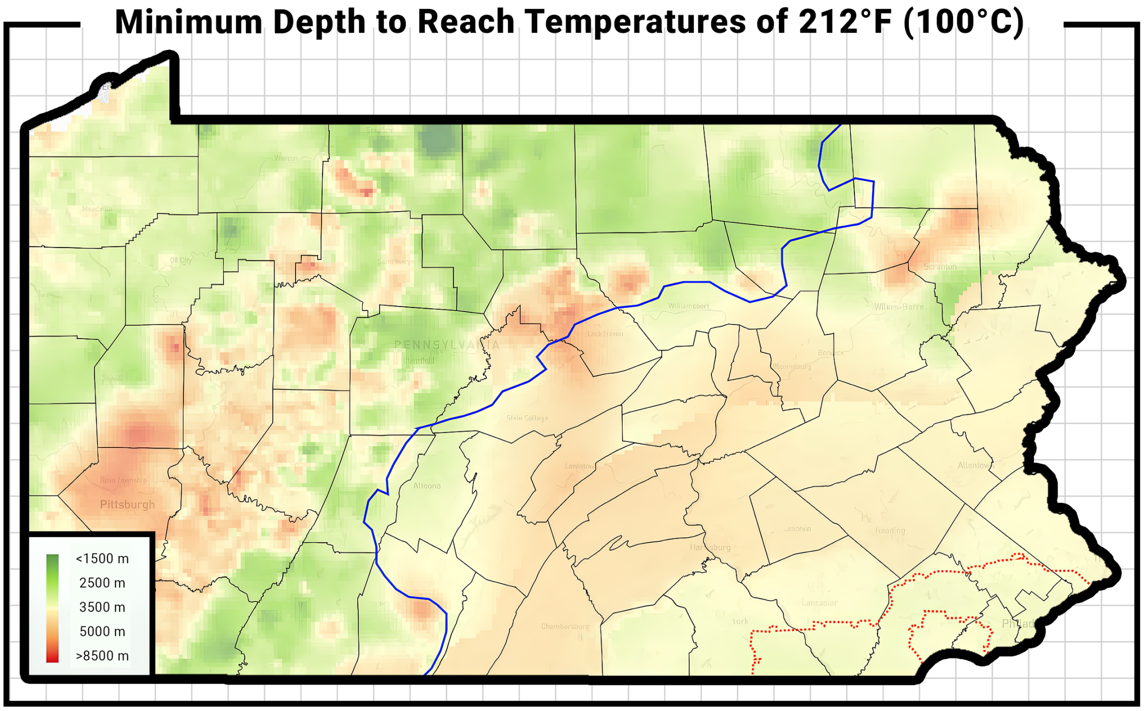


Figure 2.4: Based on available corrected temperature data. Blue and red dotted outlines have the same meaning as in Figure 2.2. Source: GeoMap

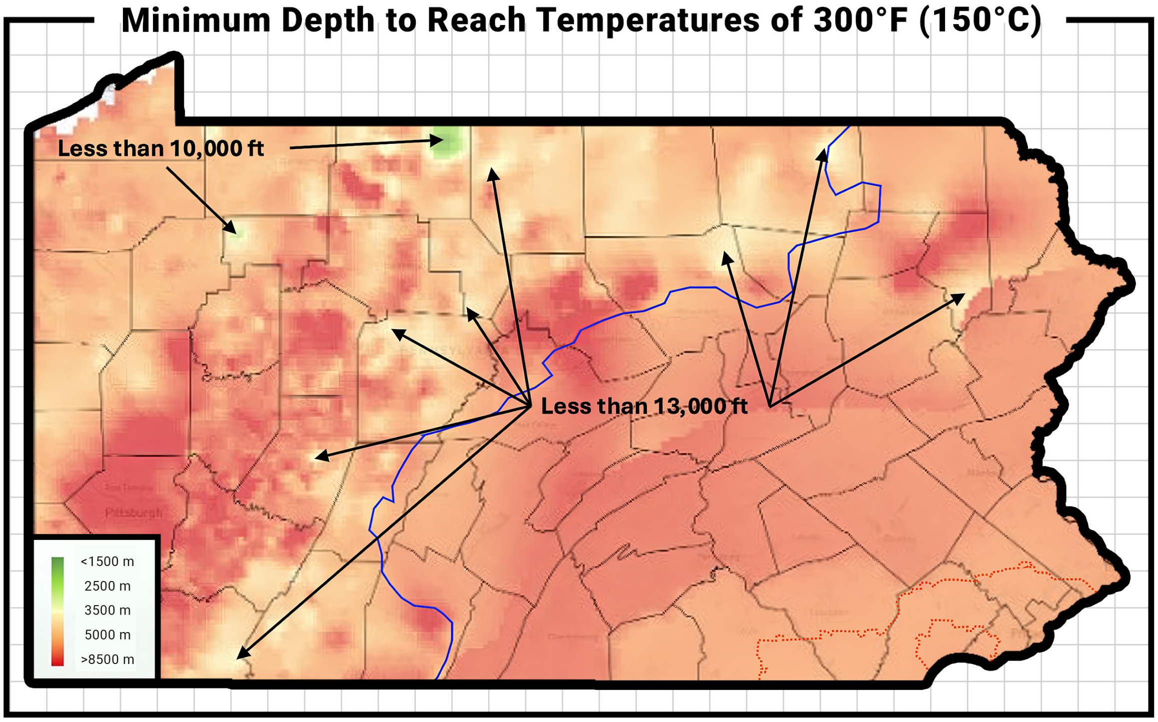


Figure 2.5: Based on available corrected temperature data. Arrows point to areas capable of reaching 300°F (150°C) at the indicated depths. Blue and red dotted lines have the same meaning as in Figure 2.2. Source: GeoMap

Sedimentary and Basement Rock

Sedimentary rocks form from the accumulation and compaction of mineral and organic particles, such as sand, silt, clay, and remains of plants and animals. These particles settle in layers over time, often in bodies of water like rivers, lakes, and oceans. Examples include sandstone, limestone, and shale.

In geology, the "basement" refers to the ancient, solid rock layer that lies beneath younger sedimentary rocks. Basement rock is typically made up of igneous and metamorphic rocks, which are much older and more stable than the sedimentary layers above. The basement rock forms the foundation of the Earth's crust and is deep underground.

Comparison of Historical Analysis: 2011 vs. 2024

In 2011, Southern Methodist University (SMU) in Texas published a project to characterize the geothermal potential of the entire continental United States. Figure 2.6 adopts a uniform color scale to allow for a comparison between the Pennsylvania portion of that historical analysis and the subsurface analysis developed for this report. The comparison shows how additional local data and more granular mapping can improve our understanding of the subsurface and reveal previously unidentified prospect areas. Differences in calculation methodologies and data availability mean the SMU maps are significantly smoothed, with the comparison maps showing much more localized variation, including higher highs and lower lows in close proximity.

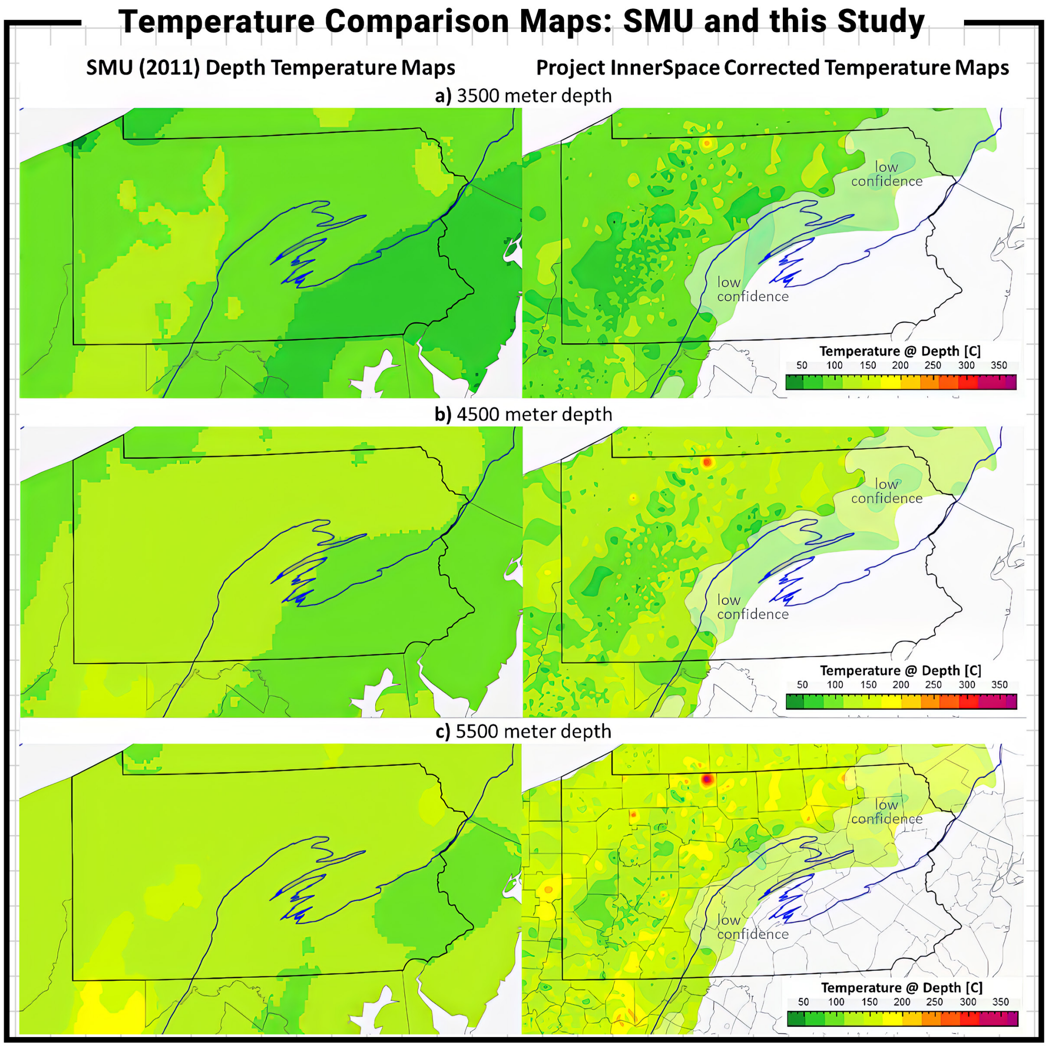


Figure 2.6: a) 3,500 meters depth, b) 4,500 meters depth, and c) 5,500 meters depth. The blue line indicates the eastern boundary of the Appalachian Basin. Low-confidence geologically modeled areas are covered by transparent white overlay. Source: Blackwell, D., Richards, M., Frone, Z., Ruzo, A., Dingwall, R., & Williams, M. (2011). Temperature-At-Depth Maps for the Conterminous US and Geothermal Resource Estimates. GRC Transactions, 35 (GRC1029452) and Project InnerSpace USA Temperature Dataset

Overview of Geothermal Applications Given Available Subsurface Temperatures

As suggested, given the temperatures and depths laid out in Figures 2.2 through 2.5, certain geothermal applications may be more feasible in some parts of Pennsylvania than others. Figure 2.7 uses a "weighted overlay analysis" to map the favorability of developing different geothermal technologies across the Commonwealth.

Dark green portions of the map are likely limited to using ground source heat pumps (GSHPs) for buildings, to provide heating and cooling. Lime green to yellow areas are still suitable for GSHPs but also offer opportunities to use geothermal directly for district heating and low-temperature industrial processes. Locations in orange into red may be suitable for electricity generation. This analysis attempts to identify the lowest-hanging fruit—the geothermal applications that can most easily be developed. Of course, as noted, drilling deeper will open up even more opportunities. But most importantly, Pennsylvania can use geothermal energy in some form everywhere across the Commonwealth.

Subsurface Fluid Flow

In addition to temperature, understanding the natural porosity or permeability of the subsurface helps determine what kind of engineering could help produce geothermal energy, and for what kind of application, in Pennsylvania. As explained in Chapter 1, all geothermal

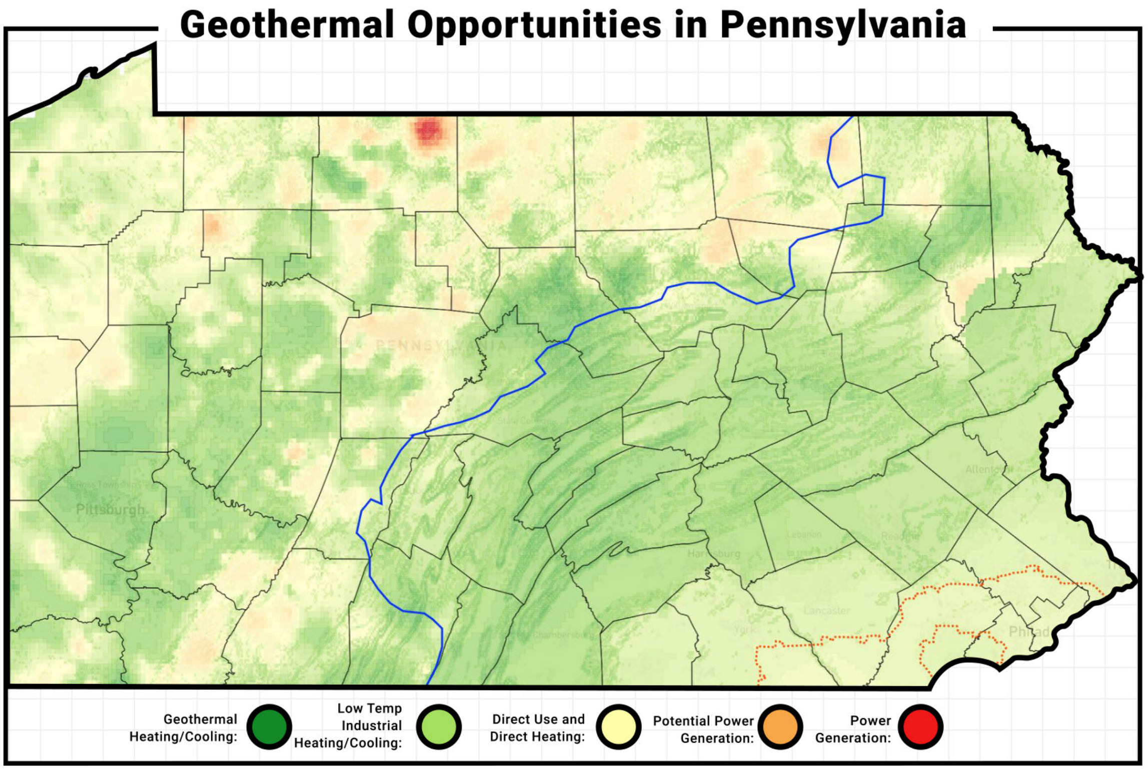


Figure 2.7: The map combines various factors: subsurface temperature, thermal gradient, seismic risk, proximity to convective features (flowing fluids), and the slope of the surface. Blue and red dotted lines have the same meaning as in Figure 2.2. Source: GeoMap

systems require heat in the form of hot rock, as well as some means for fluid to flow across the hot rock and extract thermal energy. Next-generation geothermal systems use engineering techniques to extract heat from rock formations that lack enough natural permeability or fluid content to generate electricity or provide direct heating. In engineered geothermal systems (EGS), reservoirs are created by artificially enhancing the permeability of the rock. In closed-loop advanced geothermal systems (AGS), sufficient wellbore surface area is created in a borehole network, at a sufficient depth (making the porosity or permeability of the surrounding rock irrelevant).

As explained in the expert analysis later in this chapter, Pennsylvania's subsurface is generally characterized by low porosity and permeability values. This means some form of engineered fluid flow, like hydraulic fracturing, or a closed-loop system will likely be needed to effectively use the Commonwealth's geothermal resources.

FURTHER ANALYSIS OF REGIONAL GEOLOGY AND GEOTHERMAL POTENTIAL

The remainder of this chapter provides a more in-depth and technical review of the data and methodologies used to develop the above temperature maps, and introduces additional favorability related analyses, such as geothermal gradients, formation structure, and rock property data. This information will be valuable when attempting to identify drill-ready geothermal development sites.

Geologic Overview

Key Structural Features of the Greater Appalachian Basin Region

The Greater Appalachian Basin is a prominent geological province in the eastern United States, extending from New York to Alabama and west across the Appalachian Plateau. The basin's history includes significant mountain-forming tectonic events, when the Earth's crust folded, uplifted, and eroded over millions of years. The result is today referred to as the Appalachian Mountain Range.

The Appalachian Basin contains a thick series of sedimentary rock layers.[8] (See Figure 2.A.1 in the Appendix of this chapter.) The estimated total thickness of all the combined sedimentary layers is a crucial factor in geothermal exploration. It serves as a key indicator for determining drill depth—information that significantly impacts project economics, the choice of extraction techniques, and subsurface temperatures (since sedimentary layers can insulate heat that might otherwise radiate from the inner layers of the Earth's crust and mantle). As shown in Figure 2.8a, the thickness of the Appalachian sediments varies significantly across the broader basin, from 0 to greater than 10 kilometers, with the thickest portion between Virginia and West Virginia along the western edge of the Appalachian Mountains. Across much of the East Coast, including in the greater Philadelphia area, there is no sedimentary cover, and the basement rock is exposed at the land surface (sea level is denoted by "0" in Figure 2.8a).

While thick sediment can insulate advective heatflow from the mantle (contributing to lower overall subsurface temperatures), thicker crust that is enriched with radioactive elements can generate radiogenic heat, contributing to higher heatflow at shallow depths (1-5km). As shown in Figure 2.8b, the Earth's crust below the Appalachian Basin is thin, relative to the surrounding areas, particularly to the east of the overall basin. This likely contributes to Pennsylvania's lower subsurface temperatures.

Structure and Composition of Pennsylvania's Geologic Layers

As if looking at a cliff face, Figure 2.9 shows a vertical cross-section of Pennsylvania's subsurface rock, subdividing the sedimentary fill into layers. This cross-section is heavily simplified compared to Figure 2.A.1, but its selection of depth horizons provides a representative depth distribution of Pennsylvania rock layers.[9] Notice that the available horizons or structural depth surfaces, extending diagonally from the northwest (A) to the southeast (A), are primarily confined to the western and northwestern Appalachian Basin regions of the Commonwealth. The same is evident in the overhead view of structural depth surfaces in Figure 2.10.

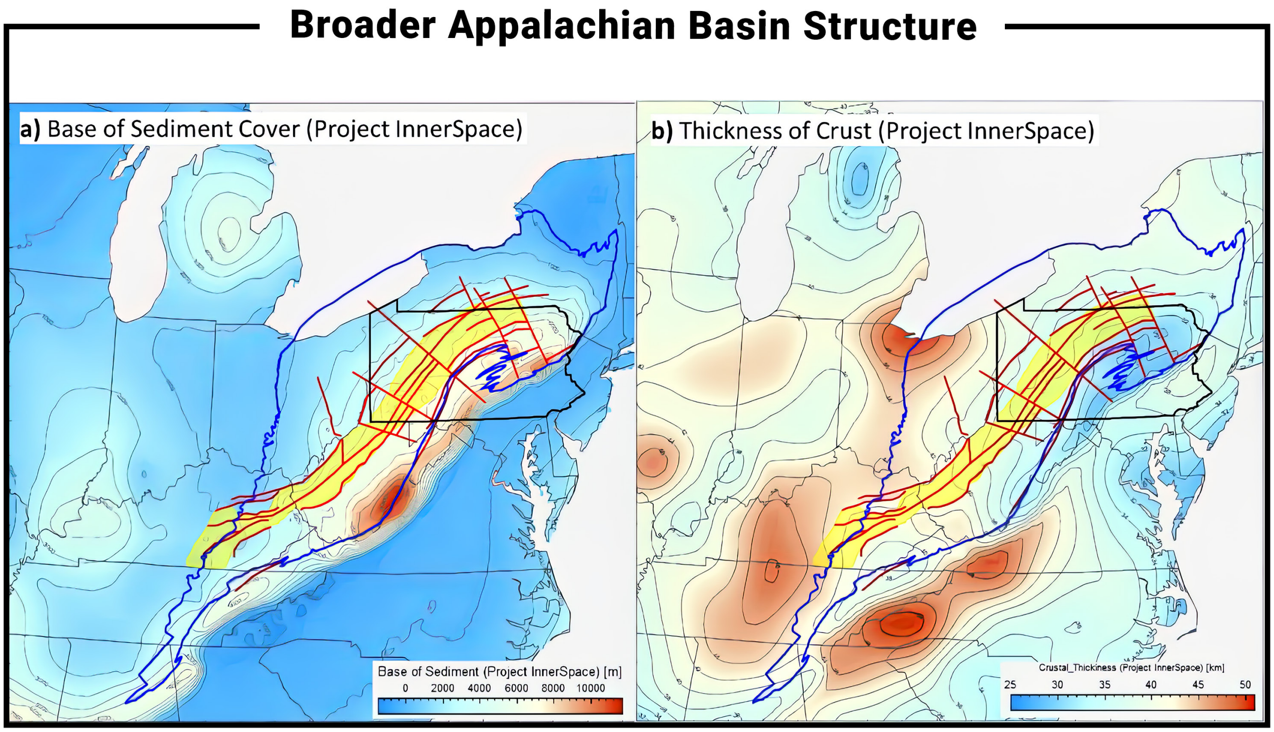


Figure 2.8: (a) Sedimentary thickness and (b) Total crustal thickness maps. The Greater Appalachian Basin is outlined in blue. Red lines indicate major fault lineaments in the lower Paleozoic Utica section. The yellow shaded area represents the approximate extent of the Rome Trough, a major fault zone. Major faults and fault zones highlight areas of geological weakness, which can reach deep into the basement. Faults act as fluid conduits and can be associated with hydrothermal activity, since deep faults can provide pathways for hot fluid to flow to shallower depths. (Sea level is denoted by "0.") Source: GeoMap and Holdt, M. and White, N.

With a general understanding of the rock layers underlying Pennsylvania, it is now possible to begin to associate measured temperatures with their corresponding structural depth surface, a critical piece of any geothermal site-specific assessment.

Subsurface Temperatures

Measured Temperature Data

Oil and gas companies measure the temperature at the bottom of each well they drill. The geothermal evaluation in this chapter combines and incorporates numerous publicly available temperature datasets (see Table 2.A.1 in this chapter's Appendix), resulting in the locations, temperature measurements, and associated depths of tens of thousands of Pennsylvania wells. As previously highlighted, the greatest concentration of Pennsylvania temperature data is in the western and northwestern parts of the Commonwealth. *The eastern and southeastern parts of Pennsylvania lack "deep" well temperature data and aren't covered by this part of the analysis.*

That said, the temperatures that oil and gas companies measure do not always reflect the actual temperatures of the subsurface rock. Deep oil and gas wells are usually drilled with fluids that temporarily cool the surrounding rock, reducing the measured temperature of the rock in the immediate vicinity of the borehole. Mathematical correction methods are applied to estimate the

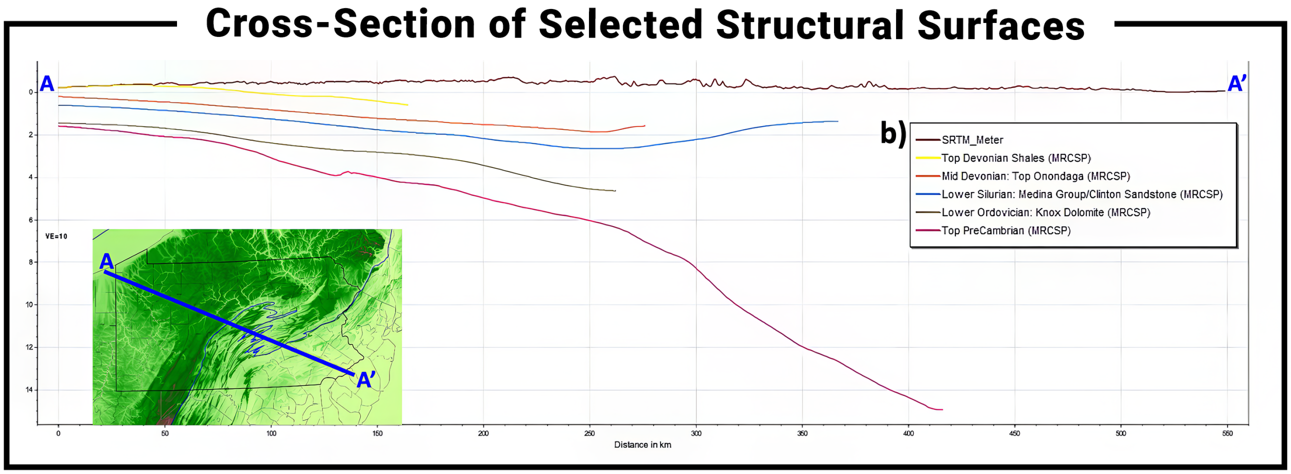


Figure 2.9: Subset of structural and stratigraphic depth surfaces providing a "representative" depth distribution of surfaces that do not intersect. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp. (See reference 8.)

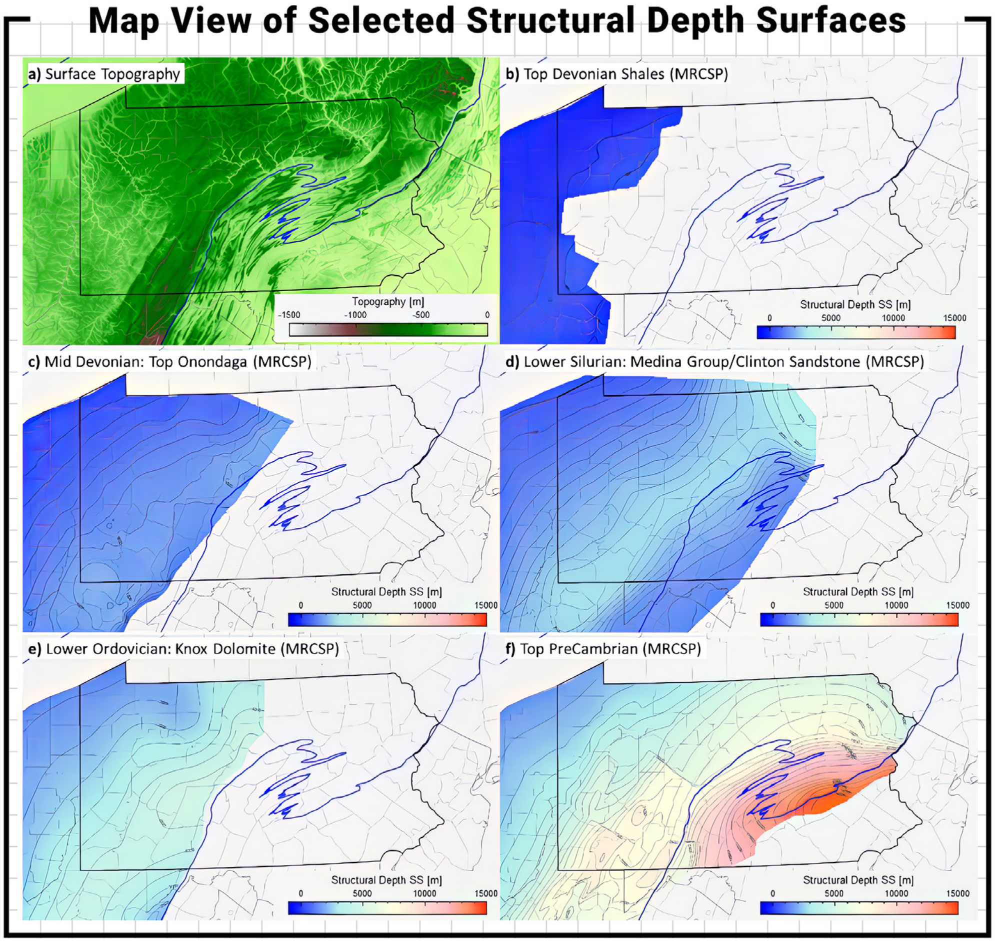


Figure 2.10: Limited data mean the extent of each map layer above may not reflect the actual area of each structural surface. The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp

original equilibrium temperature of the "undisturbed rock"—the temperature that could reasonably be accessed for a given geothermal application. Many of the public datasets used in this study (Table 2.A.1) included corrected temperature data. The available "corrected" temperatures for Pennsylvania wells are generally about 18 to 20 percent higher than "raw" temperature measurements.[10] (The difference in individual wells can be higher or lower.) Figure 2.11 maps the locations and plots the depths of corrected Pennsylvania temperature data used in this analysis.

Temperature-Depth Maps of Selected Geologic Layers

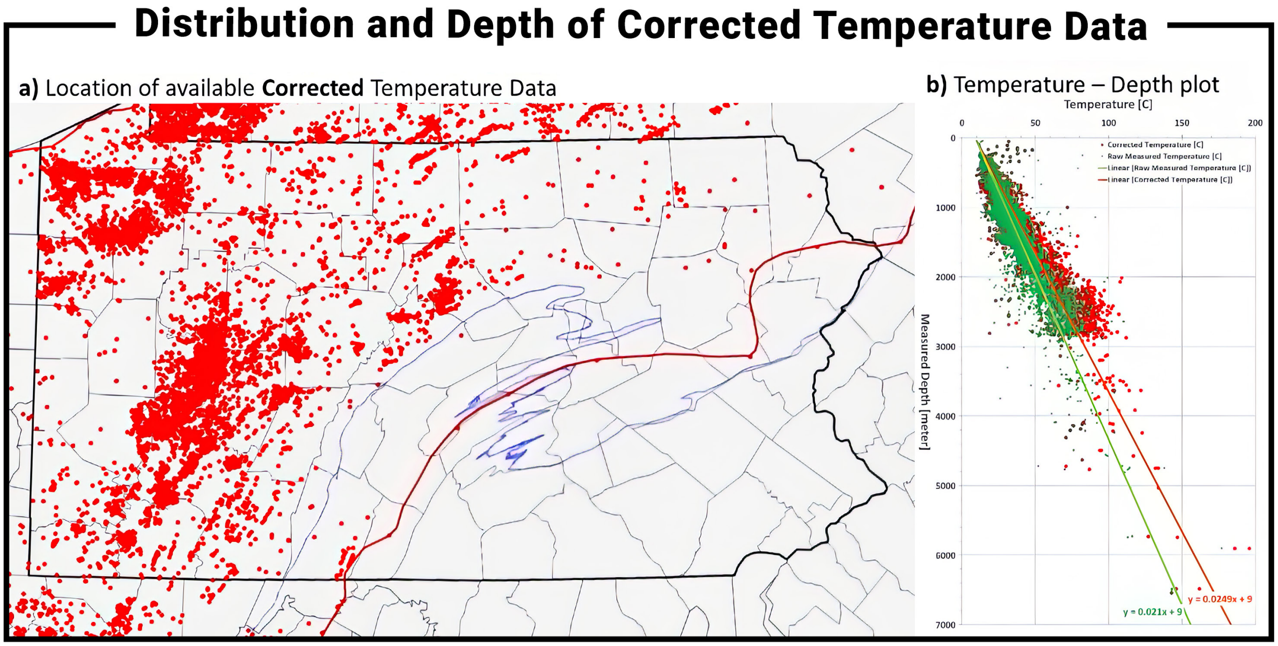
Figure 2.12 maps temperature data to the selected structural depth surfaces.[11] Further research is needed to gather additional stratigraphic and depth data to extend, update, and correct the existing suite of structural surfaces.[12]

Geothermal Gradient

The standard evaluation of the geothermal potential of an area includes the calculation of the geothermal gradient, a measure of the increase of the rock temperature with depth:

$$\text{Geothermal Gradient} = \frac{(\text{Subsurface Temperature} - \text{Surface Temperature})}{\text{Measurement Depth}}$$

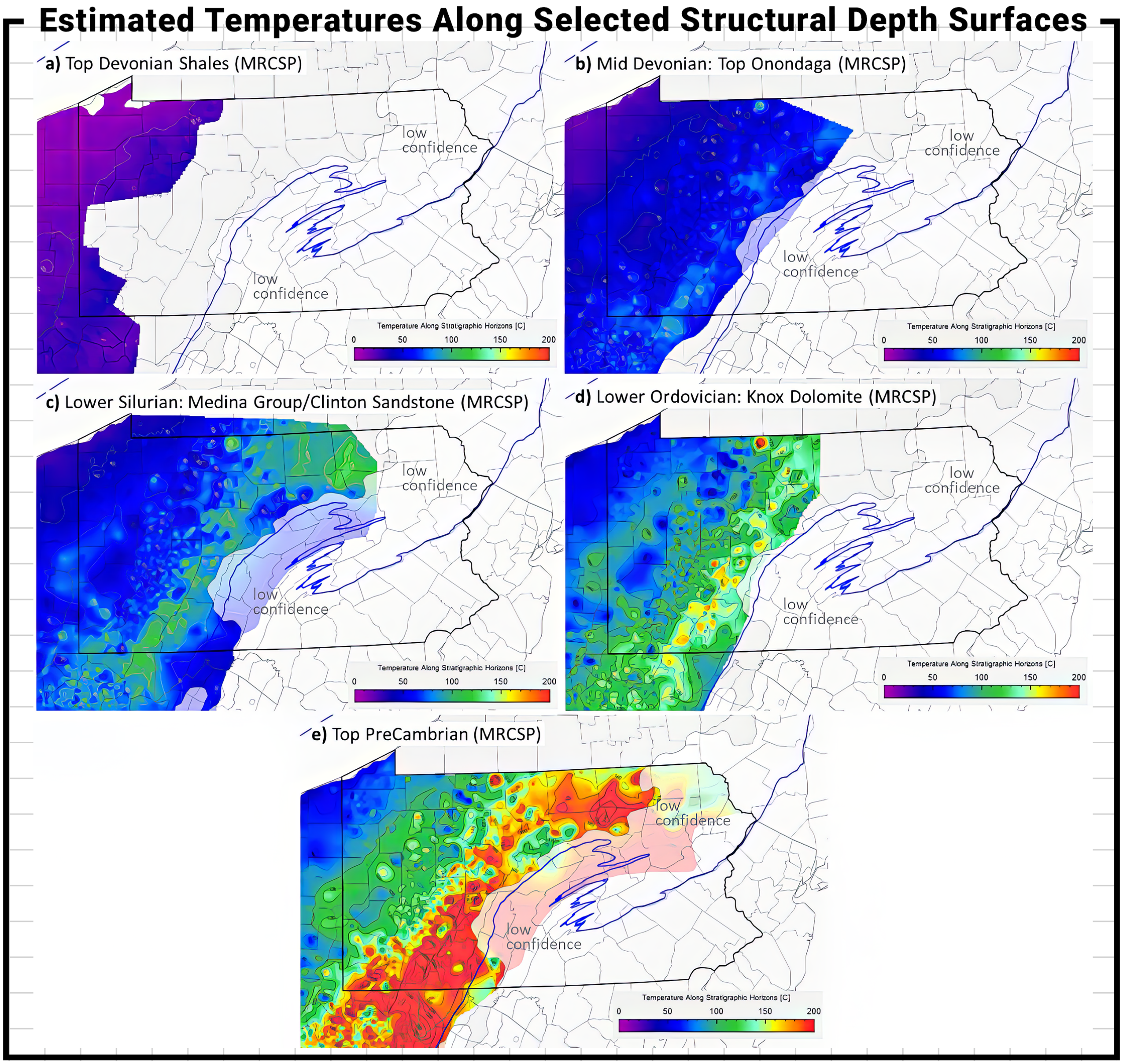
Figure 2.13 shows regional geothermal gradient maps with and without temperature measurement locations. As indicated in turquoise, green, and yellow, the western part of Pennsylvania has two bands of slightly increased geothermal gradient separated by a zone of lower gradient in blue. Similarly, a slightly increased thermal gradient is found along Pennsylvania's border with New York.



a) Location of available **Corrected** Temperature Data

b) Temperature – Depth plot

Figure 2.11: (a) The distribution of corrected temperature data across Pennsylvania (and beyond). The red line follows the limits of well locations and map gridding; no data areas fall below the red line. The blue line indicates the eastern boundary of the Appalachian Basin. (b) Temperature-depth plot showing the difference between the raw measured temperature data (green dots) and the provided and available corrected data (red dots).


Estimated Temperatures Along Selected Structural Depth Surfaces

a) Top Devonian Shales (MRCSP)

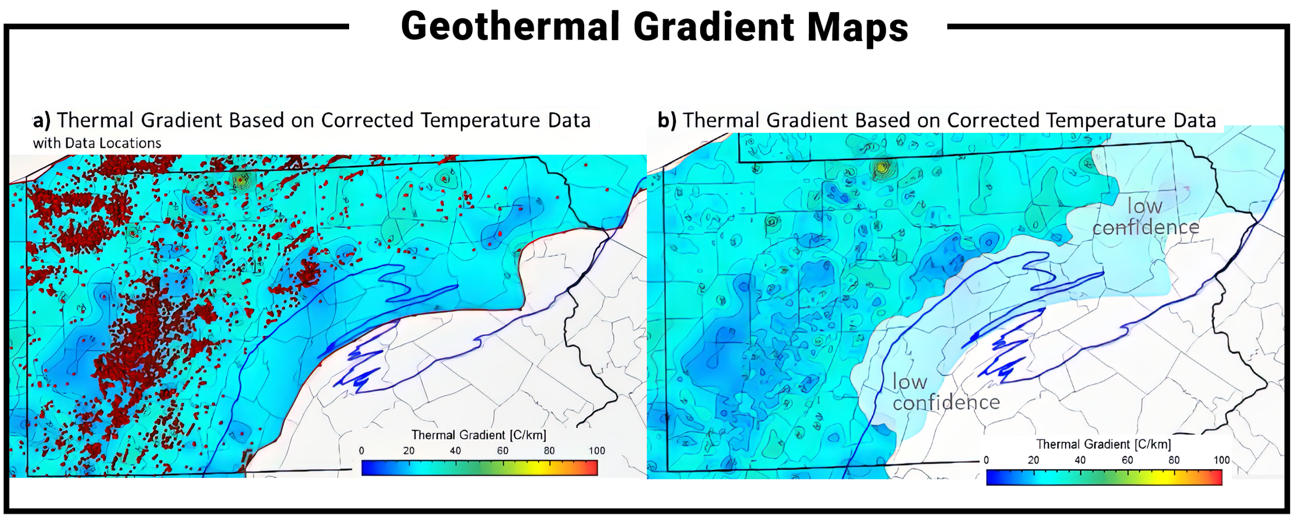
b) Mid Devonian: Top Onondaga (MRCSP)

c) Lower Silurian: Medina Group/Clinton Sandstone (MRCSP)

d) Lower Ordovician: Knox Dolomite (MRCSP)

e) Top PreCambrian (MRCSP)

Figure 2.12: Based on available corrected temperature data. Low confidence areas are covered by transparent white overlay. The blue line indicates the eastern boundary of the Appalachian Basin. Source: Authors' analysis.


Geothermal Gradient Maps

a) Thermal Gradient Based on Corrected Temperature Data with Data Locations

b) Thermal Gradient Based on Corrected Temperature Data

Figure 2.13: (a) with and (b) without data control points. The blue line represents the eastern limit of the Appalachian Basin. The red line represents the limit of the available corrected temperature data and mapping. Low confidence areas are covered by transparent white overlay. Source: Authors' analysis.

ANALYSIS OF AQUIFER PROPERTIES: LITHOLOGY, POROSITY, AND PERMEABILITY

We now turn from analysis of temperature, geothermal gradients, and formation structure to rock property data. The DOE report *Low-Temperature Geothermal Play Fairway Analysis - Appalachian Basin* (GPFA-AB) provides average bulk aquifer parameters for a number of Appalachian Basin sites in New York, Pennsylvania, and West Virginia, as shown in Figure 2.14.[13]

The most common aquifer intervals for Pennsylvania have been identified in Figure 2.15a. These aquifers consist of sandstone, limestone, and mudstone (Figure 2.15b). Porosity values for the key aquifer intervals are shown in Figure 2.15c and Figure 2.15d, ranging between roughly 3 percent and 13 percent, with a few higher values around 18 percent, as shown in figures 2.16a and 2.16c. The porosity value distribution appears to be bimodal, with maximums of around 7 percent and 11 percent. As shown in figures 2.16b and 2.16d, the aquifer permeabilities range from less than 0.001 millidarcies (mD) up to around 100 mD. Most of the permeabilities are around ±0.05 mD to ±1 mD.

Overall, the aquifer property data indicate low porosity and permeability values. These low values are related to the deep burial and strong compaction of the Appalachian Basin sediments, before their exhumation and erosion of some of the overburden. The low porosity and permeability values are unlikely to support the high fluid production rates necessary to economically implement some current conventional geothermal technologies. Aquifer stimulation such as hydraulic fracturing might be necessary for the required thermal fluid production rates, or the use of closed-loop systems.

Mapping the aquifer parameters on a formation-by-formation basis, as in figures 2.17, 2.18, and 2.19, can highlight the spatial distribution and parameter trends of potential geothermal aquifers, but based on the available data, no clear trends can be identified in the maps. Similarly, figures 2.20 and 2.21 do not show definitive depth trends in the porosity and permeability depth profiles.

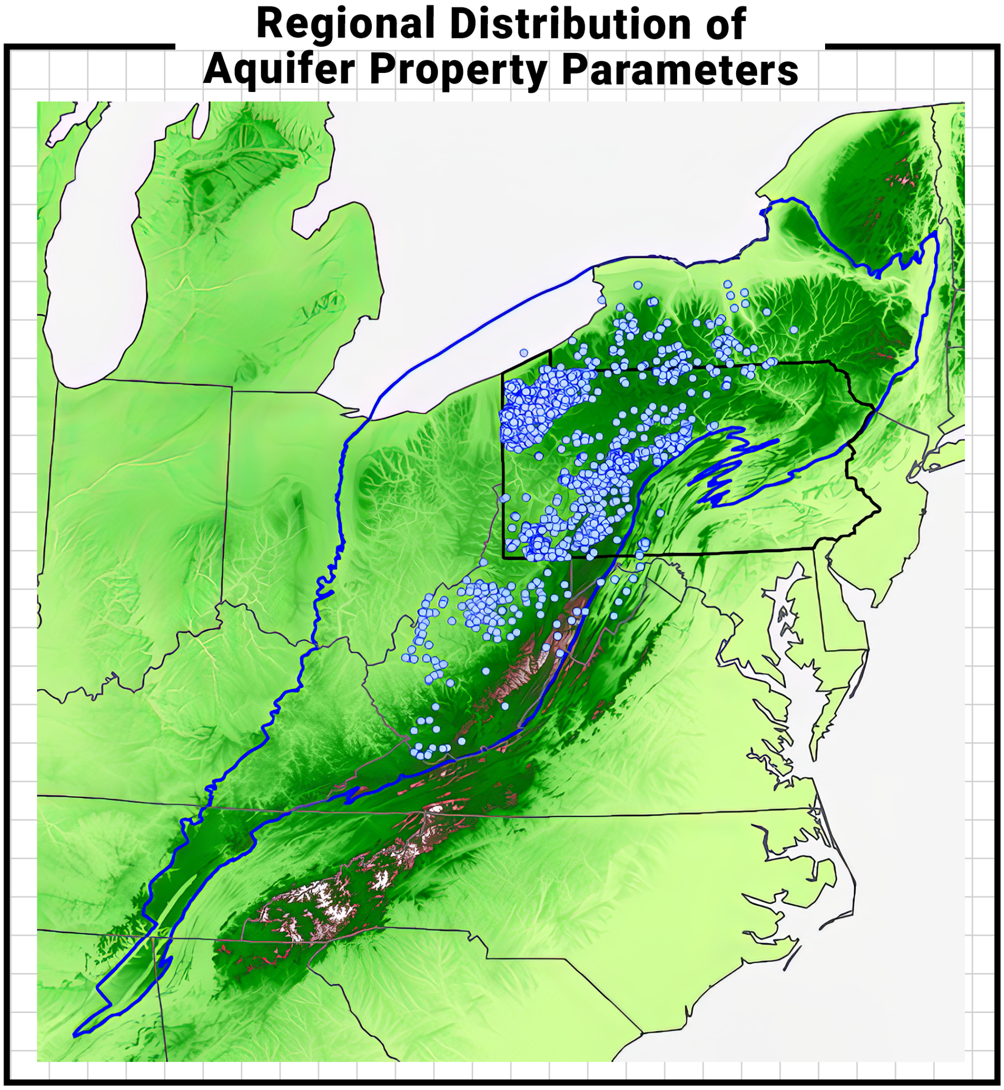


Figure 2.14: Map showing data points collected as part of the *Low-Temperature Geothermal Play Fairway Analysis - Appalachian Basin* study. Greater Appalachian Basin outlined in blue. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp. (See reference 12.)

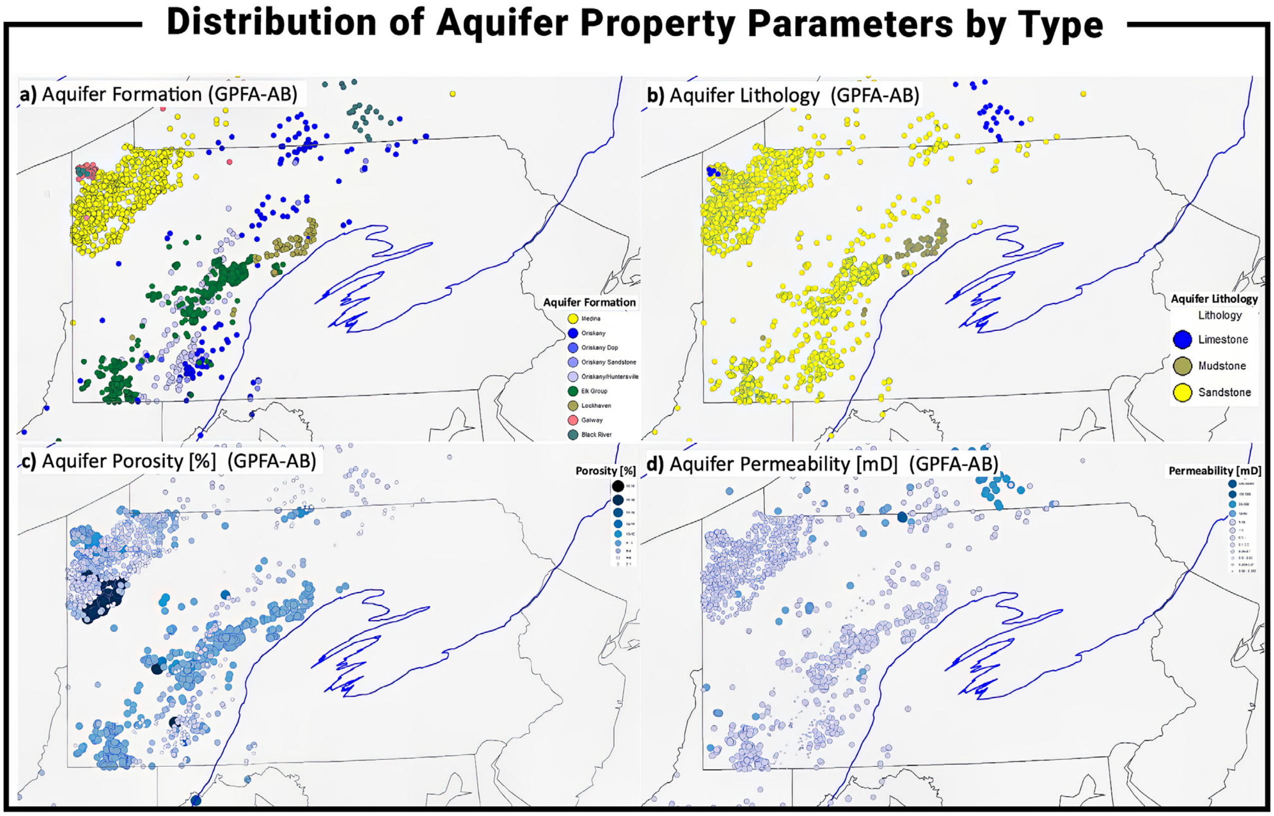


Figure 2.15: (a) Aquifer formation, (b) Aquifer lithology, (c) Aquifer porosity, (d) Aquifer permeability. The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

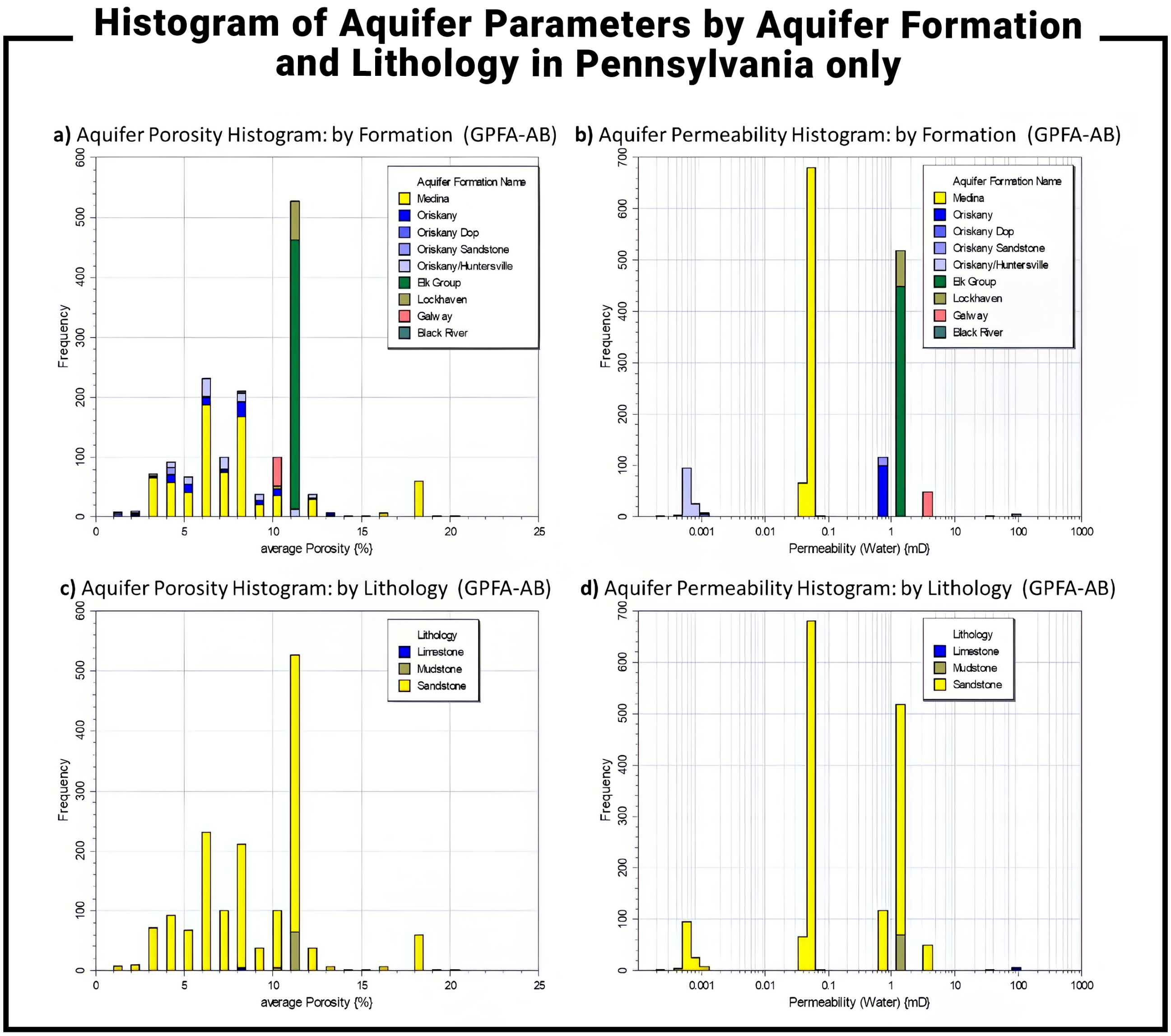


Figure 2.16: Pennsylvania only. (a) Porosity and (b) Permeability values. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

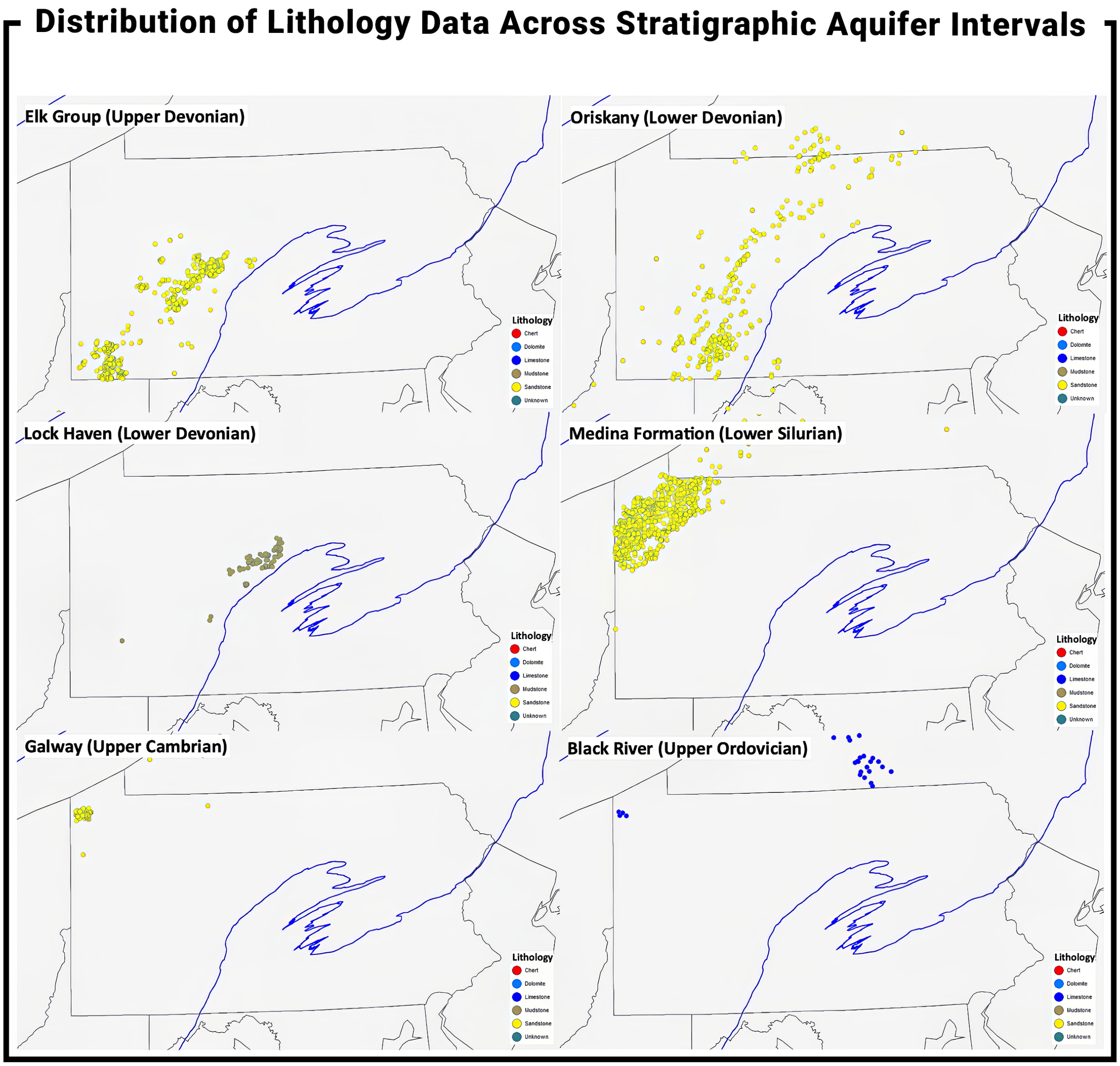


Figure 2.17: The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

Distribution of Porosity Data Across Stratigraphic Aquifer Intervals

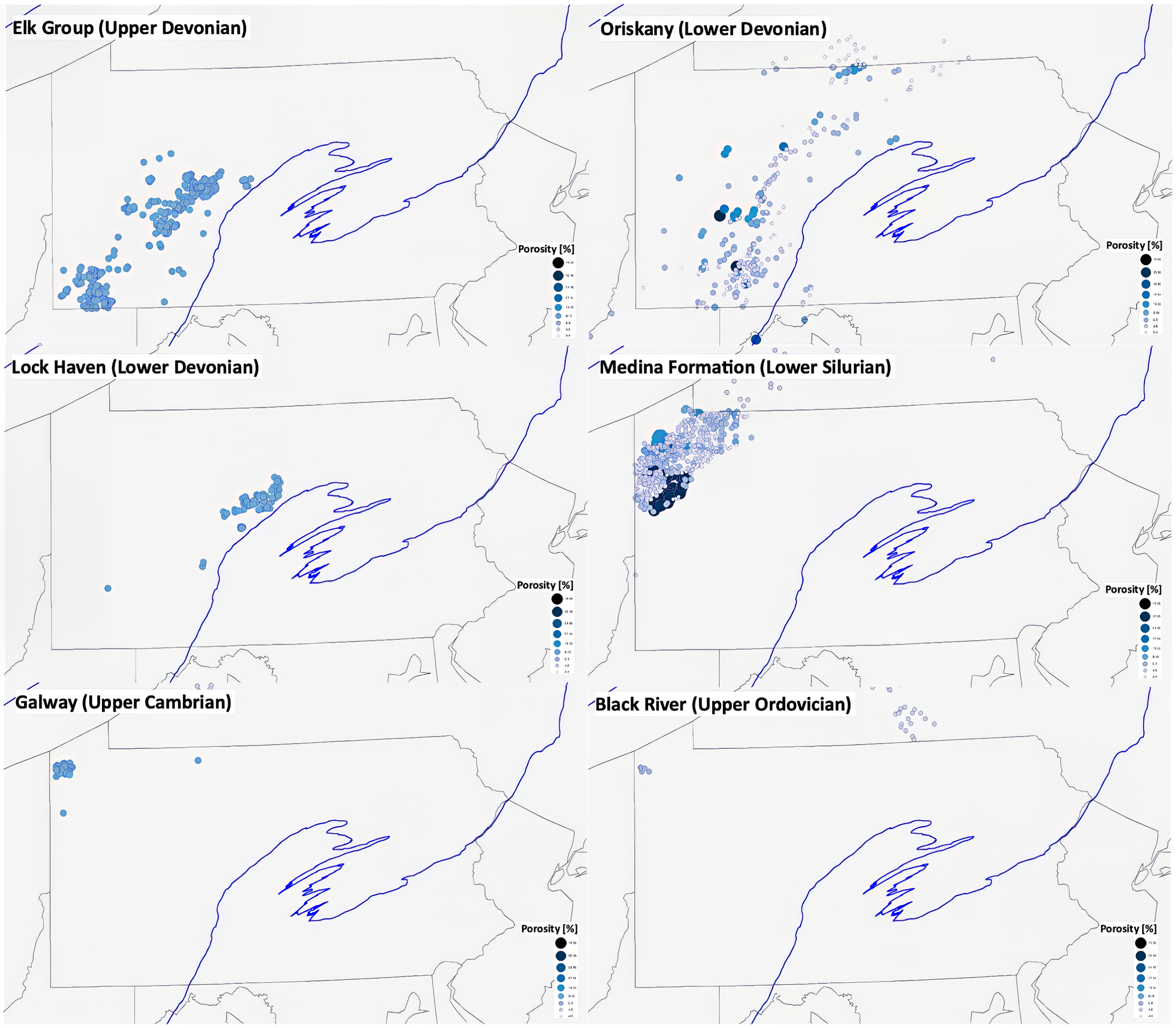


Figure 2.18: The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

Distribution of Permeability Data Across Stratigraphic Aquifer Intervals

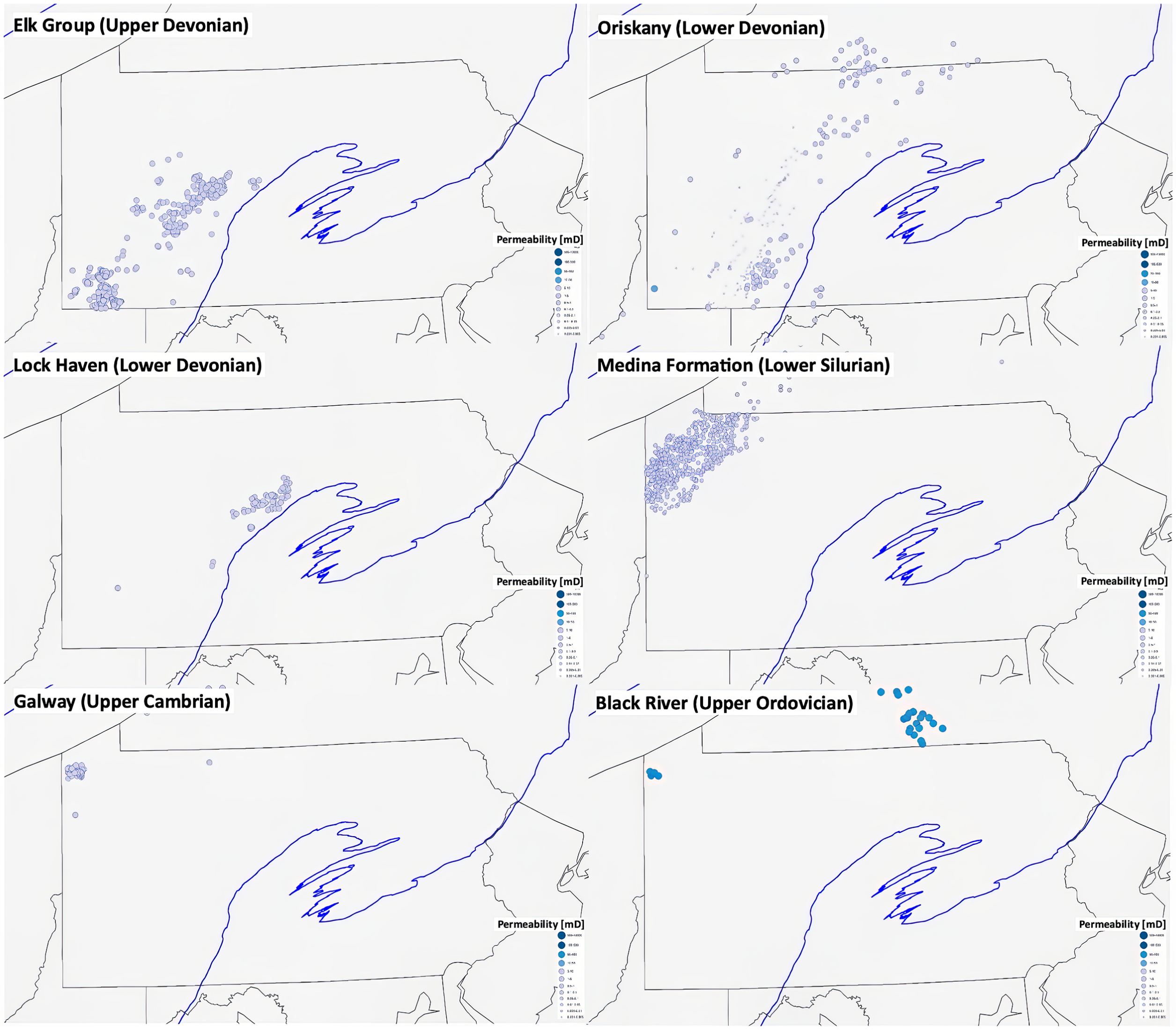


Figure 2.19: The blue line indicates the eastern boundary of the Appalachian Basin. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp.

Depth Profiles of Porosity and Permeability Colored by Formation Name (Pennsylvania only)

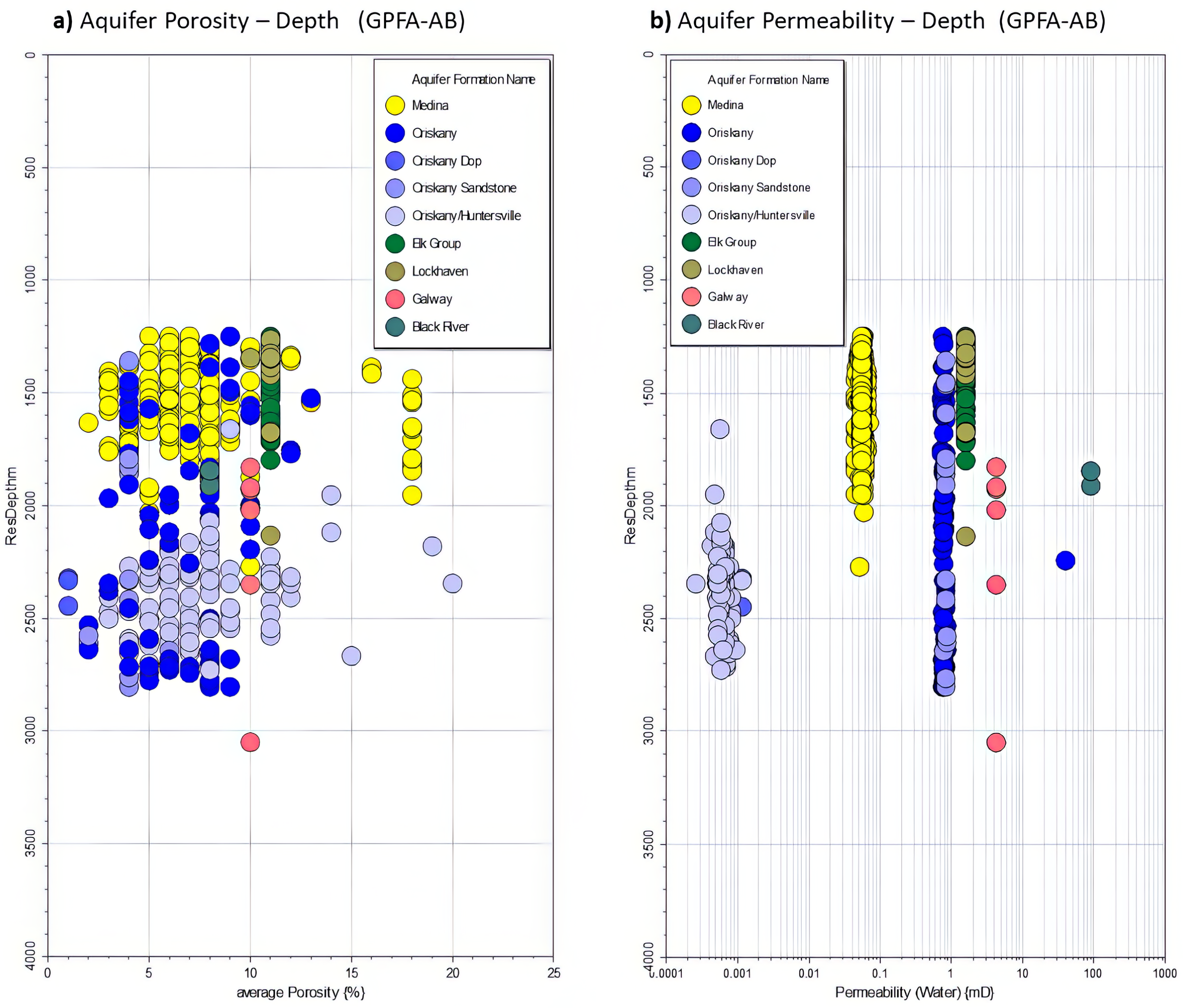


Figure 2.20: Pennsylvania only. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp. (See reference 12.)

Depth Profiles of Porosity and Permeability Colored by Lithology (Pennsylvania only)

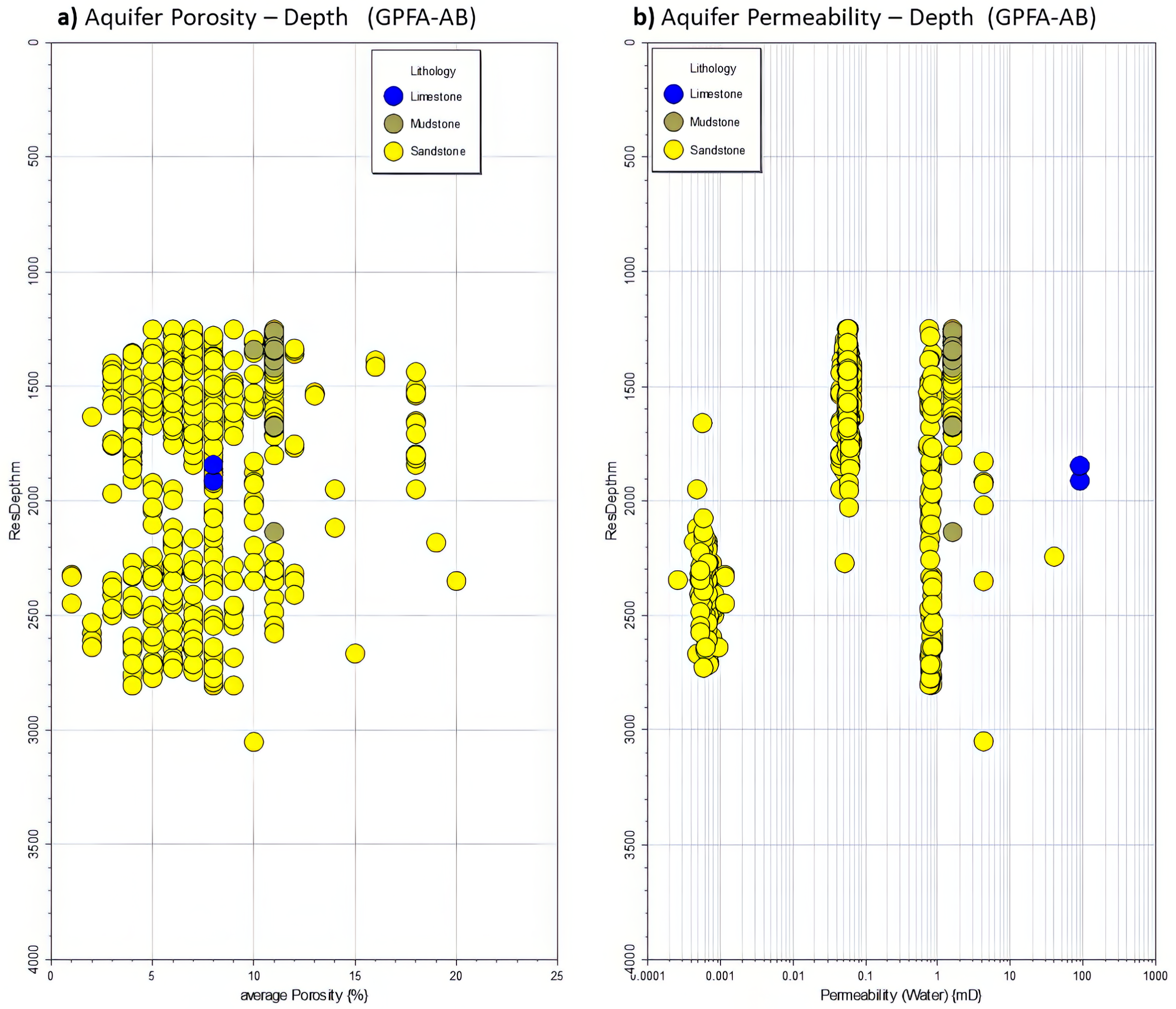


Figure 2.21: Pennsylvania only. Source: Adapted from the Midwest Regional Carbon Sequestration Partnership (MRCSP): https://netl.doe.gov/coal/carbon-storage/atlas/mrcsp. (See reference 12.)

CHAPTER 2 APPENDIX

Information Referenced in Chapter

Calculating the Scale of Geothermal Drilling Required to Meet Pennsylvania Energy Demand

	Technology Year		**2025**	**2030**	
	Vertical Depth Constraint (feet)		**15,000**	**33,000**	
	Temperature Constraint		120 ºC	250 ºC	
Commercial Energy Demand	Met w/ 90 ºC Geothermal Heat	Annual Energy Consumption (GWh Thermal)	47,971		
		Output Per Well Pair (GWh Thermal)	55		
		Number of Wells to Meet Demand	**878**		
Industrial Thermal Energy Demand	Met w/ Geothermal Heat up to Specified Range	Annual Energy Consumption (GWh Thermal)	3,626	13,379	
		Output Per Well Pair (GWh Thermal)	57	49	
		Number of Wells to Meet Demand	**64**	**272**	
Geothermal Potential w/ 2025 Constraints	Sum of Wells		**942**		
	Years of Drilling		**1.19**		
Residential Energy Demand	Met w/ 80 ºC Geothermal Heat	Annual Energy Consumption (GWh Thermal)	64,161		
		Output Per Well Pair (GWh Thermal)	55		
		Number of Wells to Meet Demand	**1,174**		
Electricity Demand	Met w/ 250ºC Geothermal Heat	Annual Energy Consumption (GWh Electric)		394,267	
		Power Output Per Well Pair (GWh Electric)		75	
		Number of Wells to Meet Demand		**5,234**	
Geothermal Potential w/ Residential & 2030 Constraints	Sum of Wells		2,116	5,506	**Total Years**
	Years of Drilling		**2.68**	**6.97**	**9.65**

Table 2.A.1: Energy Consumption statistics assume demand remains at 2023 levels. 2030 calculations assume 2025 demand already satisfied. Years of drilling calculation assumes a rate of 790 geothermal wells drilled annually, which is the rate at which Pennsylvania's oil and gas industry drilled in 2022. Residential demand not included under 2025 Geothermal Potential due to geographic distribution of Pennsylvania residences. Some calculations appear erroneous due to rounded figures—outputs and conclusions are arithmetically accurate with decimal places. GWh = Gigawatt hours.

Regional Stratigraphic Chart of the Appalachian Basin and the Greater Study Area

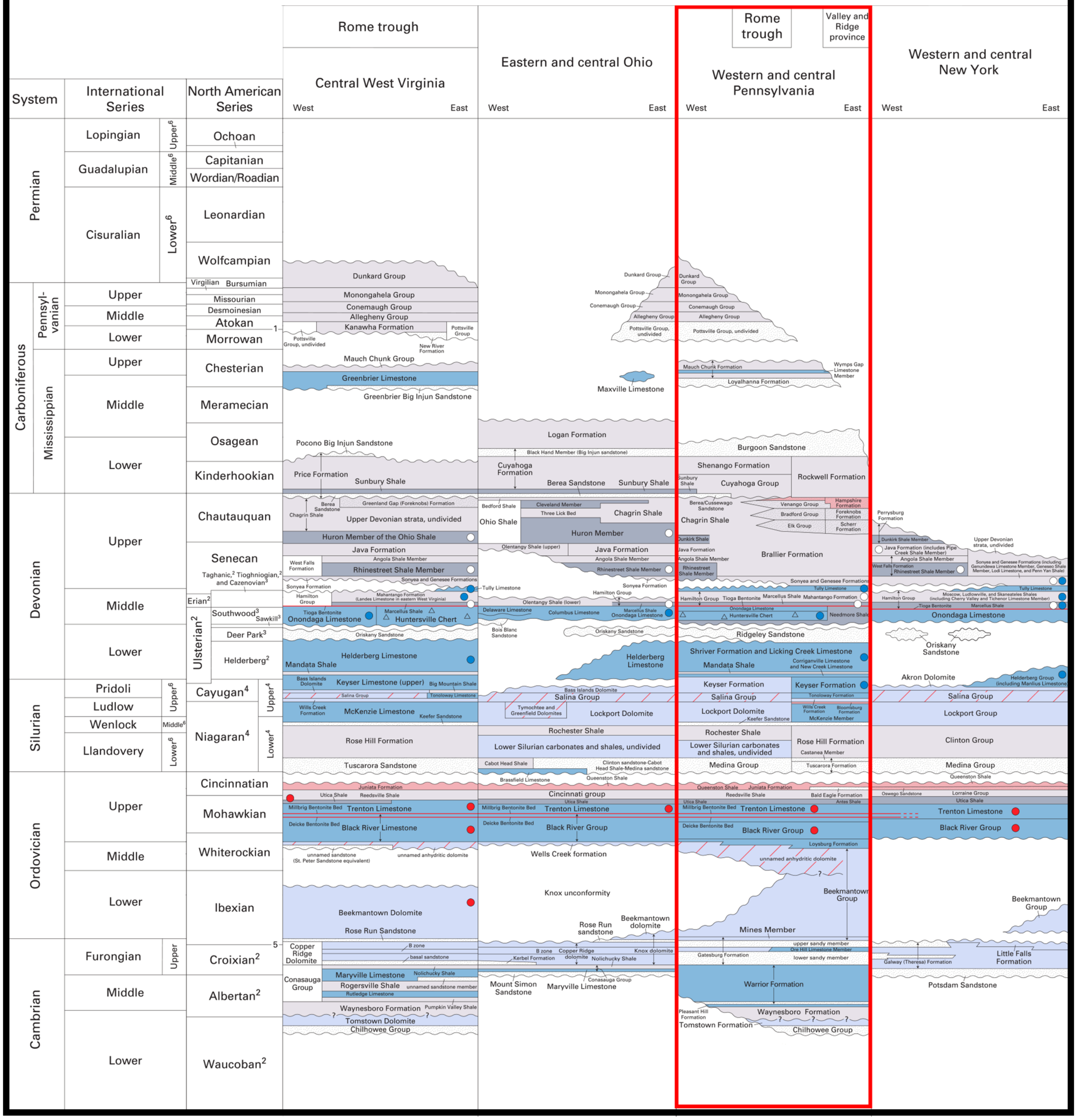


Figure 2.A.1: Source: Adapted from United States Geological Survey (USGS). (2008). SIM 3006. https://pubs.usgs.gov/sim/3006/SIM_3006_figures/SIM_3006_Fig4.pdf

Summary of Data Source Files and Source URL Links to Data of the Temperature Data Included in the Temperature Datasets

Data Source File	Data Source URL
..\001_DataSource_GDR_AASG_Geothermal_Boreholes\aasg_geothermal_boreholes.csv	https://gdr.openei.org/submissions/252
..\002_DataSource_SMU\core.surface_site_county_state_materialized_view.csv	http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm?
..\002_DataSource_SMU\core.template_borehole_materialized.csv	http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm?
..\002_DataSource_SMU\core.template_heatflow_materialized.csv	http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm?
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..\002_DataSource_SMU\staging.und_td_view_materialized.csv	http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm?
..\003_DataSource_SMU_Geothermal_Boreholes\SMU_Geothermal_Boreholes.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\004_DataSource_AASG_GDS_Data\drillstemtests.csv	https://github.com/usgin-models/DrillStemTests
..\004_DataSource_AASG_GDS_Data\heatflow.csv	https://github.com/usgin-models/HeatFlow
..\005_DataSource_NREL_geothermal-prospector\GB_hot_spring_well_analyses.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\005_DataSource_NREL_geothermal-prospector\OIT_Colocated_Sites.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\005_DataSource_NREL_geothermal-prospector\OIT_Wells_Springs.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\005_DataSource_NREL_geothermal-prospector\USGS_Wells_Springs.csv	https://maps.nrel.gov/?da=geothermal-prospector
..\006_DataSource_GDR_Low-Temperature Geothermal Geospatial Datasets An Example from Alaska\AASG_Geothermal_Boreholes.csv	https://gdr.openei.org/submissions/1518
..\006_DataSource_GDR_Low-Temperature Geothermal Geospatial Datasets An Example from Alaska\AASG_Low_Temperature .csv	https://gdr.openei.org/submissions/1518
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..\006_DataSource_GDR_Low-Temperature Geothermal Geospatial Datasets An Example from Alaska\AK_SMU_BHT_ThermalCond_HeatFlow.dbf	https://gdr.openei.org/submissions/1518
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..\010_Stanford Thermal Earth Model for the Conterminous United State\Raw_BHT_aggregated_data.csv	https://gdr.openei.org/submissions/1592
..\011_DataSource_Appalachian Basin Play Fairway Analysis\AASG_Combined.xlsx	https://gdr.openei.org/submissions/638
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Table 2.A.2: Summary of data source files and source URL links of the temperature data included in the temprature datasets

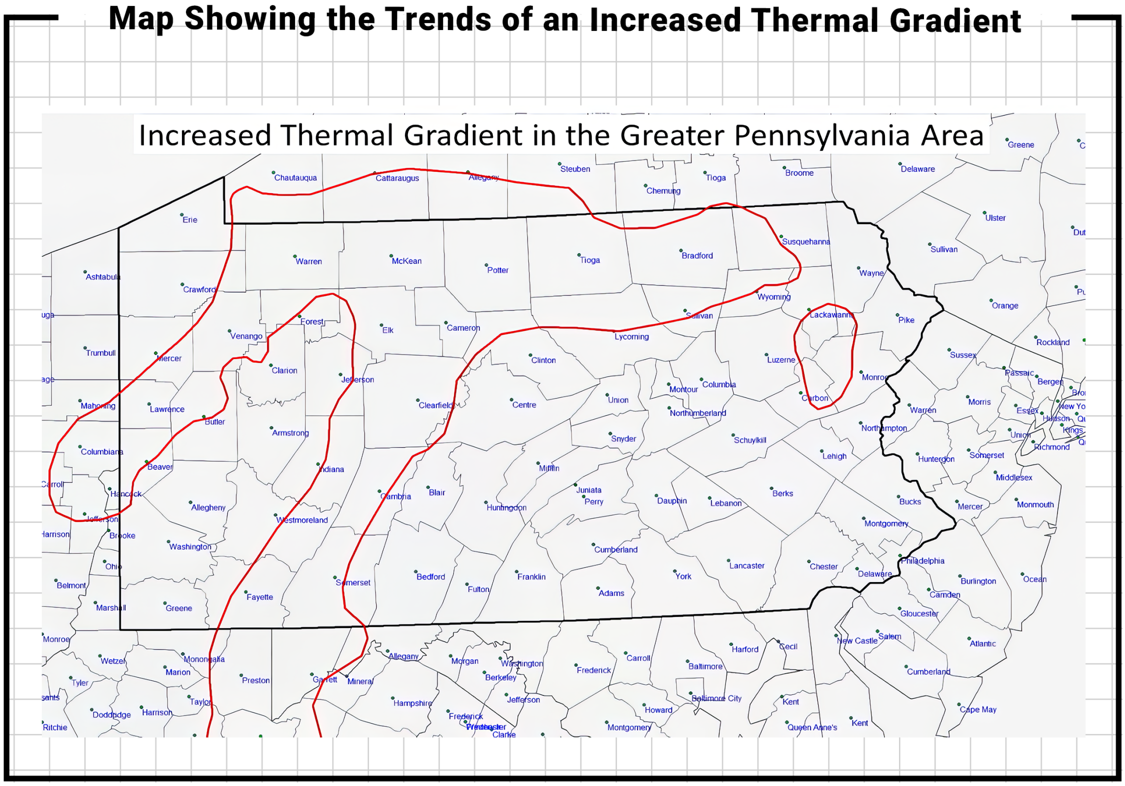
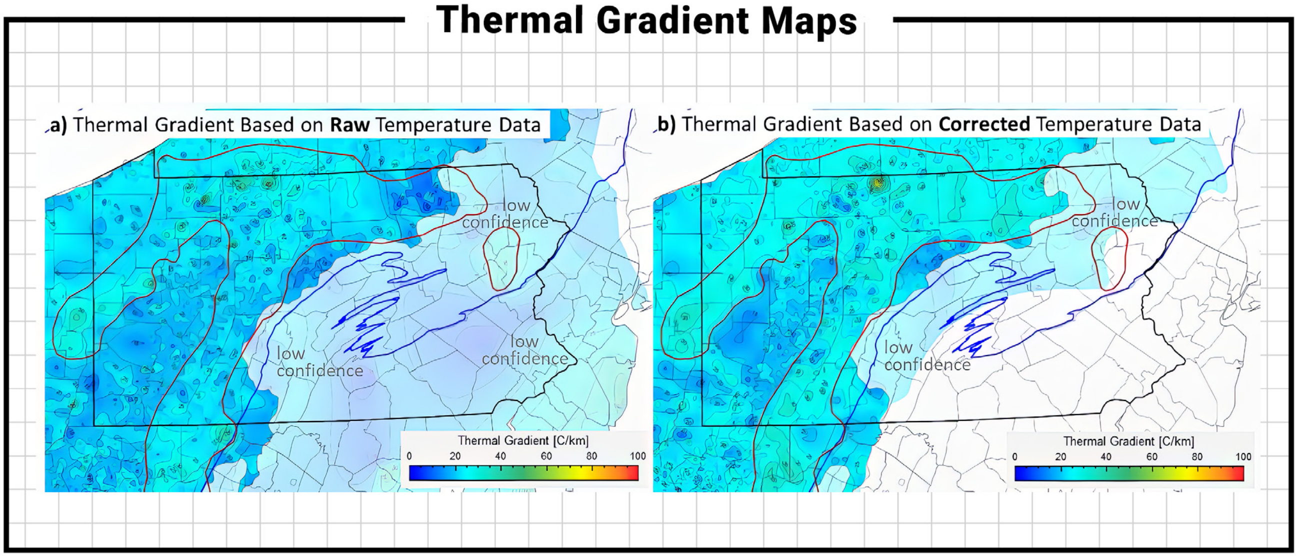

Map Showing the Trends of an Increased Thermal Gradient

Figure 2.A.2: Map showing areas with increased thermal gradient, highlighted by red polygons. Source: Author analysis.


Thermal Gradient Maps

a) Thermal Gradient Based on **Raw** Temperature Data

b) Thermal Gradient Based on **Corrected** Temperature Data

Figure 2.A.3: a) based on raw temperature data. b) based on available corrected temperature data. The blue line indicates the eastern boundary of the Appalachian Basin. Red polygon in both a and b outlines the areas of likely increased gradient based on corrected temperature data. Low confidence areas are covered by transparent white overlay. Source: Author analysis.

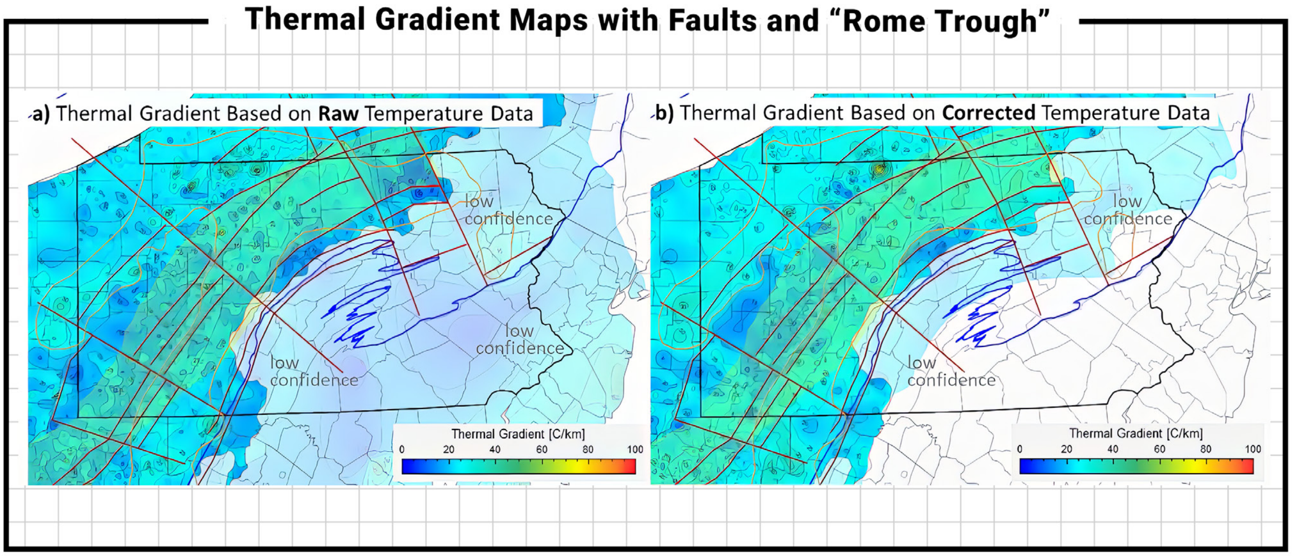


Figure 2.A.4: The yellow shaded area represents the approximate extent of the "Rome Trough." The red lines indicate major fault lineaments. The blue line indicates the eastern boundary of the Appalachian Basin. Orange polygons outline increased thermal gradient. Low confidence areas are covered by transparent white overlay. Source: Author analysis

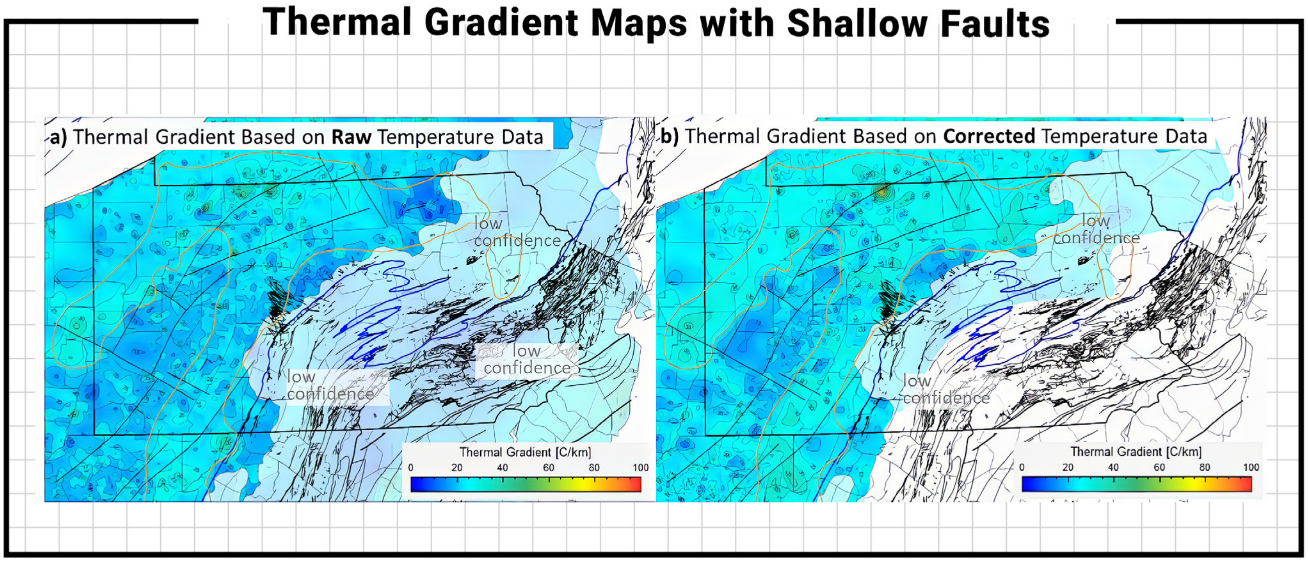


Figure 2.A.5: The irregular black lines represent shallow and major fault lines identified by Project InnerSpace. The blue line indicates the eastern boundary of the Appalachian Basin. Orange polygons outline increased thermal gradient. Low confidence areas are covered by transparent white overlay. Source: Author analysis

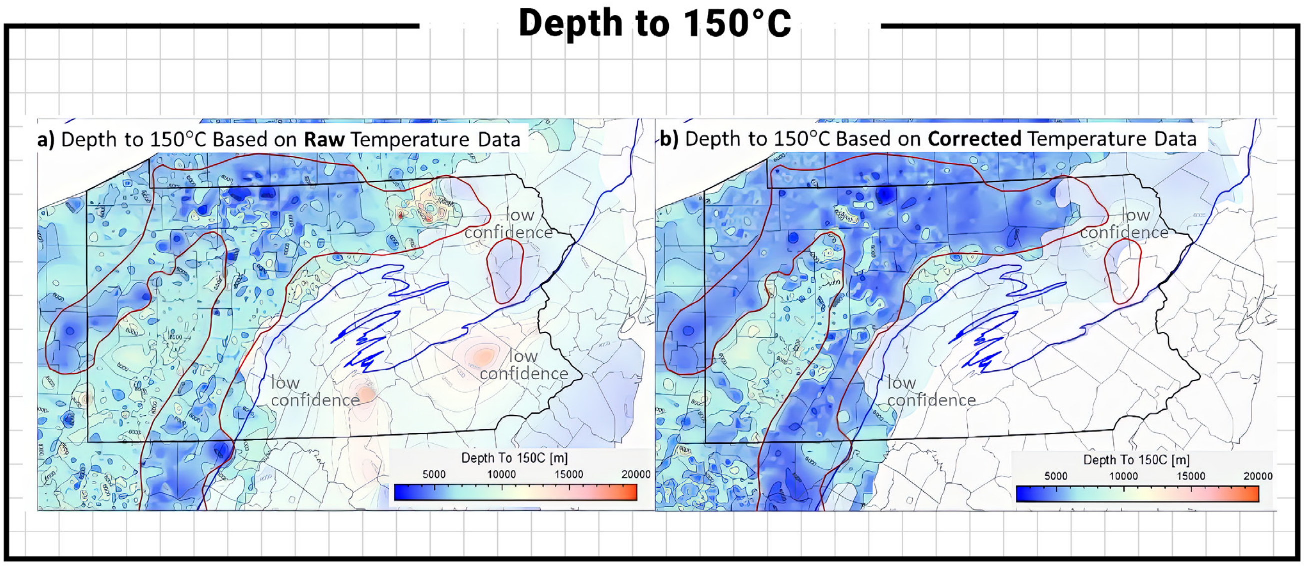


Figure 2.A.6: Based on a) raw temperature data and b) available corrected temperature data. The blue line indicates the eastern boundary of the Appalachian Basin. Red polygons outline increased thermal gradient. Low confidence areas are covered by transparent white overlay. Source: Author analysis.

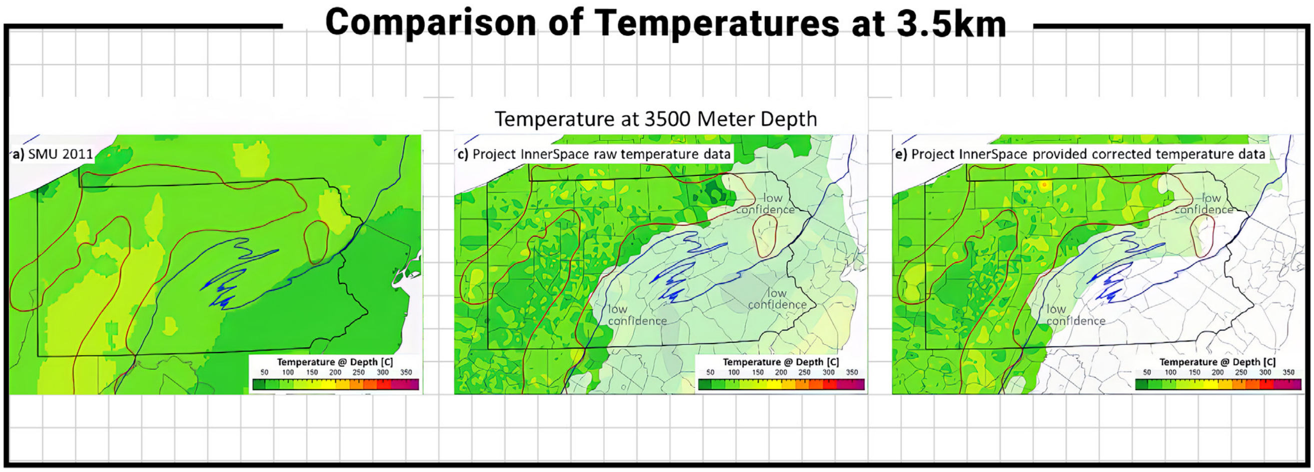


Figure 2.A.7: a) SMU 2011. c) InnerSpace raw temperature data. e) InnerSpace available corrected data. Red polygons highlight the areas of increased thermal gradient. The blue line shows the eastern boundary of the Appalachian Basin. Low confidence areas are covered by transparent white overlay. Source: https://www.smu.edu/dedman/academics/departments/earth-sciences/research/geothermallab/datamaps/temperaturemaps and authors' analysis.

Temperature Along the Available Structural Depth Surfaces

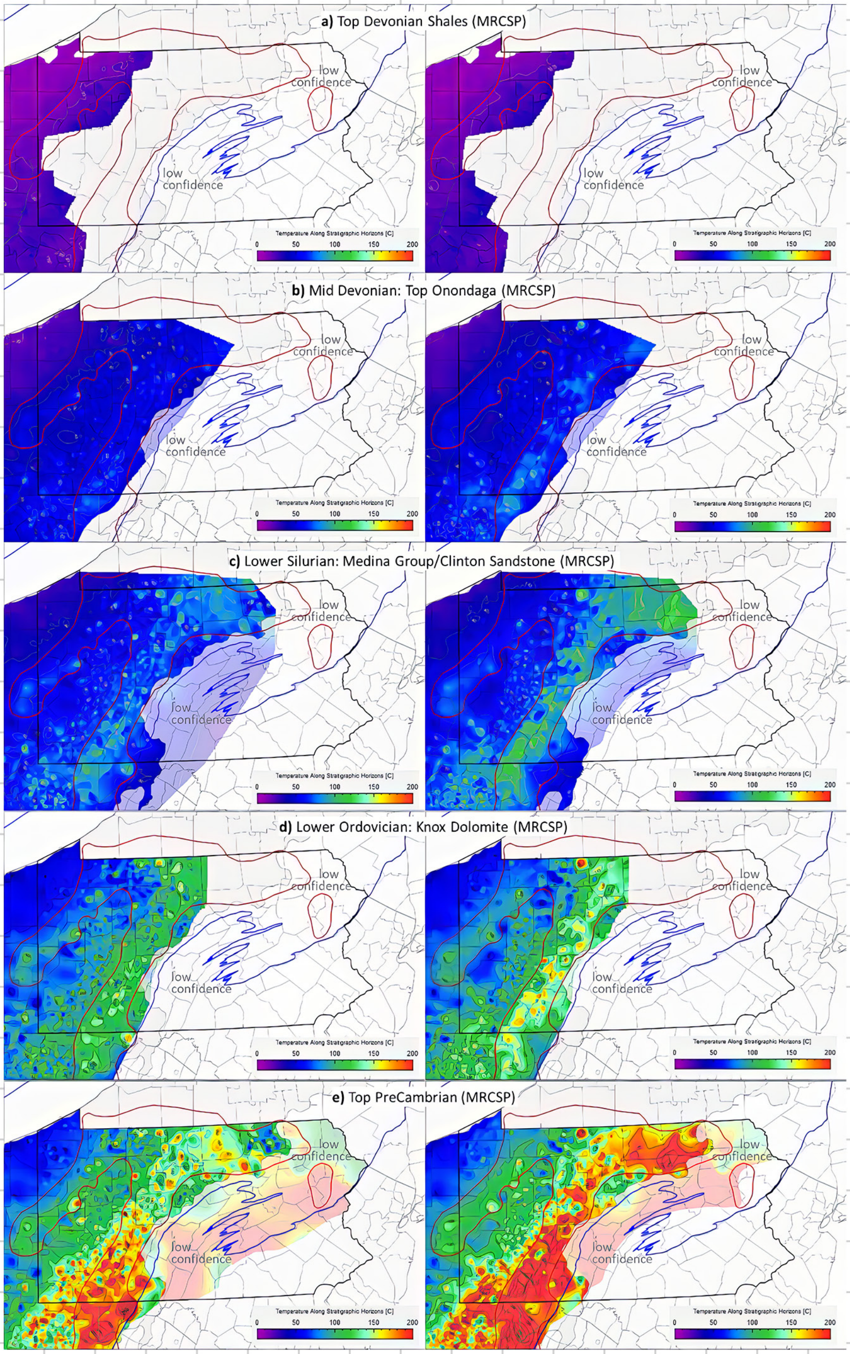


Figure 2.A.8: Left-hand side temperature values are based on raw temperature data. Right-hand maps are based on available corrected temperature data. The red polygons highlight the areas of increased thermal gradient. The blue line represents the eastern boundary of the Appalachian Basin. Low confidence areas are covered by transparent white overlay. Source: Author analysis

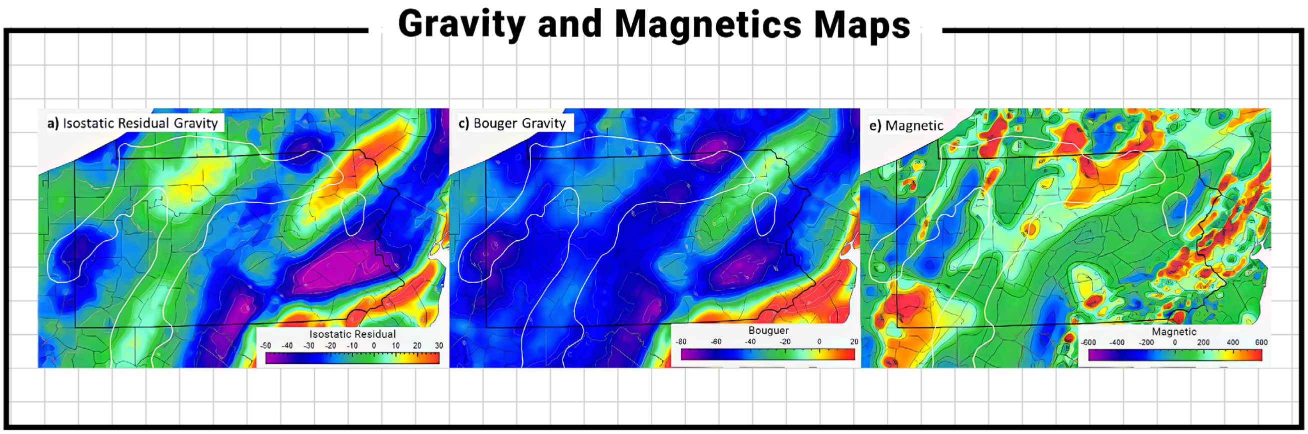


Figure 2.A.9: a) Isostatic Residual. b) Bouguer Gravity. c) Magnetic anomalies. Source: USGS. White polygons highlight the areas of increased thermal gradient.

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2 Low-temperature processes are generally defined as those requiring temperatures of less than 300°F (150°C). See Chapter 2: "Geothermal Direct-Use Opportunities" for a more in-depth look at manufacturing and industrial applications.

3 International Energy Agency (2024). The Future of Geothermal Energy. From https://www.iea.org/reports/the-future-of-geothermal-energy.

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6 Robins, Jody C., Devon Kesseli, Erik Witter, and Greg Rhodes. 2022. 2022 GETEM Geothermal Drilling Cost Curve Update: Preprint. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5700-82771. https://www.nrel.gov/docs/fy23osti/82771.pdf

7 Available data in this area consists of a cluster of shallow wells. A temperature of 152°F (67°C) represents an extrapolation of the shallower measurements. Further investigation will help confirm if the temperatures actually increase with depth and whether deep geothermal wells might provide additional geothermal opportunities.

8 This includes the Marcellus Shale, the key layer that supports the large majority of Pennsylvania’s recent natural gas exploration and production—and which has made Pennsylvania one of the largest natural gas producing states.

9 The depth surfaces presented in this study are a subset of available surfaces in the Midwest Regional Carbon Sequestration Partnership (MRCSP) dataset. They were selected because they do not intersect. Intersecting surfaces reflect contradictions from poor data rather than physical reality.

10 Where they exist, “corrected temperature” measurements were calculated as part of the original studies from which this aggregate database drew. This study relied on the original datasets and did not apply its own correction method. Properly correcting temperature data is custom site-specific work and must be undertaken at a prospect scale.

11 The accuracy and utility of these depth stratigraphic maps are limited by the extent of the available structural surfaces and the considerable uncertainty associated with their geometry and depth values. See MRCSP for additional detail.

12 A complete and consistent (not crossing/intersecting) set of depth structure/stratigraphic horizons is desirable to be able to tie the calculated temperature values to the lithology and related rock properties of the associated stratigraphic depth interval.

13 Cornell University (2016). Improvements in 2016 to Natural Reservoir Analysis in Low-Temperature Geothermal Play Fairway Analysis for the Appalachian Basin [data set]. From https://dx.doi.org/10.15121/1422756.

Chapter 3

Geothermal Direct-Use Opportunities: Meeting Heating and Cooling Demand Across the Commonwealth

J. Wen, R. Madsen (Contributing Author)

> ***Geothermal energy offers a key opportunity for Pennsylvania's industrial and agricultural sectors. Lancaster, Montgomery, and several other counties with high thermal energy demand are well-positioned to harness geothermal resources and promote sustainable growth, thereby increasing energy resilience and reducing the state's emissions.***

INTRODUCTION

As described in *Chapter 2: Where to Develop Geothermal*, many areas of Pennsylvania have a subsurface that can provide low to medium levels of heat—temperatures that could support a broad range of direct geothermal uses in industry and agriculture. This chapter outlines the opportunities for those sectors; capitalizing on them could help Pennsylvania continue its energy leadership and expand jobs for its existing energy workforce while providing abundant heat to vital economic sectors in the Commonwealth.

GEOTHERMAL DIRECT-USE IN INDUSTRY AND AGRICULTURE AROUND THE WORLD

In regions that have conventional hydrothermal resources, geothermal direct-use is already a fairly common solution for meeting industrial and agricultural thermal demands. In the United States, direct-use geothermal energy is mostly used in the food and beverage sector, for agricultural purposes, and for district heating. An onion dehydration plant in Nevada uses heat from the nearby Brady Hot Springs geothermal power plant;[1] potatoes in Oregon are dried via geothermal energy; Utah has one of the nation's largest geothermally heated greenhouses, growing poinsettias and other flowers. Many places in the U.S. use geothermal energy to melt snow and ice on roads and sidewalks. (See Lund, 2020 for more examples.)

Around the world, engineers have developed more complex geothermal direct-use applications. Iceland is perhaps the most well-known user of geothermal power and heat—harnessing it for power generation, district heating, and direct-use industrial and agricultural applications via a cascading combination of heat and power (see Figure 3.1). That said, the largest direct-use geothermal facility in the world is in New Zealand: the Norske Skog Tasman pulp and paper mill uses geothermal fluids to generate steam at 340°F (171°C) for paper drying, evaporators, and electricity generation.[2] There's also a Māori-owned dairy in New Zealand that uses geothermal to dehydrate milk powder.[3] In the Netherlands, the large greenhouse industry—which historically used as much as 8 percent of the nation's natural gas—began converting many of its operations to geothermal around 2010, and recent geopolitical conflict has accelerated its use.[4]

THERMAL ENERGY DEMAND IN PENNSYLVANIA

Overview of State Thermal Demand

Pennsylvania is one of the largest energy-consuming states in the country (see Table 3.1). In fact, the Commonwealth ranks in the top ten for energy use across the residential, commercial, industrial, and transportation sectors. Its industrial sector—manufacturing, mining, construction, and agriculture—

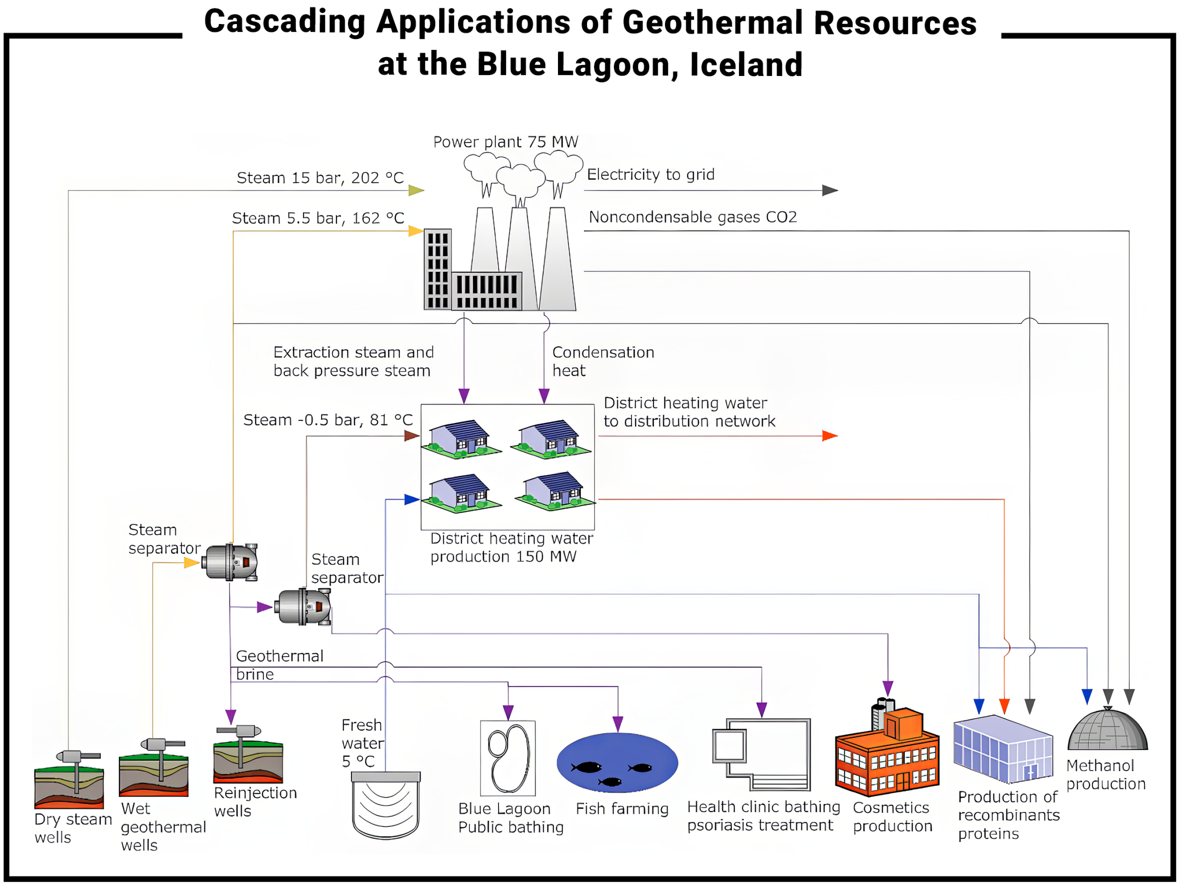
Cascading Applications of Geothermal Resources at the Blue Lagoon, Iceland

Figure 3.1: Source: Moya, D., Aldas, C., & Kaparaju, P. (2018). Geothermal energy: Power plant technology and direct heat applications. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2018.06.047

is the largest source of energy consumption in the Commonwealth (as shown in Figure 3.2) and ranks 4th for energy use in the nation. The independent research organization Rhodium Group estimates Pennsylvania's industrial energy consumption produces 45.05 million metric tons of carbon dioxide equivalent (CO_2e) per year. That amounts to as much as is produced by 11 coal-fired power plants.[5]

Much of Pennsylvania's industrial energy is used for generating heat for manufacturing. According to the Manufacturing Energy Consumption Survey (MECS) for the Northeast Census Region, fuel for manufacturing in the Northeast consumed 813 TBtu of energy in 2018, of which thermal energy (boiler use and direct-use process heating) accounted for 39.9 percent or 324 TBtu, as shown in the excerpt of MECS data in Table 3.2. Including combined heat and power (CHP) increases the amount to 448 TBtu (55.1 percent), however it is challenging to separate out how much of CHP is attributed to heat for processes as opposed to generating electricity.

Unfortunately, MECS data is not released on a state-by-state basis, so no exact figures for Pennsylvania exist. However, in 2018, the National Renewable Energy Laboratory (NREL) estimated Pennsylvania-specific manufacturing fuel consumption by combining the 2014 MECS with Census Bureau data.[6] The dataset provides thermal energy use estimates, broken down by industry and end use (boilers, CHP / cogeneration, and process heating). NREL's dataset indicates that thermal fuel consumption for Pennsylvania manufacturing accounted for 270.14 TBtu of energy in 2014.[7]

Along with manufacturing, agriculture also uses a significant amount of heat, both to keep greenhouses warm and to dry products before they are sent to market. As described in more detail later in this chapter, some of the counties that use the most heat for agriculture in the nation are in Pennsylvania.

2022 Total Energy Consumption Estimates by End-Use Sector, Ranked by State

Rank	Residential		Commercial		Industrial		Transportation		Total	
	State	Trillion Btu	State	Trillion Btu	State	Trillion Btu	State	Trillion Btu	State	Trillion Btu
1	Texas	1,633.4	Texas	1,546.1	Texas	7,338.5	Texas	3,268.8	Texas	13,760.6
2	California	1,203.7	California	1,193.1	Louisiana	2,950.5	California	2,915.8	California	6,882.4
3	Florida	1,182.6	Florida	969.8	California	1,539.3	Florida	1,738.8	Florida	4,325.0
4	New York	1,024.8	New York	930.4	**Pennsylvania**	**1,445.3**	New York	1,128.1	Louisiana	4,246.0
5	Illinois	925,5	Illinois	743.9	Indiana	1,180.0	Illinois	892.8	**Pennsylvania**	**3,736.9**
6	**Pennsylvania**	**880.7**	Virginia	734.1	Ohio	1,136.8	Georgia	875.4	Illinois	3,675.6
7	Ohio	844.5	Ohio	651.4	Illinois	1,109.0	Ohio	871.8	Ohio	3,503.2
8	Michigan	753.9	Michigan	579.0	Alabama	774.3	**Pennsylvania**	**852.5**	New York	3,452.7
9	Georgia	697.2	**Pennsylvania**	**559.4**	Iowa	771.3	N. Carolina	806.5	Georgia	2,836.2
10	N. Carolina	672.6	N. Carolina	558.3	Georgia	738.9	Louisiana	755.9	Michigan	2,706.8

Table 3.1: Source: U.S. Energy Information Administration (EIA), Table C11, eia.gov

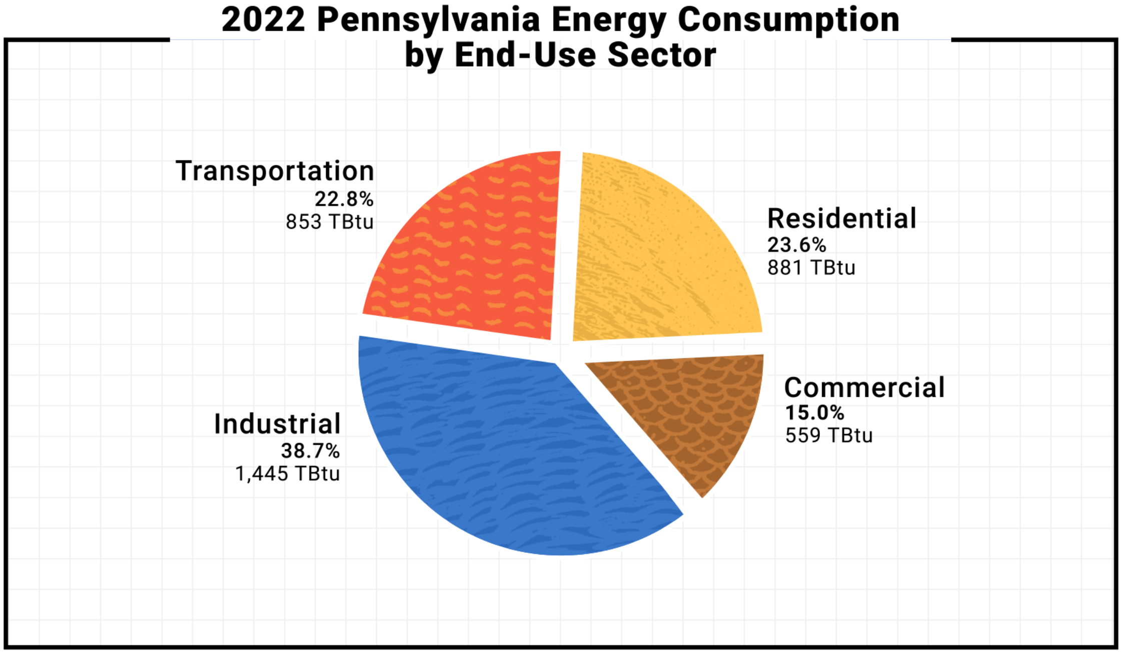

Figure 3.2: Source: EIA, State Energy Data System, eia.gov

Selected Manufacturing End Uses of Fuel Consumption

End Use	Electricity	Fuel Oil	Distillate & Diesel	Natural Gas	Gas Liquids	Coal	Total	Percentage of Total
Indirect Uses Boiler Fuel	6	2	1	177	1	13	200	24.6%
Conventional Boiler Use	6	1	*	67	1	1	76	9.3%
CHP and/or Co-generation	-	1	1	110	*	12	124	15.3%
Direct Uses - Total Process	200	1	10	242	2	6	461	56.7%
Process Heating	31	1	Q	209	2	5	248	30.5%
Other End Use	70	1	4	71	6	0	152	18.7%
Total - All Uses	**276**	**4**	**15**	**490**	**9**	**19**	**813**	**100.0%**
Total - Thermal End Uses	37	2	0	276	3	6	324	39.9%

Table 3.2: Table shows subset of 2018 Manufacturing End Uses for the Northeast Census Region. Blank cells indicate total consumption of less than 0.5 Tbtu. "Q" cells indicate a standard error of greater than 50%. "Other End Use" combines all other end uses not explicitly detailed. Source: Adapted from EIA's Manufacturing Energy Consumption Survey (MECS), Table 5.8, eia.gov

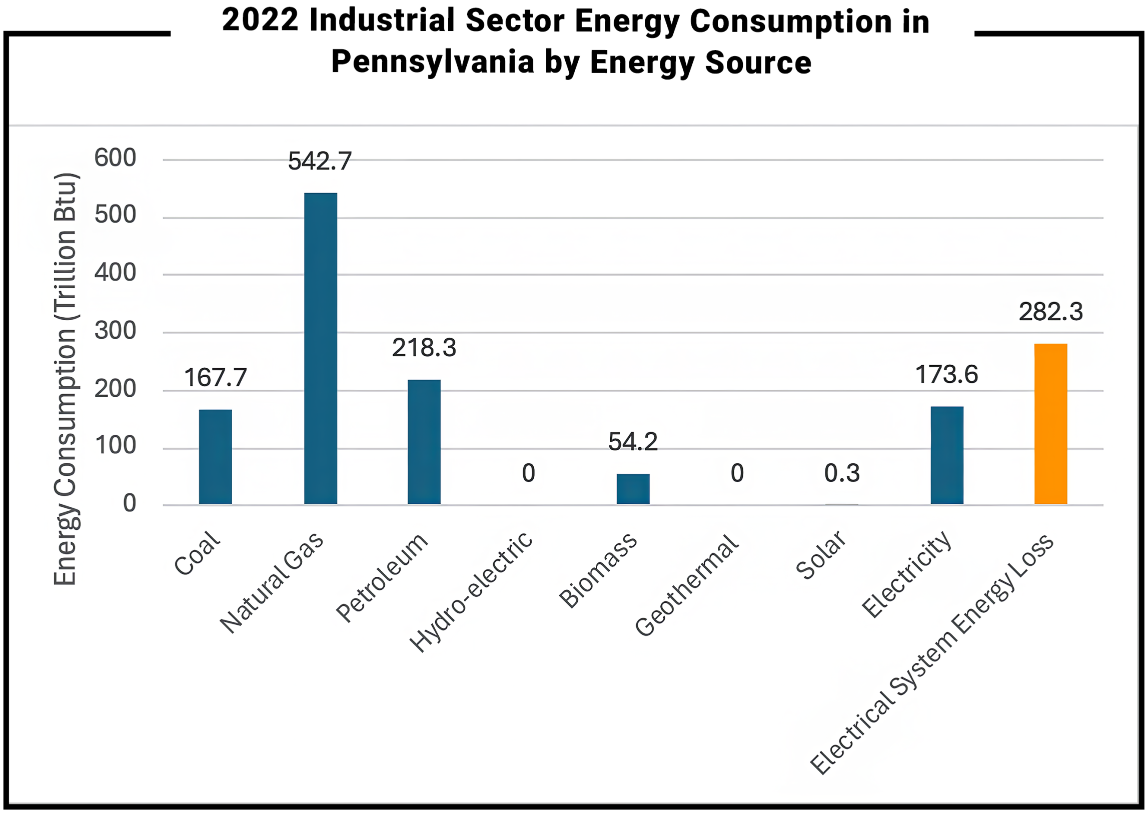

Figure 3.3: All units in Trillion Btu. Source: Based on EIA Table C7, 2022. eia.gov

Currently, almost all Pennsylvania industrial heat, whether for manufacturing or agriculture, is generated by burning fossil fuels. Figure 3.3 provides a detailed breakdown of Pennsylvania's 2022 industrial sector consumption by energy source. As shown, natural gas is the predominant energy source, powering nearly 40 percent of Pennsylvania's industry (542.7 TBtu), followed by petroleum (15 percent), electricity (12 percent), and coal (11.6 percent). Demand growth from AI and data centers is expected to substantially drive up industrial sector electricity consumption.[8] Notably, Pennsylvania's industrial sector currently uses no geothermal.

Manufacturing Process Heating and Cooling by Temperature Range, Industry, and County

Countless different manufacturing processes consume thermal energy, and their temperature needs can vary widely, from milk pasteurization on the low end to cement manufacturing on the high end.

The NREL dataset includes some process temperatures, but it is primarily a breakdown of fuel consumption by county. The authors of this chapter combined that dataset with a more granular breakdown of process temperatures from Brown, et. al (1985)—which collected hyper-granular temperatures for 108 different manufacturing processes, including industrial cooling.[9] This chapter therefore goes beyond the NREL analysis to identify the temperatures of manufacturing process demand in each of Pennsylvania's counties.[10] Reviewing data on temperatures and energy consumption for process heating and cooling across Pennsylvania's industrial landscape reveals distinct temperature needs in different manufacturing sectors across the Commonwealth (see Figure 3.4). The highest demand is seen at temperatures above 450°C, but there is also significant demand below 250°C. As of 2014, Pennsylvania had about 36 TBtu of industrial thermal energy consumption in the 100-149°C range, 14 TBtu in the 150-199°C range, and 29 TBtu in the 200-249°C range.

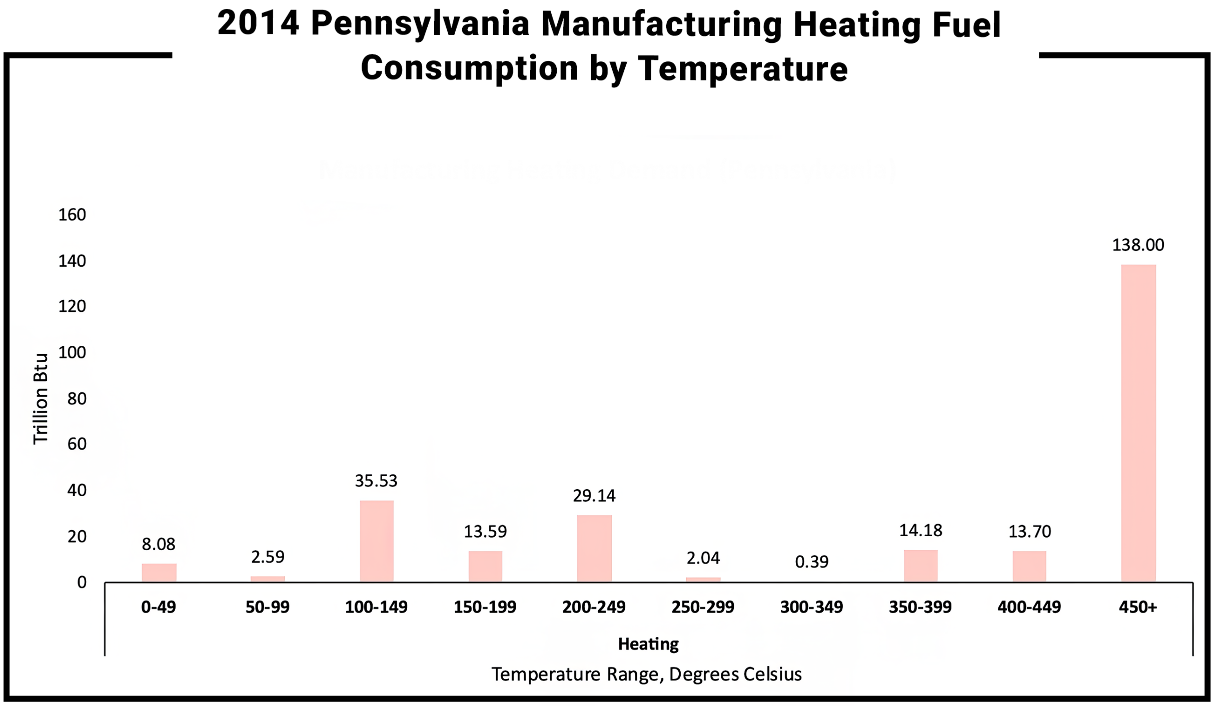

Figure 3.4: Authors' analysis of NREL dataset combined with process temperature data.

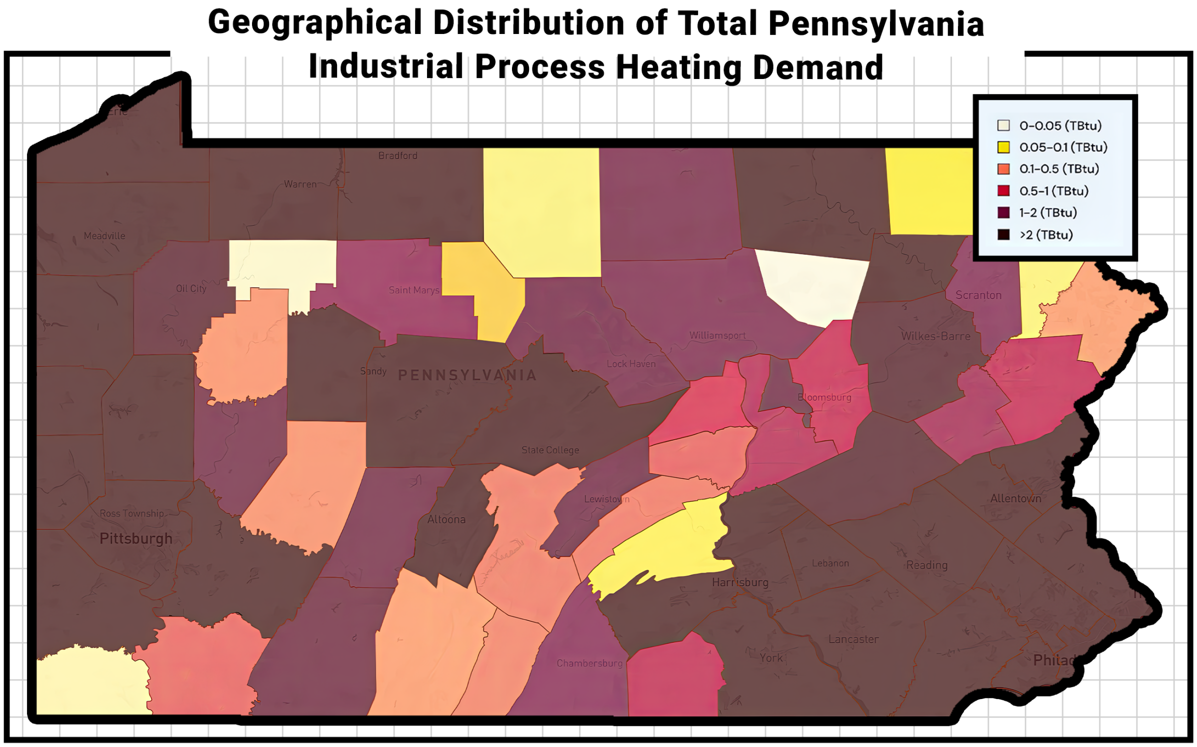

Figure 3.5: Authors' analysis of NREL dataset combined with process temperature data. Source: GeoMap

Aggregate demand is relatively distributed across Pennsylvania, with concentrations in the southeast, the central part of the Commonwealth, and along the western and northern border counties (see Figure 3.5).

While geothermal may be used for processes with higher temperatures, current technology and Pennsylvania's subsurface make geothermal especially suitable for use in lower-temperature applications, from 0 to 150°C. In Pennsylvania, industrial processes in these temperature ranges are concentrated in Wyoming, Montgomery, Philadelphia, Dauphin, Delaware, Lancaster, and York counties, all of which have 2 TBtu or more of demand in that range (see Table 3.3).

At these lower temperatures, Pennsylvania's manufacturing sector heating demand is dominated by several industries (see Table 3.4). In the 100-149°C range, the greatest demand comes from paper mills, which use steam and hot water in manufacturing. This demand is primarily located in Wyoming County.[11] Another significant source of demand in this range is the pharmaceutical and medicine sector concentrated in Montgomery County, which requires precision heating to maintain product integrity. There is also a fair amount of food manufacturing that occurs in this temperature range and the lower range of 50-99°C. In addition, while most processes in petroleum refineries need temperatures above 250°C, more than 35 percent of processes operate below that level, with 10 percent of consumption attributable to processes operating from 0 to 49°C. These low-temperature petroleum processes make up the majority of the process heating in Pennsylvania that occurs below 50°C.

Table 3.5 marries the data from the previous two tables (3.3 and 3.4) to show counties with high concentrations of demand in the 0 to 150°C range, broken down by industry. Doing so reveals clear concentrations. For example, in Wyoming County, pulp and paper mills appear to be the only meaningful source of 0 to 150°C demand. Philadelphia and Delaware counties show concentrations in petroleum and coal, followed by small fractions in pulp and paper mills. However, in Montgomery and Dauphin counties, the primary demand engines are pharmaceuticals and sugar and confectionary, respectively.

Counties with Highest Manufacturing Sector Heating Demand (0-150°C), TBtu

County	Demand (0-150°C)
Wyoming	5.64
Montgomery	4.65
Philadelphia	4.10
Dauphin	2.85
Delaware	2.52
Lancaster	2.26
York	2.07
McKean	1.61
Berks	1.44
Allegheny	1.40

Table 3.3: Authors' analysis of NREL dataset combined with process temperature data.

Online Data Exploration with GeoMap

*Much of the data presented in this analysis is available online through **GeoMap**, an interactive, open-source, and free platform on which individual users can explore and manipulate a variety of geothermal maps and relevant data, including temperature, depth, sources of energy demand, power plants, and more.*

Top 5 Pennsylvania Industries with Process Heating Demand (TBtu) in Selected Temperature Ranges (°C)

Industry	0-49	50-99	100-149
Paper (except Newsprint) Mills			8.71
Petroleum Refineries	6.74		
Dried and Dehydrated Food Manufacturing		0.85	2.59
Pharmaceutical Preparation Manufacturing			3.43
Reconstituted Wood Product Manufacturing			1.31
Other Snack Food Manufacturing		0.27	0.94
Toilet Preparation Manufacturing	0.21		
Adhesive Manufacturing	0.15		
Photographic Film, Paper, Plate, and Chemical Manufacturing		0.15	
Primary Aluminum Production	0.14		
Nonchocolate Confectionery Manufacturing		0.13	
Frozen Specialty Food Manufacturing	0.10		
Breweries		0.10	

Table 3.4: Authors' analysis of NREL dataset combined with process temperature data.

Agricultural Heating and Cooling by Temperature Range and County

The low heating and cooling temperature requirements of the agriculture sector in Pennsylvania make it an ideal candidate for ground-source heat pumps and geothermal direct-use. Heating demand in the sector is concentrated in the 0 to 99°C range, with 1.50 TBtu in the 0 to 49°C range and 5.89 TBtu in the 50 to 99°C range. Cooling requirements—for things such as food storage—are concentrated in the 0 to 24°C range, with a demand of 0.22 TBtu (see Figure 3.6).

As shown in Figure 3.7, thermal demand for Pennsylvania agriculture is geographically concentrated, with more than 1.1 TBtu of consumption in Lancaster County and another 1 TBtu in surrounding counties (York, Dauphin, Lebanon, Berks, Chester). These are some of the most heating-intensive counties for agriculture in the entire United States—in the top 1 percent—and are far and away the biggest counties for agricultural heat demand in the Northeast.

PROMISING COUNTIES AND INDUSTRIES FOR DIRECT-USE GEOTHERMAL DEVELOPMENT IN PENNSYLVANIA

The solutions to reduce emissions from industrial sector heat are still being developed, and include hydrogen, carbon capture and storage, and nuclear energy. In Pennsylvania, geothermal should also be part of the mix.

Process Heating Demand (0-150°C) for Selected Industries by Selected Counties (TBtu)

	Paper Mills	Petroleum & Coal	Pharma	Sugar & Confectionary	Other Food	Fruit & Veg.	Foundries	Soap & Cleaning
Wyoming	5.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Montgomery	0.00	0.00	3.19	0.06	0.05	0.03	0.01	0.02
Philadelphia	0.25	2.74	0.14	0.00	0.07	0.05	0.00	0.00
Dauphin	0.00	0.00	0.00	2.66	0.05	0.00	0.00	0.00
Delaware	0.31	1.60	0.01	0.02	0.00	0.01	0.00	0.00
Lancaster	0.00	0.00	0.01	0.32	0.14	0.04	0.07	0.02
York	0.29	0.00	0.02	0.00	0.82	0.23	0.07	0.00
McKean	0.00	0.96	0.00	0.00	0.00	0.00	0.00	0.00
Berks	0.28	0.00	0.02	0.32	0.05	0.12	0.09	0.01
Allegheny	0.00	0.01	0.07	0.04	0.05	0.65	0.08	0.01

Table 3.5: Authors' analysis of NREL dataset combined with process temperature data.

In *Chapter 2: Where to Develop Geothermal*, the authors provide insights into the easiest and most likely locations and depths necessary to develop geothermal resources. Overlaps between geothermal potential and low- to moderate-temperature industrial thermal demand may indicate which counties, and which industries, in Pennsylvania are likely best suited to take advantage of the Commonwealth's geothermal resources.

As noted, given current technology, it will be most economical in Pennsylvania to drill for geothermal at temperatures at or below 300°F (150°C). Combining the underlying data presented in this chapter and the information in Chapter 2, the maps in figures 3.8 through 3.10 illustrate the geographic distribution of industrial demand from 0 to 49°C, 50 to 99°C, and 100 to 149°C, overlaid with the most promising areas of geothermal potential in the Commonwealth.

As shown in Figure 3.8, thermal demand in the 0 to 49°C range and relatively favorable geothermal potential overlap in Delaware, Philadelphia, McKean, Butler, and Warren counties. As shown in Figure 3.9, there is only modest overlap of geothermal favorability and thermal demand in the 50 to 99°C range, though aggregate demand in this band is minimal. As shown in Figure

3.10, the 100 to 149°C band sees high concentrations of industrial heat overlapping with geothermal potential in Wyoming, Montgomery, and Lancaster counties.

Merging the aggregate geothermal favorability maps and the assessment of the industries within each county with thermal operating needs between 0 and 149°C can illuminate which industries in which counties might be best positioned to take advantage of geothermal energy. For example, petroleum and coal refineries in Philadelphia, Delaware, and McKean counties should look into using direct-use geothermal.[12] Low-temperature petroleum and coal processes might be suitable for geothermal energy use in Butler and Warren counties. Pharmaceutical manufacturing in Montgomery County may be especially suitable for direct-use geothermal, and the same is true for some greenhouses and other agricultural processes in York, Lancaster, and Chester counties.

Even outside the most geothermally favorable areas, ground-source heat pumps could be used across almost all of Pennsylvania for heating and cooling buildings, water heating, and refrigeration across industries.

CONCLUSION

Pennsylvania's thermal energy demand across the industrial and agricultural sectors presents a significant opportunity to diversify the Commonwealth's energy mix by taking advantage of geothermal. By leveraging low- to medium-temperature geothermal resources in the most favorable locations, Pennsylvania's manufacturers can meet their thermal energy needs while reducing emissions. The integration of geothermal energy into Pennsylvania's energy mix would not only support the Commonwealth's long-standing energy leadership but also promote sustainable economic growth. Pennsylvania's agriculture and manufacturing sectors are well-positioned to capitalize on this renewable energy resource for a more resilient future.

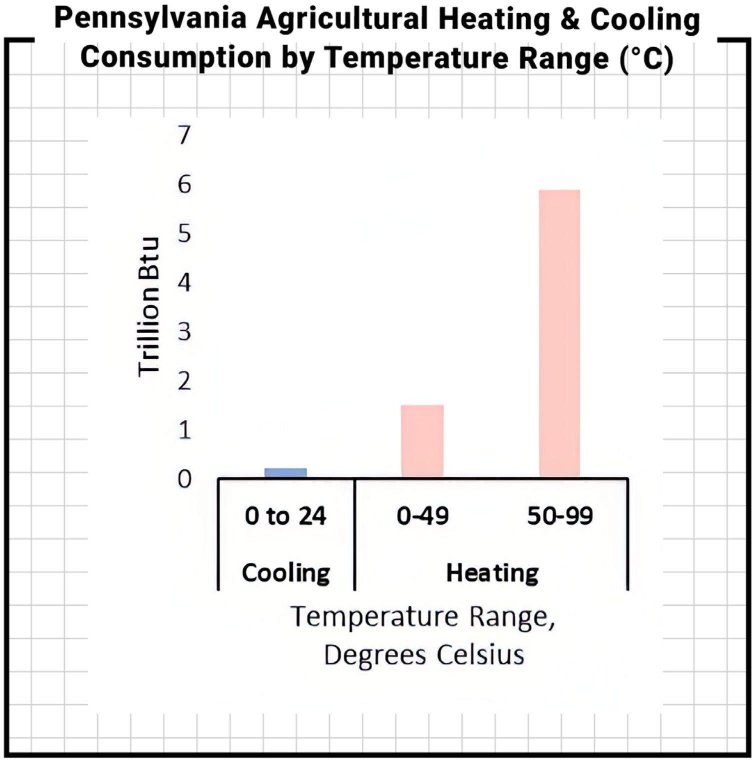

Figure 3.6: Authors' analysis utilizing NREL dataset combined with process temperature data.

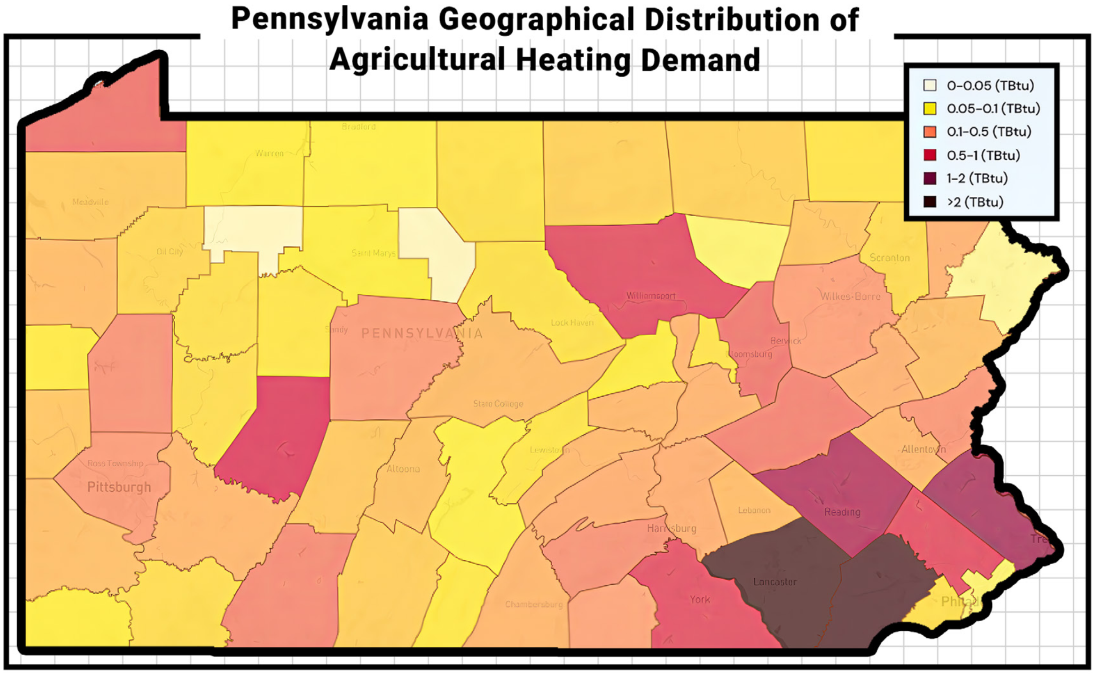

Figure 3.7: Source: GeoMap using NREL's Updated U.S. Low-Temperature Heating & Cooling Demand by County and Sector

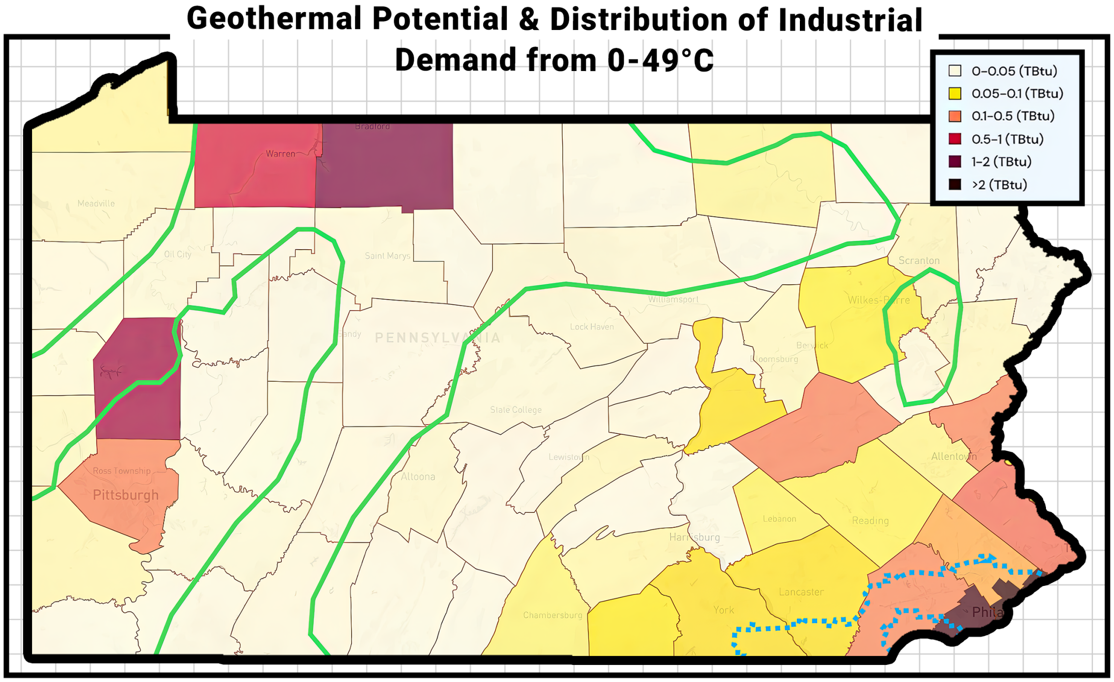

Figure 3.8: Pennsylvania's most favorable geothermal potential lies within the boundaries of the green lines, with additional exploration needed to confirm the favorability of areas within the blue line. Source: GeoMap and authors' analysis of NREL and process temperature data

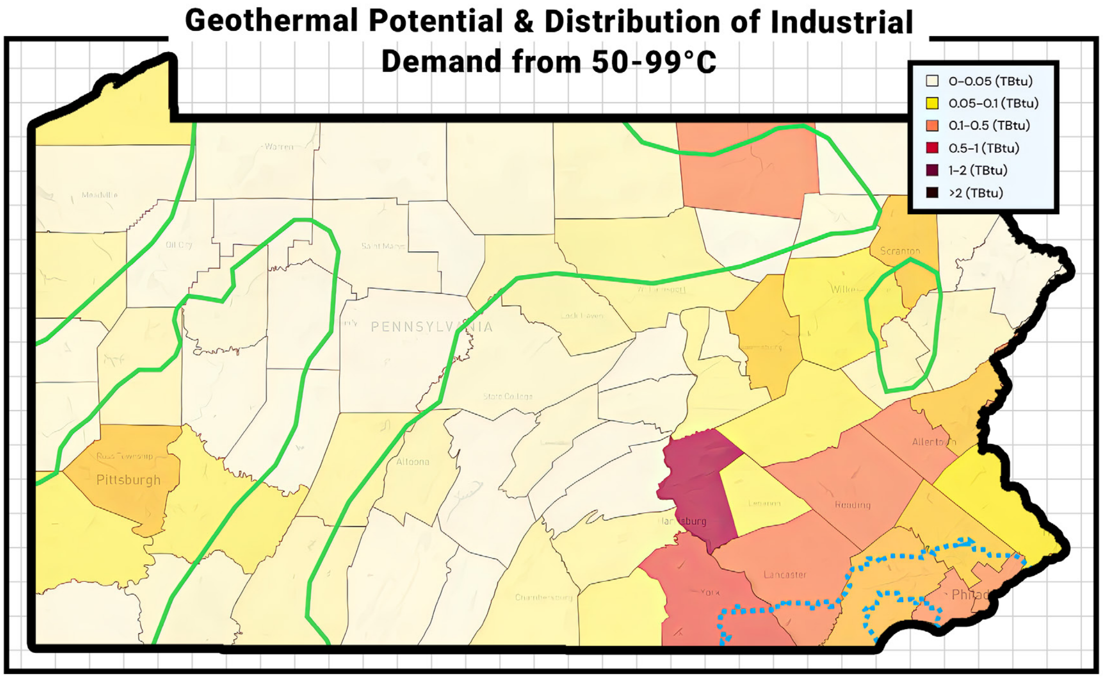

Figure 3.9: Pennsylvania's most favorable geothermal potential lies within the boundaries of the green lines, with additional exploration needed to confirm the favorability of areas within the blue line. Source: GeoMap and authors' analysis of NREL & process temperature data

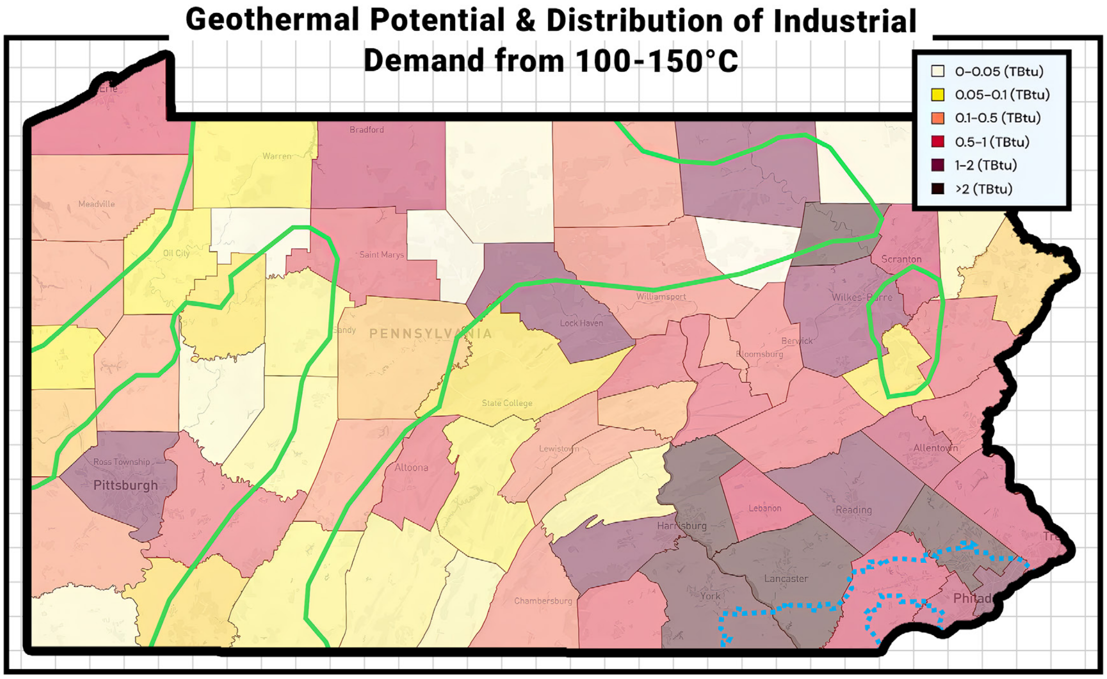

Figure 3.10: Pennsylvania's most favorable geothermal potential lies within the boundaries of the green lines, with additional exploration needed to confirm the favorability of areas within the blue line. Source: GeoMap and authors' analysis of NREL & process temperature data

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Supplement

Geothermal Cooling for Gas-Powered Data Centers in Pennsylvania

A single ChatGPT query consumes nearly ten times the electricity of a standard Google search. In early February 2025, Goldman Sachs projected that artificial intelligence (AI) would drive a staggering 160 percent increase in demand for data center power by 2030.[1] A significant proportion of that demand is used to keep data center infrastructure cool. In fact, cooling a data center can account for up to 40 percent of its total energy consumption and 50 percent of its CO_2 emissions.

Today, Big Tech companies are racing to find locations that can support the power needed for their expanding digital infrastructure. These companies would be well-served to look to Pennsylvania and geothermal energy. That is because the Commonwealth, renowned for its abundant natural gas reservoirs and production, enjoys a near-perfect nexus of energy resources and infrastructure for building new gigawatt-scale data centers powered by natural gas and cooled with geothermal.

Pennsylvania's suitability for geothermal cooling is less commonly understood but extremely valuable for data center developers. By coupling Pennsylvania's abundant natural gas resources with its subsurface cooling resources, less energy is needed to run a data center. This means companies can run less-expensive operations, or build larger data centers with little increase in power usage. And there are substantial geothermal resources in Pennsylvania's subsurface that can be used for cooling.

Using methods Project InnerSpace developed for the IEA's recent Future of Geothermal Energy Report,[2] we found that there are about 700 gigawatts of thermal resources within 13,000 feet of the surface in Pennsylvania that can be used for cooling. A 200 megawatt data center uses about 80 megawatts for cooling, so Pennsylvania has the technical potential to cool hundreds or thousands of data centers. While not all of this resource is recoverable right now, with today's technology, there is enough subsurface potential to cool

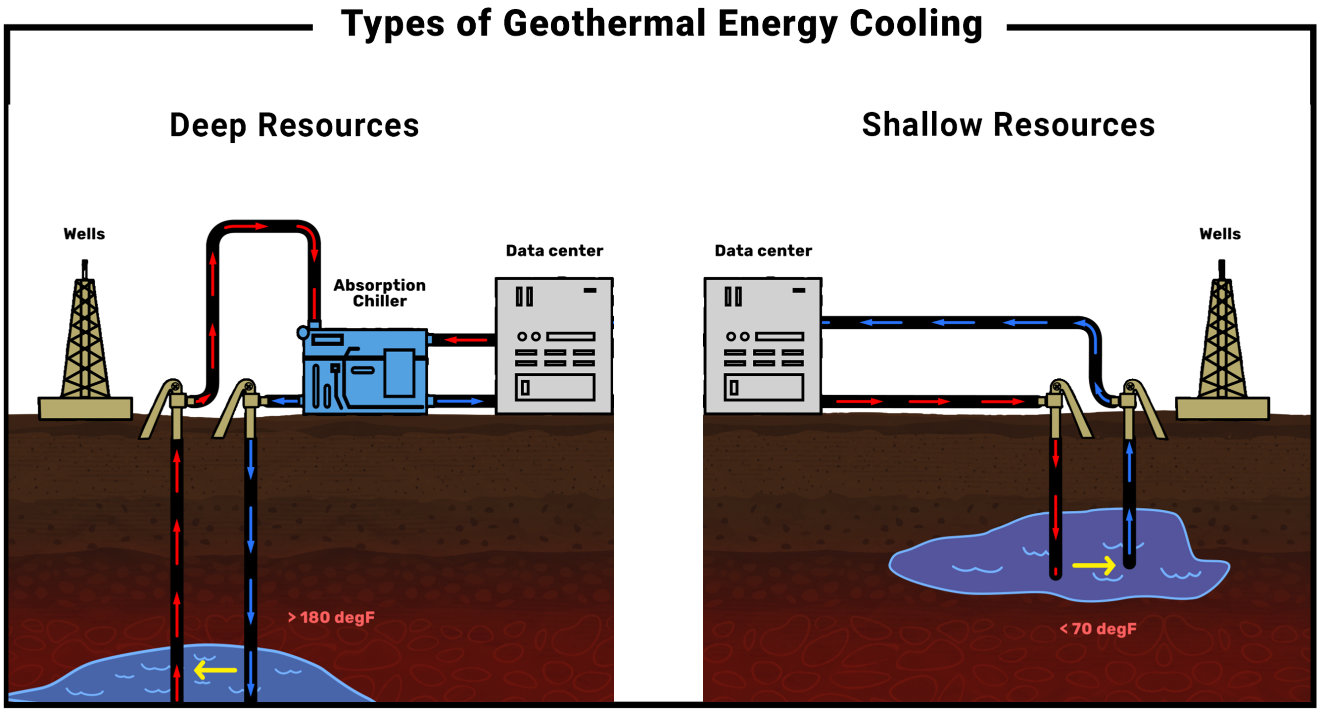

Figure 1: The geothermal resource acts as a closed circuit, where the fluid goes to the surface, delivers its energy, and is re-injected back into the subsurface to maintain the pressure and secure a long-lasting operation. Left: A deep resource requires an absorption chiller to transform the heat at 180° into cooling energy. Right: A shallow resource at less than 70° may be capable of directly providing the cooling energy to the data center.

a data center at a cost comparable to the drilling of an average onshore oil and gas well. Integrating geothermal cooling with natural gas-powered electricity reduces overall gas consumption and improves operations.

Depending on the available geothermal resources, there are two possible pathways for cooling a data center:

- A subsurface at less than 70°F allows for direct use of naturally cooled fluid to cool data centers. Examples include shallow aquifers and abandoned mines.

- A subsurface at greater than 180°F allows for the use of absorption chillers to transform hot fluids into super cold refrigerants.[3] For example, the Abu Dhabi National Oil Company (ADNOC) is using this method to provide 43°F refrigerant to cool Masdar City.

Of the 67 data centers already in Pennsylvania as of this writing—most of them close to Pittsburgh and Philadelphia—one already uses geothermal for cooling. The Iron Mountain Data Centers in Boyers, PA, uses a unique geothermal cooling system located 200 feet underground in a former limestone mine. The system uses an underground reservoir for cooling and its mechanics are not overly complex, which keeps maintenance costs low. The data center also has unlimited backup thermal storage capacity, unlike standard diesel backup generators, which can only provide energy for a limited number of hours. With this system, Iron Mountain saw a 34 percent reduction in total energy use.[4]

Integrating geothermal cooling systems with a gas-powered data center can offer several significant benefits:

1. Energy and System Efficiency

Geothermal cooling systems can significantly reduce the energy *consumption* of a data center. One study found that integrating geothermal cooling with a data center can reduce energy consumption by up to 30 or 40 percent.[5]

2. Operation and Maintenance Cost Savings

The energy efficiency gains from geothermal cooling can translate into significant cost savings for data centers. Recent studies from NREL suggest an annual cost savings of up to $1 million for a typical data center. Geothermal cooling systems can reduce energy costs by up to 30 percent compared to traditional HVAC systems.

3. Emissions Reduction

Geothermal cooling systems can help data centers reduce their carbon footprint by reducing reliance on fossil fuels. NREL found that integrating geothermal cooling can reduce CO_2 emissions by up to 50 percent.[6]

4. Water Consumption

Geothermal cooling can, when implemented as a closed-loop system, decrease the total water consumption of a data center compared to traditional cooling solutions.

5. Efficient System Design

If a data center is powered by natural gas, a geothermal cooling system can be designed to take advantage of the waste heat stream from a combined cycle gas turbine (CCGT) plant, increasing the overall efficiency of the cooling system. The same waste stream can be redirected for subsurface energy storage, thus augmenting the energy content of the cooling system. Such a design can create a significantly more energy-efficient plant.

The use of geothermal systems can also, depending on the system: offer additional benefits including a constant, secure energy supply, thereby reducing dependence on grid infrastructure; and serve as long-duration energy storage, retaining excess energy underground during periods of low demand and retrieving it when necessary.

For more information, see *Chapter 2. Where to Develop Geothermal*, and *Chapter 3: Geothermal Direct-Use Opportunities*.

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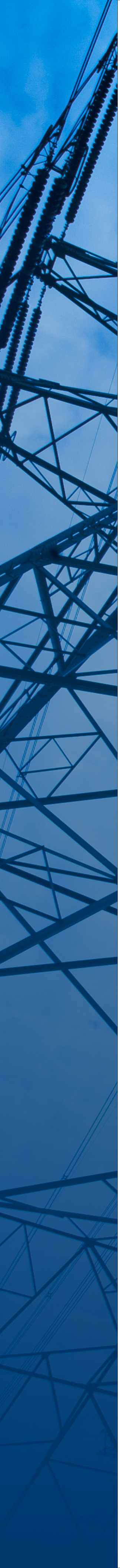

Part III

Legal, Regulatory, Environmental, and Stakeholder Considerations

Chapter 4

Who Owns the Heat? Navigating Pennsylvania's Geothermal Property Rights

T. Aagaard & R. Winfield

> ***Principles for addressing the ownership of geothermal resources and the rights of property owners can be derived from well-established rules developed over the years in Pennsylvania property law—particularly related to oil and gas, coal mining, and water extraction. This should mean that, regarding ownership, geothermal projects in the Commonwealth should be able to move forward without additional legislative action.***

INTRODUCTION

As geothermal energy becomes more widely used, questions of who owns the resources associated with geothermal energy—heat, water, steam, and pores in the earth—will become increasingly important. Although no Pennsylvania court has yet addressed these questions, or even mentioned the term "geothermal" in a published decision,[1] established principles of deed interpretation, the Dunham Rule, and other Pennsylvania case law and statutes support the conclusion that geothermal energy and the resources required to harness it are owned by the surface owner of real property (unless a deed or other conveyance dictates the contrary). Because ownership of resources associated with geothermal energy can be derived from existing Pennsylvania law, geothermal projects in the Commonwealth should be able to move forward without waiting for further clarification or change in state law on the issue. This gives Pennsylvania an advantage over some states which require legislative changes to clarify heat ownership.

FOUNDATIONAL CONCEPTS OF PROPERTY OWNERSHIP IN PENNSYLVANIA

Deed Interpretation: How Do We Know Who Owns What?

When a grantor conveys a parcel of land to a grantee, the language of the deed determines who owns the land and what interests the deed conveys.[2] The courts look to establish the meaning of the words in the deed by reference to the deed itself, taking all of the language in the deed together.[3] In other words, the courts look to the intention of the parties to determine what the deed means.[4] Pennsylvania courts have applied these principles when interpreting deeds that transfer subsurface resources, such as coal, natural gas, and oil.[5]

Ownership of the Land: Three Estates in One Parcel

In Pennsylvania, an owner of land owns her property "from the center to the surface, and from the surface to the heavens."[6] This is known as the *ad coelum* doctrine, and it is an ancient and widely followed principle of property law.[7]

Although the default rule under the *ad coelum* doctrine is that one owner owns the surface and subsurface of a parcel, a property owner's parcel can be divided into three distinct components: the surface estate, the subsurface or mineral estate, and the right of subjacent (surface) support.[8] Different people can own each part separately, in the same parcel of land.[9] If the three estates are not explicitly divided, then the owner of the property automatically owns all three estates.[10]

The surface estate is, fairly clearly, just the surface of the Earth. The subsurface estate, or the mineral estate, includes everything below the surface. Pennsylvania courts use *mineral estate* or even *coal estate* interchangeably with the term *subsurface estate*.[11] The subsurface estate can be further subdivided into smaller interests.[12] For example, the owner of a parcel of land could sell the coal rights to one owner and then sell the natural gas and oil rights to another.[13] Those portions of the subsurface estate that have not been specifically severed from the surface estate belong to the owner of the surface estate.

The right of subjacent support is not an estate in the same way that the subsurface and surface estates are. Instead, it means that the surface owner has a right to insist that the subsurface owner not damage the surface by causing subsidence. This is consistent with the general principle that each owner must enjoy their property without harming the other's property.[14] A person can also waive the right of support when severing the surface and subsurface estates, although this should be done expressly.[15] The right of subjacent support can be relevant in the geothermal context where, depending on the geological features and the geothermal technology deployed, use or withdrawal of significant amounts of water can cause the land surface to subside.[16]

Ownership of Fugitive Resources: The Relationship with Adjoining Parcels

The general principle of *ad coelum* does not apply to so-called fugitive resources such as oil, gas, and groundwater that can pass underground from one parcel to another. Pennsylvania courts characterize these resources as minerals *feroe naturoe*—those that "have the power and the tendency to escape without the volition of the owner."[17] Subsurface oil, gas, or water are in theory owned by the surface owner of the parcel under which the resource is resting, or the owner of the relevant subsurface estate.[18] However, once those resources travel to another piece of property, they belong to the owner of that parcel.[19] Ownership of the fugitive resource is only fully established when it comes under someone's control, such as when it is pumped to the surface from a well.[20] In other words, "if an adjoining, or even a distant, owner drills his own land, and taps your gas, so that it comes into his well and under his control, it is no longer yours, but his."[21] This is known as the *rule of capture*.[22]

The rule of capture is potentially relevant to the ownership of geothermal resources. For example, if a property owner extracts subsurface water from under their property to harness geothermal energy, and thereby reduces the water under a neighbor's property,

the property owner actively extracting the water would be seen as the owner of the subsurface water.

The Meaning of Owning "Minerals": The Dunham Rule

As noted, the language of a deed is all-important in estate rights. Many subsurface deeds or leases convey the rights to minerals, thereby generating disputes over what falls within the category of minerals. In the majority of states, courts define minerals to include all inorganic substances for which mining or drilling is commercially profitable.[23] Pennsylvania, however, takes a different approach, known as the Dunham Rule, from the 1882 Pennsylvania Supreme Court case of *Dunham v. Kirkpatrick*.[24]

Dunham involved a dispute between the owner of the surface estate—Kirkpatrick—and the owner of the mineral estate of the parcel—Dunham.[25] The pertinent clause in the deed gave the mineral estate owner rights to "all minerals."[26] When the owner of the mineral estate entered the parcel and began to drill for oil, the surface owner objected.[27] The Pennsylvania Supreme Court held that the term minerals as used in the deed did not include oil.[28] Instead, the court reasoned that, although oil would be included in the most comprehensive meaning of the term, the court's job was to interpret the deed based upon the parties' intention in drafting the deed.[29] The parties did not intend a broad, scientific meaning of minerals because normal laypeople would understand the term to mean a metallic substance.[30]

In support of its reasoning, *Dunham* cited the earlier case of *Gibson v. Tyson*.[31] In that case, a deed had granted the rights to "all mineral or magnesia of any kind" in a subsurface estate.[32] The Pennsylvania Supreme Court held that the term mineral should be construed in its "ordinary" sense, as it is employed in "general and popular use," and that in this use the term meant "ores and other metallic substances found beneath the surface of the earth, and all other substances which are the object of mining operations."[33] Applying *Gibson*, the *Dunham* court concluded that, absent clear and convincing evidence showing the parties' intentions to the contrary, the term minerals does not include oil.[34]

Subsequent Pennsylvania cases have reaffirmed *Dunham*, despite its unpopularity in other states.[35] In the 1960 case of *Highland v. Commonwealth*,[36] the Pennsylvania Supreme Court held that the Dunham Rule creates a strong presumption that an interest in subsurface "minerals" does not implicitly include oil or natural gas.[37] The 2013 case of *Butler v. Charles Powers Estate ex rel. Warren* again reaffirmed *Dunham*, finding that the owners of "minerals" did not also own the shale gas.[38]

In repeatedly rejecting bids to limit or overrule the Dunham Rule, the Pennsylvania Supreme Court has reaffirmed that "the common, layperson understanding of what is and is not a mineral is the only acceptable construction of a private deed."[39] Thus, a long line of cases supports the ongoing vitality of the Dunham Rule in Pennsylvania. As applied to deeds and leases that convey a right to subsurface minerals, the meaning of the rule is relatively clear: deeds or leases should be construed as they would be understood by those negotiating them, and substances not specifically identified or contemplated in the deed or lease should be presumed to have not been conveyed (and are thus owned by the surface owner).

As applied to geothermal resources, the Dunham Rule seems to support the rights of the surface owner as opposed to an owner of the subsurface estate, in the absence of specific language to the contrary in the deed or lease. This is because a deed for a traditional subsurface resource such as oil, gas, coal, or minerals was almost certainly not intended to include the rights to geothermal resources such as heat, steam, or water. In other words, if parties intend to convey the rights to geothermal resources, they should explicitly name those resources in the conveyance.

Ownership of Pore Space

There are no cases in Pennsylvania that address the ownership of pore space.[40] However, case law does provide some reasoning relevant to the issue of title over pore space in the Commonwealth. In the 1990 Superior Court case of *Pomposini v. T.W Phillips Gas & Oil Co.*,[41] a lessee was conveyed rights for drilling and operating for oil and gas, but for twenty-seven years, they were using the land primarily for storage of gas.[42] The court had to interpret the deed to determine whether the lessee had misused the lease.[43] The court determined that, because the lease only conveyed the ability to drill and operate, "the right to extract gas did not include the right to use the cavernous spaces owned by the lessor for the storage of gas in the absence of an express agreement."[44]

Then, in the 2012 federal district court case of *EXCO Resources, LLC v. New Forestry, LLC*,[45] New Forestry owned a surface estate, under which EXCO owned the oil and gas rights via a deed that severed all "rights, titles, and interests in and to all of the oil and gas ... and the space occupied thereby."[46] The issue presented was "whether EXCO's ownership rights permit[ted] it to dispose of liquid waste from fracking operations beneath New Forestry's land" in the space once occupied by oil and gas.[47] The court acknowledged that the owner of the oil and gas rights has an interest in the space occupied by the oil and gas, but reasoned that a plain reading of the deed showed that the parties did not intend for the oil and gas rights owner also to have rights to use the subsurface space for waste fluid disposal.[48]

As this paper was being completed, the Pennsylvania General Assembly gave even more support to those past rulings: Act 87 explicitly gives surface owners the ownership of pore space "unless the agreement expressly includes conveyance of the pore space."[49]

RELEVANT PRINCIPLES RELATED TO USE OF PROPERTY

The Implied Right of Use

Conflicts between mineral owners and surface owners are common.[50] The entity who has the rights to the subsurface of a piece of land has, implicit in the grant of subsurface rights, the right to use the surface for "reasonably necessary" operations.[51] But when using the surface land, the subsurface owner must exercise "due regard" for the surface.[52]

These rights are implicit; they don't have to be spelled out in a deed or lease. Nevertheless, many subsurface deeds and leases do contain language expressly giving the subsurface rights holder the right to use the surface to the extent that such use is "necessary" or "convenient" to the extraction of the subsurface resources.[53]

Just as the subsurface estate owner has the right to use the surface to access the subsurface, the surface owner (or an owner of another subsurface estate) has the right to use other aspects of the subsurface to reach their property (see *Chartiers Block Coal Company v. Mellon*).[54]

For geothermal energy purposes, this would mean that, if a property owner had conveyed the coal rights or natural gas rights to another party, then the property owner—or their grantee or lessee of the rights to the geothermal resources—would still have the right to go through those resources to reach the heat, water, or other resources needed for geothermal energy. As described below, however, this right would potentially be subject to restrictions to protect against harm to the coal or natural gas resource.

Interference with Use

The courts have not resolved all questions about the relationship between owners of different estates when it comes to implied rights to subsurface resources. Harmonizing relationships among owners of different estates on the same lands requires principles that enable access but also protect against interference. The same is true regarding relationships between owners of subsurface rights and owners of rights on nearby parcels.

In general, when different estates on the same land are separate, the owners of each estate must try to prevent wanton interference with the other's estate.[55] This rule is similar, in a sense, to the right of support and the implied right of use described earlier in this chapter. The owner of an estate must enjoy her rights in such a way that it does not interfere with the lawful exercise of the rights of the owners of other rights in the same land.[56] For example, the court has held that a surface owner has every right to the portion of the estate underlying another subsurface interest—say coal strata—conveyed to another, but he has to exercise his right to that portion without causing damage to the coal strata.[57] If he did cause harm, the coal rights owner would be entitled to damages, though the court left open the question of what limitations may be necessary.[58]

Pennsylvania cases have not resolved the question of what claims different subsurface rights holders have against one another when one's extraction activities hinder another's. Presumably, a subsurface rights holder is not strictly liable when its activities to extract its resources cause damage to other subsurface resources, just as a subsurface rights holder is not strictly liable for any damage it causes to the surface.[59]

Similarly, concerns may arise with one parcel owner interfering with the rights of the owner of another adjacent or nearby parcel. Pennsylvania courts, for instance, have long addressed disputes between adjoining property owners upset about the disruption of their underground water supplies. In deciding such cases, the courts have held that acts by adjoining owners can damage, or even destroy, a spring that depends upon filtrations and percolating waters underneath and through their lands without liability, so long as the interference is not malicious or negligent.[60] An adjoining landowner would, however, be liable for interference caused by an "ultrahazardous activity," such as blasting rock.[61]

In the 2020 case of *Briggs v. Southwestern Energy Production Company*,[62] the Pennsylvania Supreme Court addressed the issue of interference in the context of hydraulic fracturing. The court applied the rule of capture to hydraulic fracturing, holding that a plaintiff alleging trespass due to the drainage of gas from underneath their property must allege that the defendant physically invaded the subsurface of the plaintiff's property.[63] On remand, the Superior Court held that "the propulsion of fracturing fluid and proppants into an adjoining property can constitute a physical intrusion." In other words, that would be a trespass.[64]

Some geothermal systems use hydraulic fracturing to help collect geothermal heat from subsurface rock formations that would otherwise be impermeable or poorly permeable. Geothermal systems also often inject water underground to be heated and then extracted. It appears, based on *Briggs*, that Pennsylvania courts would likely hold that propelling fluids under a neighboring parcel for the purpose of geothermal resource development would constitute a trespass if done without permission. Merely extracting groundwater or heat from underneath a neighboring parcel, however, would not create liability, at least where (a) no equipment extends underneath the neighboring parcel and no fluids are propelled underneath the neighboring parcel;[65] and (b) the extraction is not malicious or negligent. It is unlikely that geothermal energy development would be considered an ultrahazardous activity, because drilling down to harness the energy of steam and water is not at all similar to blasting rock.

Geothermal resources generally will belong to the surface owner, unless a deed or lease says differently.
Owners of geothermal resources will have the right to cross other surface and subsurface parts of the property to access the resources, but they are obligated to avoid unnecessary damage to those other estates.
Owners of geothermal resources will have the right to extract heat, water, and steam from underneath adjoining parcels but must avoid physically intruding under the surface of those other parcels without permission.

CONCLUSION

Although the Commonwealth's courts have not yet interpreted a deed in the context of geothermal energy and its associated resources, principles for addressing the ownership of geothermal resources and the rights of property owners can be derived from well-established rules developed over the years in Pennsylvania property law—particularly related to oil and gas, coal mining, and water extraction. First, geothermal resources generally will belong to the surface owner, unless a deed or lease says differently. Second, owners of geothermal resources will have the right to cross other surface and subsurface parts of the property to access the resources, but they are obligated to avoid unnecessary damage to those other estates. Finally, owners of geothermal resources will have the right to extract heat, water, and steam from underneath adjoining parcels but must avoid physically intruding under the surface of those other parcels without permission. These settled principles should mean that geothermal projects in the Commonwealth can move forward without any additional action from the legislature regarding ownership of subsurface resources associated with geothermal energy.

CHAPTER REFERENCES

1 Pennsylvania has four separate statutes that mention "geothermal energy." It is included in the definition of "renewable energy source" in the Municipalities Planning Code, 53 Pa. Cons. Stat. § 10107; in the definition of "renewable resource" in the Public Utility Code, 66 Pa. Cons. Stat. § 2803; in the definition of "energy producing facilities" in the Economic Development Financing Law, 73 Pa. Cons. Stat. § 373; and in its own right as an "alternative energy source" in the Alternative Energy Portfolio Standards Act, which defines it as "electricity produced by extracting hot water or steam from geothermal reserves in the earth's crust and supplied to steam turbines that drive generators to produce electricity," 73 Pa. Cons. Stat. § 1648.2.

2 *See Highland v. Commonwealth*, 161 A.2d 390, 402 (Pa. 1960).

3 *Id.*

4 *See Butler v. Charles Powers Estate ex rel. Warren*, 65 A.3d 885, 891 (Pa. 2013).

5 *Id.; see also Highland*, 161 A.2d 390.

6 *Algonquin Coal Co. v. Northern Coal & Iron Co.*, 29 A. 402, 403 (Pa. 1894).

7 *See U.S. v. Causby*, 328 U.S. 256, 260 (1946); see also *Algonquin Coal*, 29 A. at 403. The one exception, perhaps, to the *ad coelum* doctrine in the modern world is the airspace above one's land. See *Causby*, 328 U.S. at 260 (stating that, in the modern world, owning one's land "to the heavens" was not practicable when Congress had declared the airways a public highway). This limitation, while important generally, has not been extended past airspace and so is not particularly relevant to geothermal energy and subsurface resources. Moreover, even as to airspace, the surface owner has some ownership rights. Cf. Tiffany Real Property § 583 (noting that "[w]hether the owner of the land ... actually owns the air space above the land ... is a question of difficulty").

8 *See Penn. Services Corp. v. Texas Eastern*, 98 A.3d 624, 629 (Pa. Super. 2014).

9 *Id.*

10 *See Algonquin Coal*, 29 A. at 403.

11 *See, e.g., U.S. Steel v. Hoge*, 468 A.2d 1380, 1384 (Pa. 1983).

12 *See, e.g., Hetrick v. Apollo Gas Co.*, 608 A.2d 1074, 1077-8 (Pa. Super. 1992).

13 *Id.* Once the subsurface estate has been severed from the surface estate, adverse possession of the surface estate does not acquire title to the subsurface estate, although adverse possession of the subsurface estate can take title to the subsurface. *See Delaware & Hudson Canal Co. v. Hughes*, 38 A. 568, 569 (Pa. 1897).

14 *See Carlin v. Chappel*, 101 Pa. 348, 352 (1882).

15 *Walter v. Forcey*, 151 A.2d 601, 605 (Pa. 1959).

16 See Anthony Mossop & Paul Segall, *Subsidence at The Geysers Geothermal Field, N. California from a Comparison of GPA and Leveling Surveys*, 24 Geophysical Research Letters 1839 (1997).

17 *See Westmoreland & Cambria Nat. Gas Co. v. De Witt*, 18 A. 724, 725 (Pa. 1889).

18 *See Briggs v. Southwestern Energy Prod. Co.*, 224 A.3d 334, 336 (Pa. 2020).

19 *See id.*

20 *Westmoreland*, 18 A. at 725.

21 *Id.*

22 *See Briggs*, 224 A.3d at 336; *see also* Keith B. Hall, *Ruminations on the Continuing Evolution of Trespass Law in the Context of Mineral Development*, 8 LSU J. Energy L. & Resources 505, 536 (2020)(noting that "the rule of capture has been universally adopted" in the United States).

23 *See* Mark T. Wilhelm, *"All" Is Not Everything: The Pennsylvania Supreme Court's Restriction of Natural Gas Conveyances in* Butler v. Charles Powers Estate ex rel. Warren, 59 Vill. L. Rev. 375, 385 (2014).

24 101 Pa. 36, 43 (1882).

25 *See id.* at 37.

26 *Id.*

27 *Id.*

28 *Id.*

29 *Id.* at 44.

30 *Id.*

31 5 Watts 34, 41-42 (Pa. 1836)

32 *See id.* at 34.

33 *Id.* at 38.

34 101 Pa. at 44.

35 *See, e.g., Dye v. CNX Gas Co.*, LLC, 291 Va. 319, 325 (2016) (noting that *Dunham* represents the "minority rule").

36 161 A.2d 390 (Pa. 1960).

37 Pennsylvania courts also have applied the *Dunham* rule to conveyances of "other minerals." See, e.g., *Winnett v. Winnett*, 39 Pa. C.C. 668, 672 (Pa. Com. Pl. 1912) (construing a grant of a specific vein of coal "and all other minerals" to include other coal veins but not oil and gas). The Pennsylvania Supreme Court has also applied *Dunham* and its progeny to a deed's reservation of the right to drill for "gas", finding that it does not apply to coalbed methane, since at the time the deed was written, coalbed gas was generally viewed as a dangerous waste product of coal mining, so the parties negotiating the deed would not have intended to include it within the reservation. *See U.S. Steel v. Hoge*, 468 A.2d 1380 (Pa. 1983).

38 *See id.*

39 *Id.* at 888; *see also id.* ("Notwithstanding different interpretations proffered by other jurisdictions, the rule in Pennsylvania is that natural gas and oil simply are not minerals because they are not of a metallic nature, as the common person would understand minerals.").

40 *Stefanie L. Burt, Who Owns the Right to Store Gas: A Survey of Pore Space Ownership in U.S. Jurisdictions*, 4 Joule: Duq. Energy & Envtl. L.J. 1, 8 (2016).

41 *See Pomposini*, 580 A.2d 776, 778 (Pa. Super. 1990).

42 *Id.* at 777.

43 *Id.*

44 *Id.* at 778.

45 2012 WL 3043008 (M.D. Pa.). Although filed in federal court because the parties were citizens of different states—what is known as diversity jurisdiction—the case was decided applying Pennsylvania state law.

46 *Id.* at *1.

47 *Id.* at *2.

48 *Id.* at *4.

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50 *See* Douglas Hale Gross, *What Constitutes Reasonably Necessary Use of the Surface of the Leasehold by a Mineral Owner, Lessee, or Driller Under an Oil and Gas Lease or Drilling Contract*, 53 A.L.R.3d 16.

51 *See Oberly v. H.C. Frick Coke Company*, 104 A. 864 (Pa. 1918); *Humberston v. Chevron U.S.A., Inc.*, 75 A.3d 504 (Pa. Super. 2013); *see also Belden & Blake Corp. v. Dep't of Conservation & Natural Resources*, 969 A.2d 528, 532 (Pa. 2009).

52 *Belden & Blake Corp.*, 969 A.2d at 532 (quoting *Chartiers*, 25 A. at 598).

53 *See, e.g., Rochez Bros. v. Duricka*, 97 A.2d 825, 825 (Pa. 1953); *Herder Spring Hunting Club v. Keller*, 93 A.3d 465, 467 (Pa. Super. 2014), *aff'd*, A.3d 358 (Pa. 2016); *Shawville Coal Co. v. Menard*, 421 A.2d 1099, 1101 (Pa. Super. 1980).

54 *Chartiers Block Coal Co. v. Mellon*, 25 A. 597, 599 (Pa. 1893).

55 *Chartiers*, 25 A. at 599.

56 *See id.*

57 *Id.*

58 *Id.* at 599-600.

59 Professor Joseph Schremmer has argued that, when conflicts arise between subsurface estates, the common law rules in many states give preexisting uses priority over later-initiated uses. *See* Joseph A.

Schremmer, *The Concurrent Use of Land for Carbon Sequestration and Mineral Development*, 75 Baylor L. Rev. 630, 660 (2023). Pennsylvania does not appear to have adopted such a rule, which arguably would conflict with the Pennsylvania Supreme Court's reasoning in *Chartiers*, which seems to place the earlier coal rights on par with the later natural gas rights. 25 A. at 599. In SB 831, adopted as this paper was being finalized, the Pennsylvania General Assembly specified that among subsurface uses, coal, oil, and gas have priority over pore space. SB 831 (2024).

60 *See Wheatley v. Baugh*, 25 Pa. 528, 531-32 (1855).

61 *See Bumbarger v. Walker*, 164 A.2d 144, 148 (Pa. 1960).

62 224 A.3d 334 (Pa. 2020).

63 *See id*. at 352.

64 *See Briggs v. Sw. Energy Prod. Co.*, 245 A.3d 1050 (Table), 2020 WL 7233111 (Pa. Super. Ct. 2020).

65 *See Briggs*, 224 A.3d at 352.

Chapter 5

Additional Policy and Regulatory Issues: A Guide to Building a New Geothermal Energy Industry for the Commonwealth

S. Blumsack

> ***By modifying a few existing policies and adopting targeted new ones outlined in this chapter, Pennsylvania could leverage its oil and gas know-how to catalyze geothermal across the Commonwealth, bringing it economic, energy security, and environmental benefits.***

INTRODUCTION

According to data from the U.S. Energy Information Administration, Pennsylvania is the second-largest energy producing state in the United States, and a major electricity supplier to the Mid-Atlantic region.[1] As one would expect, especially from an energy leader, the Commonwealth has a suite of energy-related policies, programs, and incentives. While some of them can support geothermal energy development (for heat or electricity), most are broadly designed without significant focus on geothermal.

But small changes to these existing policies and targeted new measures can accelerate the deployment of geothermal energy in Pennsylvania. These include 23 specific actions across the following six key areas of focus:

1. Provide industry with regulatory certainty and eliminate red tape;
2. Encourage adoption of ground source heat pumps for building heating and cooling;
3. Create and expand targeted incentives for direct-use geothermal applications for the industrial and agricultural sectors;
4. Catalyze the creation of thermal energy networks to serve residential, commercial, academic, and public buildings;
5. Advance comprehensive state and regional power

POLICIES TO PROMOTE GEOTHERMAL ENERGY

Provide Industry with Regulatory Certainty and Eliminate Red Tape

- Clarify regulatory authority
- Permitting reform and improved siting
- Define "geothermal resources"
- Hold legislative hearings
- Pursue Class V primacy

Encourage the Adoption of Ground Source Heat Pumps (GSHP) for Building Heating and Cooling

- Amend Act 129 to incentivize GSHPs
- Adopt PUC incentives
- Educate about GSHP tax credits

Create and Expand Targeted Incentives for Direct-Use Geothermal Applications for the Industrial and Agricultural Sectors

- PTC/ITC for clean geothermal heat
- Expand AEIA for industrial process heat
- Fund exploratory geothermal projects
- Ensure incentive effectiveness

Catalyze the Creation of Thermal Energy Networks to Serve Residential, Commercial, Academic, and Public Buildings

- Allow utilities to own and operate TENs
- Create TEN incentives
- Expand TEN ownership pathways

Advance Comprehensive State and Regional Power Market Policies that Promote Clean, Firm, Flexible Power

- Revitalize Pennsylvania's Renewable Portfolio Standard
- Adopt carbon reduction targets and cap-and-invest
- Capacity market reform to encourage clean baseload
- Incentivize abundant, flexible energy sources

Educate Stakeholders and Create Geothermal Development Strategies

- Pennsylvania "Geothermal Future Plan"
- Incorporate geothermal into state energy planning
- Expand TA programs into geothermal
- Improve online information sources

Figure 5.1

market policies that promote clean, firm, flexible power; and
6. Educate stakeholders and create geothermal development strategies.

Collectively, these 23 targeted actions, described in more detail below, can help make Pennsylvania a geothermal leader and ensure the Commonwealth continues as an energy-producing powerhouse.

CURRENT POLICY CONTEXT

Pennsylvania is no stranger to promoting energy development. The policies, programs, and incentives already in place that could accelerate geothermal energy development in the Commonwealth include:

- *Alternative Energy Investment Act (AEIA) Programs*—This Act[2] was passed in 2008 when the nation was dealing with high fuel costs and wholesale electricity prices.[3] The Act established several grant and loan programs for businesses, municipalities, and individuals to pursue alternative energy projects. The programs are jointly administered by the Pennsylvania Department of Environmental Protection (DEP) and the Department of Community and Economic Development (DCED) through the Commonwealth Financing Authority (CFA). Some of them could be applied to geothermal. For example, under DCED's Renewable Energy Program, ground-source heat pumps (GSHPs) for small businesses and individual residences are eligible for CFA-administered loans that can cover as much as 50 percent of the installation cost.[4]

- *Alternative Energy Portfolio Standard (AEPS)*—This Act, of 2004, established a set of statewide mandates for electric distribution companies in Pennsylvania to buy power from alternative generation sources.[5] The AEPS divided qualifying technologies into two tiers, with distribution companies needing to meet different requirements for each tier on an escalating basis, as shown in Figure 5.1. Geothermal energy is included in Tier I, along with wind, low-impact hydropower, and other resources. The AEPS narrowly defined geothermal as "electricity produced by extracting hot water or steam from geothermal reserves in the earth's crust and supplied to steam turbines that drive generators to produce electricity."[6] No electric distribution company has used geothermal to meet the requirements to date. The final target increases under the AEPS occurred in 2021; the program requirements will remain on a plateau until the state legislature takes action to renew or update them.

- *Pennsylvania Energy Development Authority (PEDA) Funding*—PEDA finances clean energy projects in the Commonwealth, primarily through loans and loan guarantee programs. Funding is aimed at helping with residential efficiency upgrades and household electrification, including for geothermal projects.[7]

- *Reducing Industrial Sector Emissions in Pennsylvania (RISE PA)*—In August 2024, DEP received a Climate Pollution Reduction Grant from the U.S. Environmental Protection Agency (EPA) of almost $400 million to implement the RISE PA program to reduce emissions from the state's industrial sector. Geothermal projects qualify for RISE PA funding, but as of this writing none of the funds have been distributed yet.

POLICY RECOMMENDATIONS

While the policies described above provide a foundation for progress on geothermal energy in Pennsylvania, more could be done to catalyze geothermal development. Minor changes to these existing policies and creation of new policies and programs could advance Pennsylvania's geothermal energy leadership. This report recommends 23 targeted ideas across six areas of focus as described below.

I. Provide Industry with Regulatory Certainty and Eliminate Red Tape

Pennsylvania has relatively clear regulatory structures related to energy, as one would expect from an energy leader, but state regulatory language and structures are not yet where they could be with respect to geothermal. Pennsylvania could:

1. Clarify regulatory authority for geothermal development.

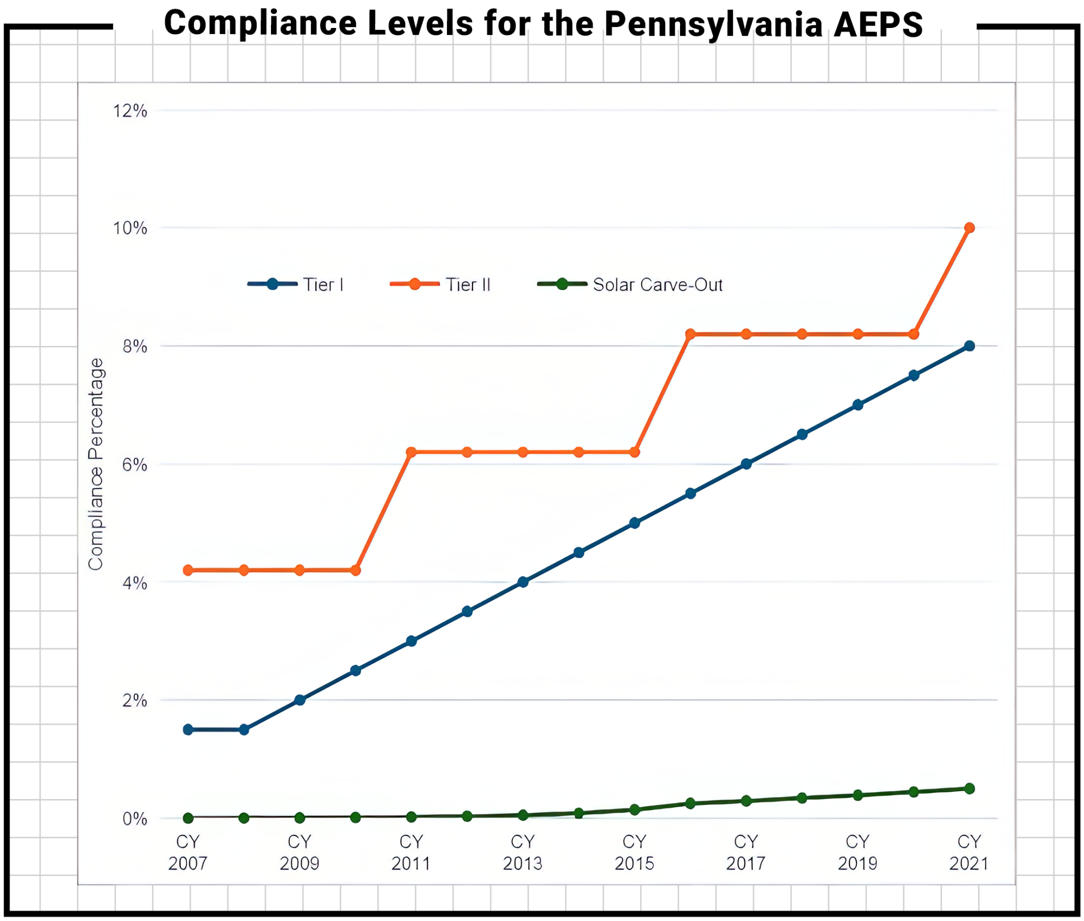


Figure 5.1: Author graph based on data from the Database of State Incentives for Renewables & Efficiency (DSIRE). Source: https://programs.dsireusa.org/system/program/detail/262/alternative-energy-portfolio-standard

Who Takes Action: General Assembly

There is no clear, designated regulator in Pennsylvania to whom geothermal developers can submit plans for approval. Pennsylvania's water well drilling statute imposes some minimal requirements on "non-oil and gas wells" which are designed to protect water resources from pollutants,[8] however these aren't adequate for next-generation geothermal. Deep geothermal wells are quite similar to oil and gas wells; Pennsylvania's oil and gas is regulated via the Office of Oil and Gas Management within DEP. Given the similarity of operations and well-developed nature of Pennsylvania's oil and gas regulations, the General Assembly could designate the same office (perhaps with a broadened name) to regulate next-generation geothermal drilling. These regulations could contain similar safety protocols as for oil and gas, with the caveat that, given the greatly reduced risk of environmentally damaging spills and the absence of a need to manage pooling of mineral rights, geothermal permitting is much simpler than oil and gas permitting.

2. Accelerate clean geothermal with permitting reform and improved siting.

Who Takes Action: General Assembly; Executive agencies (Governor's Center for Local Government Services for model ordinances)

Getting energy infrastructure built for thermal or electricity needs is hard. Pennsylvania could enact permitting reform to streamline geothermal permitting timelines and ensure timely completion of environmental review of projects. Such streamlining would be especially helpful for shallow GSHPs, as the environmental impacts are typically minimal and well understood. State agencies, led by the Governor's Center

for Local Government Services within the DCED, could develop model ordinances that municipalities or other local governments could use to address local zoning issues associated with siting of geothermal and other clean energy projects.

In addition, in May 2024, the Pennsylvania Senate passed SB 832 along party lines. If it were to pass the House and be signed into law, the bill would reorganize the Pennsylvania Energy Development Authority as the Pennsylvania Opportunities with Energy Reliability (POWER) Authority. As with PEDA, the POWER Authority would still fund demonstration of innovative energy projects, but it would also fund research projects for energy extraction, transmission, storage, conversion, or any other project that increases the use or movement of energy in the Commonwealth. The POWER Authority would then create an accelerated alternative permitting program, authorizing third-party professionals to review permits for new electric generation projects and waiving regulations hindering their construction or operation. While further details on applicable project criteria would need to be defined, geothermal (for heat and for power generation) would likely be eligible for funding and may be eligible for the accelerated permitting approach. As of this writing, a different PEDA reform bill that passed the House (HB 2338) is pending in the Senate. HB 2338 would reform PEDA to enable it to better apply for and leverage various federal funding streams that could accelerate clean energy deployment in the Commonwealth.

3. Define "geothermal resources."

Who Takes Action: General Assembly

As mentioned, the AEPS defines geothermal solely in the context of electricity generation. This is the only statutory definition of geothermal in Pennsylvania. Development of in-state geothermal requires a regulatory pathway, and any regulatory pathway must first have a clear understanding of which energy sources are covered. NREL provides a set of best practices to use when crafting definitions for geothermal.[9] Paired with the proposal on regulatory clarity, the General Assembly could adopt a definition for geothermal that focuses on the resource (hot rock) rather than the use case (heat vs. power), which is especially important when geothermal can be deployed for multiple cascading uses.

4. Hold legislative hearings on geothermal development.

Who Takes Action: General Assembly

Advancing any of the recommendations above will benefit from congressional committee hearings. The Environmental Resources and Energy Committees in both the Pennsylvania House and Senate could hold hearings on geothermal energy production and potential applications in power, industry, buildings, and other areas. These committees have held multiple hearings in recent years on solar, wind, and nuclear energy, as well as energy efficiency, but none on geothermal.

5. Pursue "primacy" for Class V non-hazardous fluid injection wells.

Who Takes Action: Governor (letter of support), General Assembly (statutes and appropriations), DEP (regulations), Attorney General (letter certifying adequate statutory and regulatory authority).

The federal Clean Water Act (CWA) gave the EPA the authority to regulate all underground injection of fluids to ensure substances pumped into the subsurface don't contaminate aquifers and sources of drinking water. All deep geothermal wells fall under the EPA's Class V rule, which regulates the injection of non-hazardous fluids. To reduce the burden on the federal bureaucracy, the CWA allows states with regulatory processes at least as stringent as the EPA's to manage their own in-state wells.[10] Pennsylvania could apply for this "primacy" designation, further accelerating the geothermal permitting process.

II: Encourage Adoption of Ground Source Heat Pumps for Building Heating and Cooling

Ground source heat pumps provide heating and cooling with one set of equipment. GSHPs are clean, exceedingly energy efficient, and cost-saving for Pennsylvania consumers. A recent DOE study found that wide-spread use of GSHPs would reduce US annual electricity demand by about 15 percent and reduce electrical grid requirements by 33 percent, bringing significant cost savings to consumers.[11] To promote GSHP deployment and tap into these savings, Pennsylvania could:

1. Amend Act 129 to account for total energy savings from fuel switching.

Who Takes Action: General Assembly

Act 129 is Pennsylvania's principal energy efficiency law. The law is squarely focused on reducing electricity use and requires the state's electric distribution companies to demonstrate annual reductions in total electric energy demand during both peak times and throughout the year. It does not account for emissions reductions due to electrification as a form of "fuel switching." As it stands, converting a home from fuel oil to a GSHP does not meet the requirements of the law because, even though installing GSHPs improves overall energy efficiency (and reduces emissions), heat pumps use small amounts of electricity and thus increase total electric load.[12] Vermont[13] has adopted a more holistic energy efficiency program to incentivize homeowners and builders to install geothermal systems, aligned with the overall decrease in energy use. Likewise, states such as Illinois[14] and Minnesota[15] permit utilities to incorporate fuel-switching into energy efficiency portfolios.

2. Enact policies at the PUC that accelerate the use of GSHPs.

Who Takes Action: PUC

There are multiple actions the Pennsylvania Public Utility Commission (PUC) could take to accelerate adoption of GSHPs. It could, for instance, authorize electric distribution companies to enact rebate programs that help reduce the costs to consumers of converting to GSHPs, particularly for consumers who use heating oil.

Maine has pursued such a policy, offering a $3,000 rebate for GSHPs.[16] In addition, the PUC could quantify how much GSHPs help reduce peak-energy loads, and integrate that value into program and utility funding, perhaps in areas of the state with high load growth forecasts.

3. Engage in awareness-building about the new economics of GSHPs.

Who Takes Action: Any state agency with a nexus to building owners, especially public sector owners such as municipalities, school districts, higher education, and health care facilities.

With tax credits existing as of publication of this report, GSHPs may be the lowest first-cost HVAC system option for new construction, major modernizations, and perhaps even system replacements. Building owners, especially large public sector customers, could be good targets for an awareness-raising campaign and technical assistance. Engaging private sector partners such as architects and HVAC designers to ensure they are aware of how the IRA tax credits affect relative system costs could be a valuable way to support a wide array of construction projects. Finally, finding opportunities for agencies to require and support lifecycle cost analyses that incorporate available tax credits could help drive demand for GSHPs by building owners.

III. Create and Expand Targeted Incentives for Direct-Use Geothermal Applications for the Industrial and Agricultural Sectors

As noted in Chapter 3: Geothermal Direct-Use Opportunities, Pennsylvania is the nation's fourth-largest industrial consumer of energy, and meaningful amounts of industrial thermal demand could be well-served by direct use of geothermal energy. Pennsylvania's industrial emissions are also expected to grow as needs like controlled-environment agriculture (greenhouses) expand and as data centers seek to build near low-cost energy supplies. Targeted incentives could accelerate the deployment of direct-use geothermal heat in industry and agriculture. Possible actions include:

1. Enact a production tax credit and/or an investment tax credit for clean geothermal heat.

Who Takes Action: General Assembly

The Pennsylvania General Assembly could establish an industrial process heat credit to support the generation of geothermal heat for use in agriculture, manufacturing, and other strategic sectors. Such a credit should be limited to heat directly related to an industrial process—like heating foodstuffs (e.g., pasteurization or tempering), melting materials, or driving chemical reactions. Allowing the credits to be transferable would provide developers an upfront source of financing, helping them to more readily deploy capital-intensive next-generation geothermal projects.

2. Expand AEIA grant and loan programs to include clean industrial process heat.

Who Takes Action: General Assembly

As noted, Pennsylvania offers grant and loan programs under the AEIA, such as a renewable energy loan program that includes GSHPs. However, the statutory language orients these programs towards residential and small businesses for heating and cooling buildings. Expanding the renewable energy loan program to include users of clean industrial process heat, such as controlled-environment agriculture, dairy processing, or low-temperature petroleum refining, could simultaneously support strategic industries in Pennsylvania, add more renewable energy to the grid, and accelerate the development of the state's geothermal energy industry.

3. Fund exploratory geothermal projects.

Who Takes Action: General Assembly

The DEP and DCED could support next-generation geothermal energy exploration efforts in promising regions across Pennsylvania. For example, Chapter 2, Where to Develop Geothermal highlighted the possibility that the greater Philadelphia area may have good geothermal potential. Funding for exploration wells could help overcome first-of-a-kind barriers, confirm the geothermal resource potential, and lead to geothermal heat pilot projects. Funding for exploratory efforts would require some level of fiscal authorization.

4. Ensure incentive effectiveness.

Who Takes Action: Governor

The Governor's office could convene a group of industrial stakeholders to refine proposals for the above policies to ensure they will incentivize the uptake of geothermal heat.

IV. Catalyze the Creation of Thermal Energy Networks for Residential, Commercial, Academic, and Public Buildings

Pennsylvania could adopt policies and initiatives to promote development of geothermal district heating and cooling, or (TENs). Deploying more TENs could provide clean, affordable heating and cooling to neighborhoods and networks of buildings. The Commonwealth could:

1. Allow gas utilities to build, own, and operate TENs.

Who Takes Action: General Assembly

Gas-fired district heating services already exist in Pittsburgh and Harrisburg, which are regulated by the (PUC). It is not a jump to convert natural gas utilities to directly provide geothermal heating and cooling, as much of the fuel these entities distribute is already used for building heat. And gas utilities already have the experience, workforce, and infrastructure to develop and distribute thermal energy across wide areas. However, current Pennsylvania statutory language is likely to make it difficult for existing natural gas utilities to convert their distribution networks to geothermal district heating. Under state law, a PUC-regulated natural gas distribution company is defined as: "A public utility or city natural gas distribution operation that provides natural gas distribution services and which may provide natural gas supply services and other services."[17] While TENs may be allowed as an "other service" under the definition, the statutory language may be interpreted to require the provisioning of natural gas, making it challenging for Pennsylvania utilities to widely adopt alternative building heating and cooling methods. At the very least, the language is ambiguous. New York and Maryland, with support from gas utilities, labor, and environmental stakeholders, have modified statutory definitions to make it clear that gas utilities can distribute "heat," including through the creation of TENs.[18] Pennsylvania could follow the example set by these states and clarify in statute that gas utilities may opt to build, own, operate, and convert existing natural gas distribution into geothermal TENs.

2. Provide incentives for and encourage adoption of TENs.

Who Takes Action: General Assembly (for financial incentives); Executive agencies and other public entities with large buildings (for serving as anchor tenants) .

Beyond merely allowing the creation of geothermal district heating networks, Pennsylvania could take steps to actively encourage them. Massachusetts, for instance, has a law that allows for networked geothermal projects to be funded out of dollars earmarked for gas-pipe replacement.[19] In Colorado, the state energy office has a Geothermal Energy Grant Program that provides funding support for eligible public and private entities to develop geothermal energy projects, including TENs.[20] Minnesota requires utilities to develop innovation plans, including plans for adoption of ground source "district energy" systems;[21] the state also passed a new law in 2024 bolstering financial support for TENs, including via appropriations for geothermal planning grants and statewide TEN deployment studies.[22] Another form of support could be for publicly owned buildings to serve as "anchor tenants" for TENs, guaranteeing offtake for entities willing to develop the networks.

3. Expand the range of potential owners/operators of TENs.

Who Takes Action: General Assembly

Pennsylvania law could broaden opportunities for TEN development. Vermont law, for instance, opens multiple pathways for TEN ownership.[23] Municipalities can form thermal energy utilities without PUC approval (as they do for water and sewer utilities); existing utilities, businesses, developers, co-ops, and nonprofits can also seek authorization to operate TENs under PUC supervision, setting rates and providing service to thermal energy customers.

V. Advance Comprehensive State and Regional Power Market Policies that Promote Clean, Firm, Flexible Power

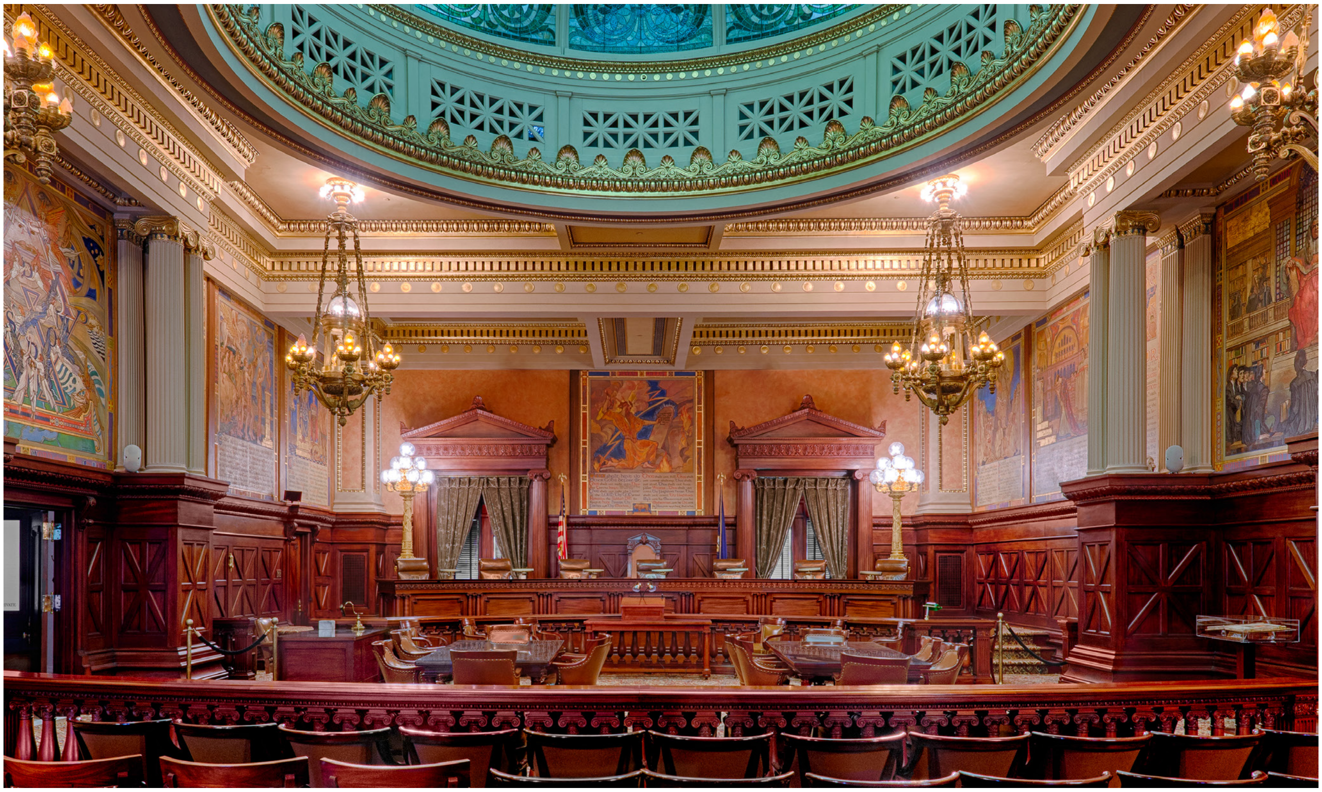
In addition to the thermal-focused policies recommended above, there are more comprehensive state policies that could accelerate clean energy broadly, including geothermal applications in electricity. Given the state's status as a major electricity producer, the rising demand for power, and policy initiatives to reduce the environmental and climate impacts of electricity generation,[24] it is important to consider ways to encourage geothermal power development. In addition to some of the policies already listed (such as AEPS renewal), Pennsylvania could advocate for changes in the design of regional power markets to create incentives for clean firm power sources such as geothermal. As explored in *Chapter 2, Where to Develop Geothermal*, the Commonwealth has some hotspots that are suitable for geothermal power generation.

1. Renew, revise, and revitalize the Commonwealth's alternative energy portfolio standard to incentivize next-generation geothermal power and heat.

Who Takes Action: General Assembly

As noted, the AEPS already includes geothermal among the Tier I resources, but its targets have plateaued, and no geothermal has been used to meet the Tier I targets. The AEPS could be renewed, with added provisions to benefit both geothermal heat and power. Governor Shapiro recently proposed an AEPS renewal through his Pennsylvania Reliable Energy Sustainability Standard (PRESS), but policymakers should also consider replicating two aspects of the original AEPS—ones that have helped to jump-start solar energy—for geothermal in Pennsylvania.

First, Pennsylvania could establish a modest but separate compliance target for geothermal technologies, akin to the 0.5% solar set-aside in the AEPS. As Figure 5.2 suggests, the separation of solar energy from other Tier I resources yielded credit prices high enough to induce investment, and as the solar industry matured and costs fell, solar credit prices also fell. Other states are taking similar action for geothermal energy. Maryland[25] and Virginia,[26] for example, have recently passed laws that create or explore set-asides for geothermal heating and



cooling within their Renewable Portfolio Standards. In October 2023, California passed a law aimed at accelerating procurement of reliability-enhancing zero-carbon resources, including geothermal.[27]

Second, to bolster the development of the geothermal industry in Pennsylvania, the Commonwealth could require geothermal resources to be in-state to qualify for credits. That would be a shift similar to a 2017 amendment to the AEPS establishing in-state solar requirements, which led Pennsylvania solar investment to increase by roughly a factor of four.[28]

2. Adopt broad carbon reduction targets and carbon pricing.

Who Takes Action: General Assembly

Pennsylvania has no binding policy target to reduce the greenhouse gas intensity of its energy sector or broader economy. In 2019, Governor Tom Wolf directed the DEP to develop a rule that would permit Pennsylvania to enter the Regional Greenhouse Gas Initiative (RGGI), a cap-and-trade program for the electric power sector in which several northeastern states currently participate. RGGI participation would have placed an explicit price on greenhouse gas emissions from certain power plants in Pennsylvania.[29] Pennsylvania's move to join RGGI is, at the time of this writing, in legal limbo as the Pennsylvania Supreme Court considers challenges. The Shapiro administration has proposed its own carbon policy for the electric power sector, the Pennsylvania Carbon Emissions Reduction Act (PACER), a Pennsylvania-only emissions cap-and-invest regime. Whether through RGGI, PACER, or an economy-wide (as opposed to electricity-only) system, pricing carbon emissions would benefit geothermal energy technologies (and all low- or zero-carbon energy resources) by making them more economically competitive relative to fossil fuels.

3. Encourage clean baseload power in capacity markets.

Who Takes Action: PUC

PJM, the regionally administered grid operator, operates a forward market for electric generation capacity to ensure there are sufficient resources to meet future demand. This market is cost-driven and doesn't, at the moment, differentiate between resources based on their carbon footprint. A recent study by PJM recognized that growth in weather-dependent renewable power generation (especially if not coupled with large-scale energy storage) will likely not be sufficient to meet increasing electricity demand.[30] New baseload resources will be needed. PJM has recently reformed its capacity market to reflect how weather-dependent resources can participate. This type of capacity market approach is advantageous for geothermal power, but Pennsylvania should continue to advocate for capacity market reforms that encourage rapid and substantial investments in the generating of clean firm power.

4. Encourage flexibility in energy markets.

Who Takes Action: PUC

PJM's grid has a need for increased flexibility to allow the grid to absorb higher levels of renewable generation, and manage larger levels of distributed generation and price-based demand response.[31] The PJM market, however, has no current way to incentivize or price flexible services like what geothermal could provide. Pennsylvania could advocate within PJM for the rapid development of such a flexibility market design.

VI. Educate Stakeholders and Create Geothermal Development Strategies

A fundamental challenge to accelerating geothermal energy deployment in Pennsylvania is that many stakeholders don't know much about it, or don't know it is an option in the Commonwealth today. The government could pursue a range of initiatives to educate stakeholders about the potential of next-generation geothermal, and develop strategies to realize it. Pennsylvania could:

1. Develop a Pennsylvania Geothermal Future Plan.

Who Takes Action: Governor, DEP

The Energy Programs Office (EPO) at DEP (or another entity) could spearhead the development of a roadmap charting the future of geothermal energy growth in Pennsylvania. Such a report could be modeled after the Pennsylvania Solar Future Plan,[32] both in the

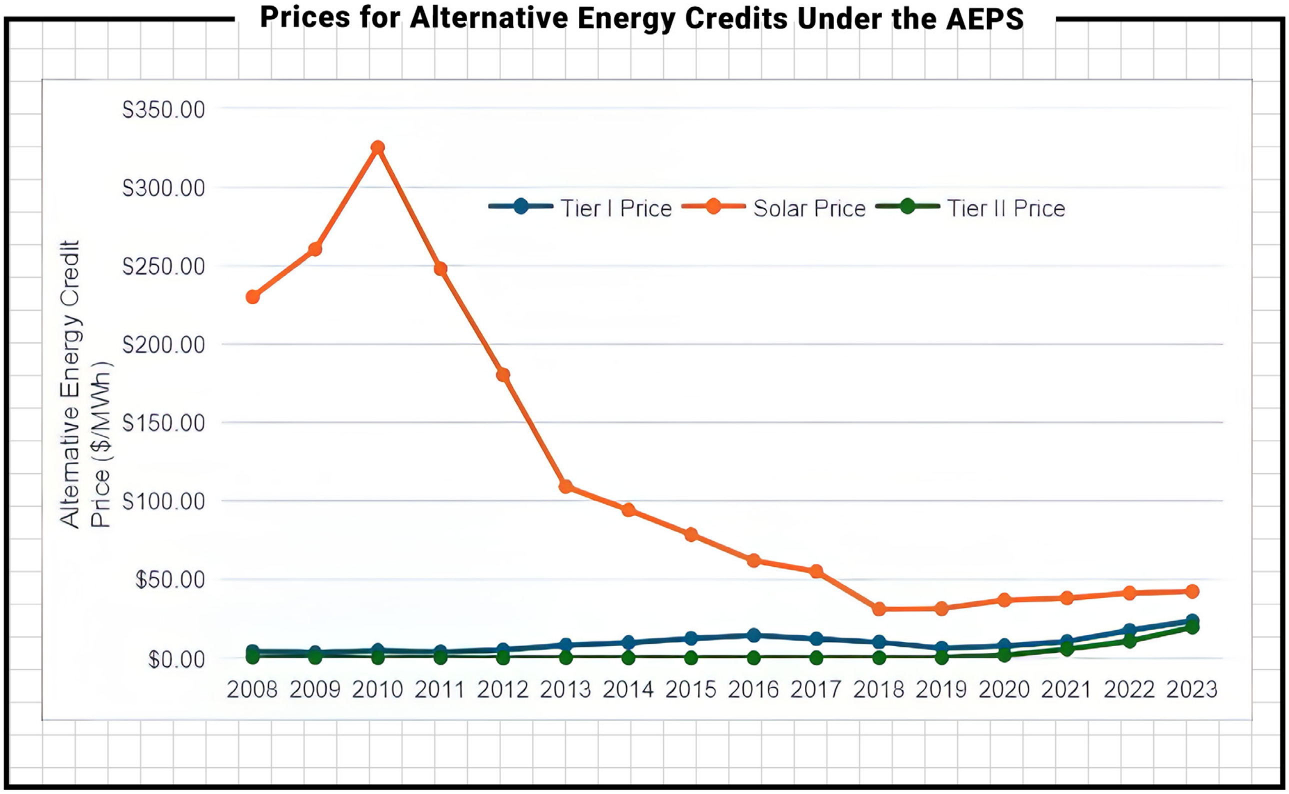


Figure 5.3: Source: Author graphics based on data from the Pennsylvania PUC

scope of its analysis and recommendations, and in its multi-stakeholder approach. Focus areas for a Pennsylvania Geothermal Future Plan could include:

- Assessments of geothermal energy's potential to support the energy needs of strategic sectors of the Pennsylvania economy, including agriculture and manufacturing. This could draw on existing technical assessments of geothermal heat and electricity generation resources (including information in chapters 2 and 3 of this report).
- Strategies and recommendations for how next-generation geothermal could power and cool data centers in Pennsylvania.
- Ambitious but realistic ten-year targets for geothermal energy deployment in Pennsylvania. Targets focused on industrial heating (including agriculture) and building space could be especially useful in giving direction to other potential support mechanisms recommended in this chapter.
- Prioritization of policies to support geothermal deployment targets. This could include incentive programs, ways to reduce administrative burdens or barriers at multiple levels of government, and other measures laid out in this chapter.
- Strategies to harness the deep technical expertise of Pennsylvania's oil and gas sector to support subsurface energy development via geothermal. Oil and gas producers, for example, could earn incentives for drilling geothermal wells.
- Assessment of workforce needs to support a robust geothermal industry in Pennsylvania. This is another area where Pennsylvania's long history of oil and gas development could be leveraged to promote geothermal development.
- Proposals for how government procurement could leverage next-generation geothermal, as it has for a range of other technologies.

- A roadmap for expedited geothermal well and surface facility permits from federal and state regulators.

- Strategies to increase federal geothermal funding in Pennsylvania. For example, Pennsylvania could help farmers and manufacturers using low-temperature thermal energy apply for Rural Energy for America Program (REAP) loans and grants to convert processes to geothermal.[33]

2. Incorporate geothermal into state energy planning.

Who Takes Action: Governor, DEP

The EPO could include a greater role for technologically mature and next-generation geothermal energy in its next Clean Energy Program Plan. The plan is a strategic document that guides the EPO's priorities for programs and activities in clean energy and energy efficiency, among other areas. The current version of the plan will need to be updated at the end of 2025.[34] Several priority areas identified in the current plan are relevant to geothermal energy in Pennsylvania, particularly around energy efficient buildings and industrial decarbonization, but the EPO's discussions of these areas do not currently address geothermal specifically. Geothermal energy is also not considered in the current plan's portfolio of emerging technologies. In the next iteration of the Clean Energy Program Plan, the EPO could more explicitly consider how geothermal energy could contribute to both current and emerging strategic clean energy needs in Pennsylvania.

3. Offer technical assistance for implementing geothermal projects.

Who Takes Action: Governor, PennTAP

Pennsylvania could support a technical assistance program specifically for geothermal. Existing programs of this type in Pennsylvania, like Penn State's PennTAP, focus on end-use energy efficiency (including building energy audits) and combined heat and power technologies.[35] Technical assistance programs help to identify potential users and applications, perform research to outline use cases and benefits, and produce informational resources. A geothermal-specific program could also help with initial feasibility analysis. These types of programs are primarily aimed at larger commercial and industrial customers, but with time and sufficient resources, they could expand to residential and smaller commercial applications (particularly if Pennsylvania could improve incentives for geothermal adoption in residential or small commercial properties). Agricultural applications for geothermal could also be considered as part of such a technical assistance program.

In conjunction with a technical assistance program, state agencies could produce a geothermal playbook that walks school districts, universities and colleges, hospitals, and other big public campuses through the benefits of GSHPs, the steps needed to develop GSHP projects, and the federal tax incentives available.

4. Provide more information on geothermal energy on state websites.

Who Takes Action: Governor, DEP

The EPO could provide more resources about geothermal energy, particularly for direct-use geothermal. The EPO currently offers limited information on next-generation geothermal energy compared to other renewable sources, with only a brief overview of geothermal heating and cooling systems. The content could be expanded to provide more location-specific information about geothermal resources for commercial and industrial customers. It could also identify which electric distribution companies in Pennsylvania offer rebates for residential geothermal heat pumps.

CONCLUSION

Existing measures such as the AEPS, PEDA, and RISE PA could help accelerate geothermal development in Pennsylvania, but additional policies, programs, and initiatives are needed. Implementing the recommendations in this chapter could harness the state's energy leadership and expertise in subsurface energy development to deploy ground-source heat pumps and spur development of next-generation geothermal for industrial direct-use, thermal energy networks, and geothermal power production. Doing so would create economic savings for consumers, create jobs that benefit labor unions and oil and gas companies, and reduce emissions and improve air quality.

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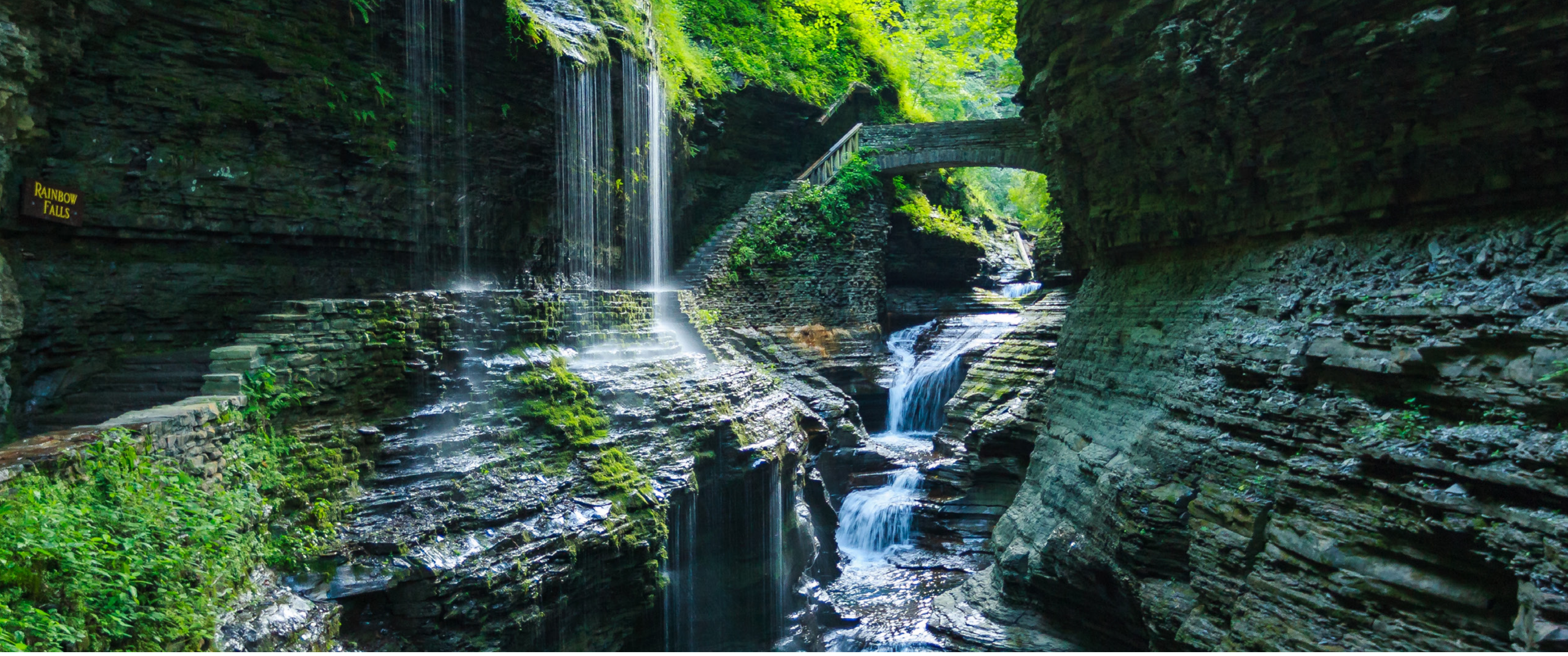


Chapter 6

Environmental Considerations: Stewarding Responsible Geothermal Development

A. Menefee, S. Blumsack

> ***The development of geothermal energy in Pennsylvania offers great potential with minimal impacts. The challenges, including wastewater disposal and water use, are manageable. The benefits—including a small land footprint, low emissions, and minimal wildlife impacts—are substantial. With the proper approach, geothermal represents a promising, low-impact energy option.***

OVERVIEW

Geothermal energy offers myriad environmental benefits, but like all energy sources, its development can come with local environmental impacts that need to be carefully managed. These environmental considerations vary with location, the type of geothermal resource or reservoir, and the geothermal process deployed—and each geothermal development will involve different local and state-wide considerations.

This chapter reviews considerations related to wastewater (and other liquid and solid wastes), water consumption, induced seismicity, land subsidence, land use, noise, and air emissions. Whether installing GSHPs or district heating,[1] repurposing abandoned oil and gas wells to tap into geothermal energy,[2] or developing next-generation geothermal, all types of geothermal can have impacts, though those impacts are entirely manageable. Wherever possible, we draw comparisons between geothermal and other energy sources used for heating, cooling, and electricity generation in Pennsylvania.

WASTEWATER AND OTHER LIQUID AND SOLID WASTES

Tapping into geothermal resources requires drilling and operations in underground geologic formations. Particularly for next-generation geothermal systems such as EGS, which uses techniques similar to those used in the oil and gas industry.

Since the 1800s, when Pennsylvania was an epicenter of American oil production, the Commonwealth has undergone extensive drilling and exploration. In recent years, Pennsylvania has risen to the forefront of the shale gas industry, with advancements in drilling techniques that have allowed for extraction of hydrocarbons (primarily natural gas) directly from shale. These wells are often drilled vertically through many kilometers of subsurface, then horizontally. As a new well is drilled, muds are used as lubricants and cooling agents, leading to the production of drilling fluids and solid cuttings at the surface. The fluid components, or drilling wastewater, are typically low in volume but have high levels of total dissolved solids (TDS) that can be difficult or expensive to treat, while solid components are commonly deposited in landfills.[3,4] Although there may be concerns over Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) from liquid and solid wastes in drilling operations, the Pennsylvania Department of Environmental Protection (DEP) has determined there is little potential for harm to workers or the public from TENORM exposure from oil and gas development. The same should be true for geothermal development.[5]

After drilling, developing EGS requires hydraulic fracturing, similar to the shale gas industry, to create a reservoir where the heat is collected. Significant amounts of hydraulic fracturing fluids ("frac fluids") injected into the well to create the fractures flow back to the surface in the early weeks to months of operations. This wastewater is commonly referred to as "flowback water" and needs to be treated or disposed of. Flowback water can be difficult to manage: large volumes are generated in short periods of time, and flowback water may contain an array of frac fluid chemicals that would be site-specific depending on the operation.[6] In the shale gas industry, flowback water is typically held in containment tanks on site until it can be either reused in another operation or treated or disposed of appropriately.

Wastewater treatment or disposal is a familiar challenge for energy producers in Pennsylvania.[7] Over the past 10 to 15 years, shale gas production has generated unprecedented levels of flowback and produced waters across the state. The initial shale gas boom outpaced regulation, and municipal wastewater treatment plants were receiving, treating, and discharging wastewater from fracking operations. In many instances, chemical analyses revealed that effluent from these facilities did not meet U.S. Environmental Protection Agency (EPA) water quality criteria—and posed risks to human and ecological health.[8] In 2011, at the request of the DEP, wastewater treatment plants stopped accepting shale gas industry wastewater. The practice of sending the fluids to wastewater plants was formally banned by the EPA in 2016. Like the shale gas industry, wastewater from geothermal development in the Commonwealth, if not stored and reused in some capacity, would require alternative off-site treatment or disposal methods.

One option for wastewater disposal is underground injection. Pennsylvania has very few permitted wastewater disposal wells in operation (fewer than 20, according to DEP). Wastewater from shale gas operations that cannot be reused at nearby sites is mostly transported to Ohio for underground injection, as Ohio has hundreds of brine disposal wells in operation.[9] Wastewater can also be sent to centralized waste treatment facilities (CWTs) that are specifically designed to handle the volumes and compositions of industrial waste streams, but there are only a handful of such facilities in operation in Pennsylvania. Being few in number and sparsely located, transporting wastewater long distances to CWTs from smaller operations may be difficult and economically inefficient. Current CWTs also often have restrictions on the types of wastewater they will accept (for example, only from shallow gas wells).

Figure 6.1 shows wastewater treatment or disposal options across the state that are amenable to fracking waste, and by extension, likely candidates for geothermal waste streams. Disposal wells in Ohio are also included. CWT facilities are mostly concentrated in the southwest portion of the state (and in adjacent states) to service active shale gas activity in the region. Understanding

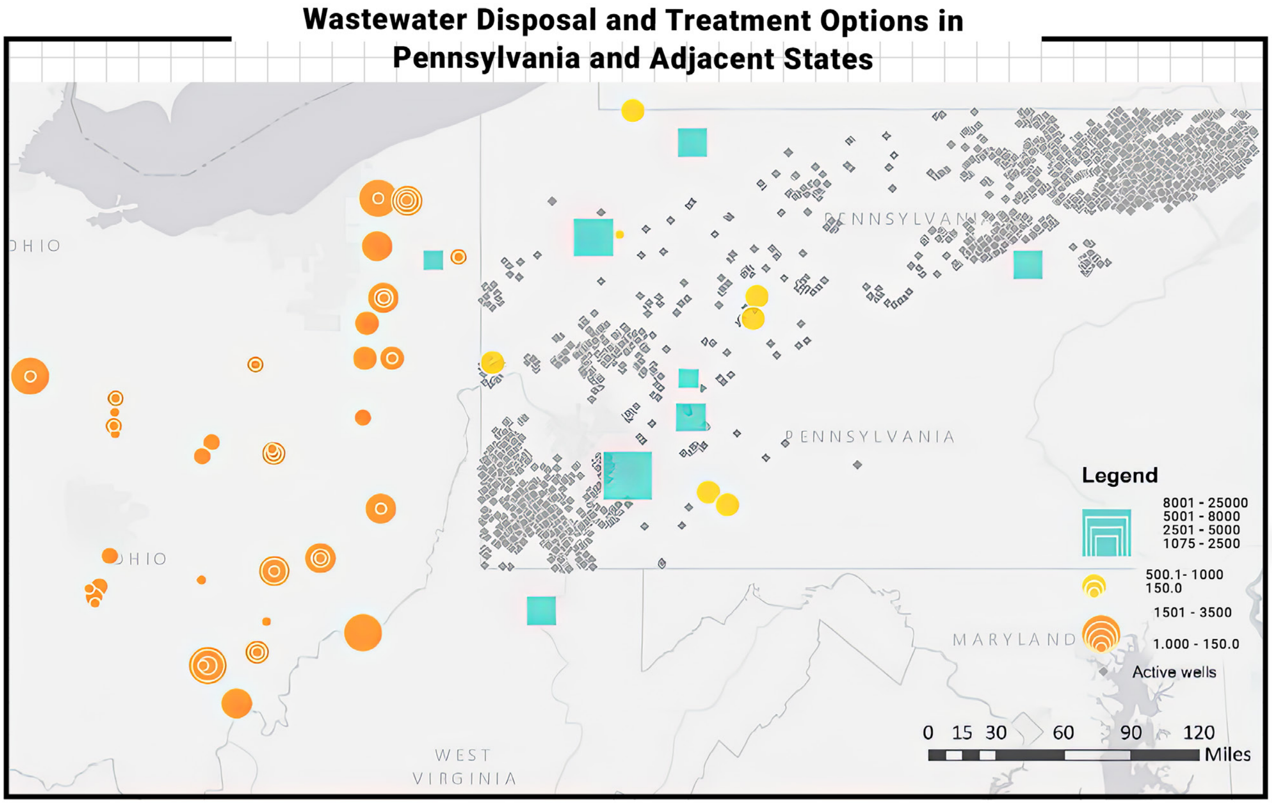


Figure 6.1: The size of the markers is proportionate to the wastewater disposal capacity at a site, in barrels per day (bbl/day). Blue squares correspond to CWT facilities. Yellow circles are dedicated wastewater disposal wells in Pennsylvania. Orange circles are dedicated wastewater disposal wells in Ohio. Note that the grey markers correspond to active unconventional (shale gas) wells. Source: adapted from Menefee and Ellis (2020)

the volumes and compositions of drilling and produced waters associated with geothermal energy expansion in Pennsylvania, as well as the available re-use, treatment, and disposal options, will be critical to avoiding negative environmental and human health impacts associated with improper treatment or discharge of wastewater into the environment.

WATER USE: WITHDRAWAL AND CONSUMPTION

Energy production can be water intensive, but some technologies use far more water than others. Energy sector water use is typically categorized into two metrics: withdrawal and consumption. Withdrawals are defined as the amount of water removed or diverted from a water source for use, while consumption is the portion of that withdrawn water that evaporated, transpired, was incorporated into products or crops, or was used and not returned to the immediate water environment.[10] Figure 6.2 shows historic and projected cumulative water use within the U.S. power sector for all generation types; geothermal's contribution can be directly correlated with the size of its contribution to the energy mix. Even as geothermal's contribution grows, though, it is not likely to add significant additional power sector freshwater demand on a national scale.

Despite its relatively low contribution to current and projected water use, it is important to understand the prospective water-use implications of developing geothermal in the Commonwealth, particularly with EGS development.

If drilling wells and hydraulic fracturing for EGS development in Pennsylvania are indeed similar to shale gas development, there could be environmental impacts because large volumes of water may be necessary. Completing a typical gas well in the Marcellus Shale uses on the order of 85,000 gallons of freshwater during drilling and 5.6 million gallons during hydraulic fracturing. Operators typically source this water from surface water in the region, or they reuse waters from previous operations. One life cycle analysis estimated freshwater consumption for shale gas production in the Marcellus at 185 to 305 gal/MWh.[11] Most of the water consumption occurs at the power plant or facility used to convert processed gas to energy, but a substantial amount of water is also used in the initial hydraulic fracturing stage.

Water use for geothermal development will naturally vary by location and specific technology. While many geothermal technologies would likely consume less or similar amounts of water compared to shale gas production, EGS development does have the potential to consume water at significantly higher levels than shale gas. Freshwater consumption across the life cycle of an EGS site, including initial drilling, stimulation, and the operating phase, is estimated to be on the order of 235 to 4,210 gal/MWh.[12]

The fracturing stage for EGS would be similarly water intensive as for shale gas, but there are significant losses of water in the reservoir during fluid circulation, as well as cooling losses during power plant operations. Thus, EGS may present long-term concerns and impacts in regard to water use, particularly when using freshwater resources. (Geothermal developers will need to consider current water oversight in a prospective region; for instance, the Susquehanna River Basin Commission regulates water withdrawals greater than 100,000 gal/day and water consumption greater than 20,000 gal/day.[13])

The main concern with geothermal water use, as with any water use in the energy sector, will be consumptive—

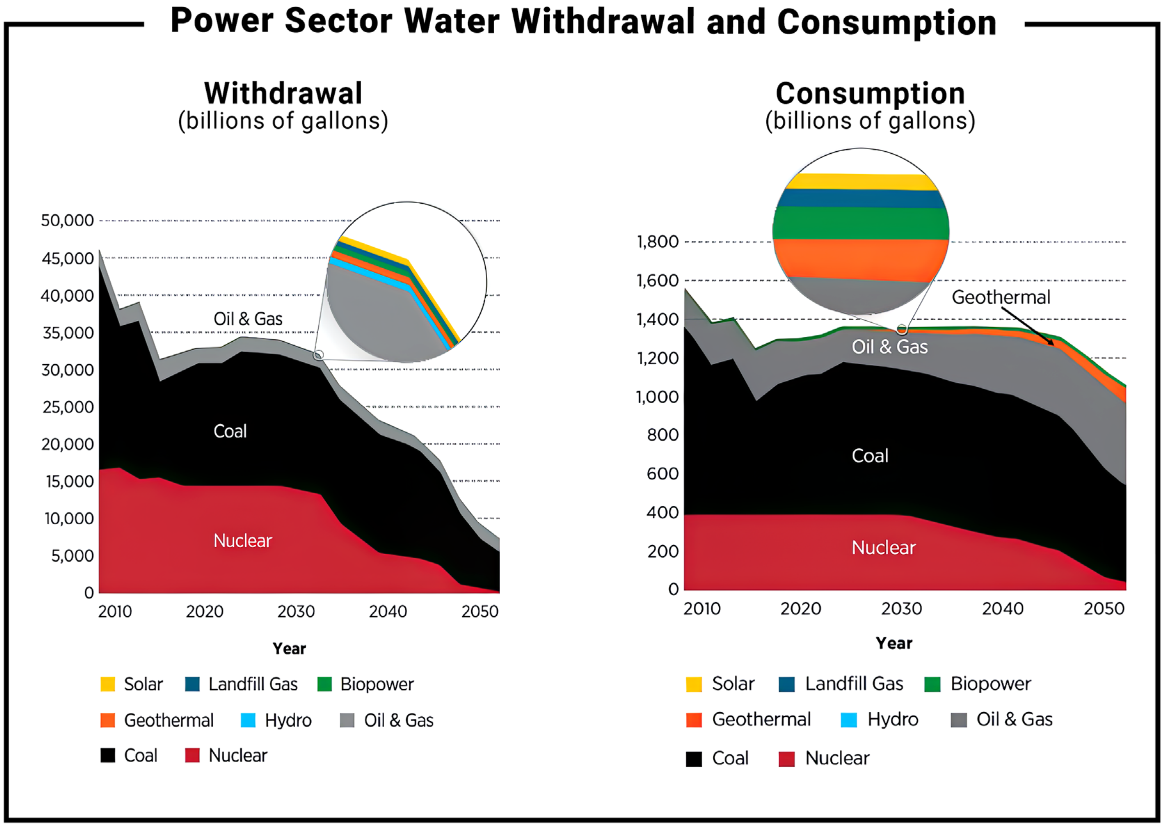


Figure 6.2: Water withdrawal and consumption impacts in billions of gallons (1 gallon=3.8 liters) over time and by energy type. Source: *The Future of Geothermal Energy in Texas: The Coming Century of Growth & Prosperity in the Lone Star State*, 2023. University of Texas at Austin Energy Institute. 2023. https://doi.org/10.26153/tsw/44084

water (groundwater or surface) removed from a watershed rather than being returned to a watershed at the same quality. That makes wastewater treatment particularly important. As noted earlier, various chemicals are mixed into frac fluids, and the quantities of chemical additives, as well as safety considerations for their transportation and storage, are important aspects of protecting water resources during EGS site development. Adequate treatment and discharge through a CWT can help avoid some net consumption of water from Pennsylvania watersheds.

INDUCED SEISMICITY

Induced seismicity is a concern with any process that involves injecting fluids into and/or extracting fluids from the subsurface. Again, shale oil and gas production offers a potential analogue. Shale production through hydraulic fracturing, with disposal of associated wastewater via underground injection, can trigger microseismic events. This became a major point of contention in Oklahoma, historically a seismically inactive region. The wave of induced seismicity in Oklahoma that started around 2008 was attributed to hydraulic fracturing that began in the region around the same time. (Technically the seismic events resulted from wastewater injection, rather than the fracturing events; Oklahoma used deep injection wells, near the basement rock, as opposed to shallower wells used in other regions.[14]) Microseismic events in Ohio have likewise been attributed to wastewater injection from oil and gas activity.[15] Induced seismicity, however, has not been seen in Pennsylvania despite similar levels of unconventional oil and gas development and hydraulic fracturing activity. In part, this is because wastewater is less frequently disposed of in wells in Pennsylvania.

Seismic activity can stem from geothermal energy development, depending on the location and type of geothermal system. For instance, the Geysers geothermal site in northern California has become one of the most seismically active regions in the state. Induced seismicity associated with condensate injection and steam extraction at Geysers has already contributed to land subsidence, and interactions with surrounding fault lines could trigger larger seismic events.[16] Recent computational modeling linked the extent of induced seismicity at the Geysers to fluid injection rates. This indicates that there are likely tradeoffs between increasing fluid volumes and injection rates for better productivity and limiting volumes and rates to minimize seismic activity. There is little reason, however, to expect that the challenges faced at the Geysers site in California would be replicated in Pennsylvania, which is seismically inactive and quite different geologically.

Broadly speaking, induced seismicity can be managed by effectively characterizing sites (avoiding development in tectonically active regions), properly engineering fluid circulation and injection rates during operations, and limiting injection rates and pressures in wastewater disposal wells. The EPA's Underground Injection Control program regulates underground disposal of wastewater and places limits on maximum injection pressures and rates in a given well, depending on the prevailing geology and characteristics of the formation. Given Pennsylvania's geology, lack of seismicity, and relatively few wastewater disposal wells, responsible geothermal development in the state should pose little risk of induced seismicity—and the risk should be even lower for non-EGS geothermal developments, such as local uses of lower-temperature geothermal resources (such as district heating).

LAND SUBSIDENCE

Subsidence happens when compaction in the subsurface leads to a lower ground level at the surface. Land subsidence in Pennsylvania has been mostly connected to the mining industry. It is is a possibility in geothermal development, depending on the local geology and the technology. For example, subsidence has been measured in California at the Geysers geothermal site, partially tied to induced seismicity and associated changes in stress states in geologic reservoirs, but as just noted, these are not expected to be issues in Pennsylvania.

It is also possible for subsidence to occur because of groundwater withdrawals associated with geothermal field development.[17] This can happen when fluids are extracted from unconsolidated aquifers (where the solid sediments are loose and not compacted), which are more susceptible to compaction as fluids in the reservoir's pore space are depleted. In other words, fluids in the pore space of a reservoir provide support;

as fluids are removed, stresses from overlying geologic formations tend to compact the solid material.

Take the Ogallala aquifer in Nebraska. It has been declining for years, leading to marked land subsidence. Compaction of the subsurface not only causes subsidence at the surface, but also reduces aquifer capacities, which can increase flooding risks. High levels of groundwater withdrawals for geothermal development, therefore, could theoretically lead to iterative impacts of aquifer depletion, aquifer compaction, land subsidence, and reduced ability of the aquifer to accept groundwater recharge and buffer against flooding during storm events. However, it is unlikely that geothermal development in Pennsylvania would rely on large groundwater withdrawals. As noted earlier, most freshwater used in the shale gas industry is sourced from surface waters in the region, and geothermal development would probably utilize surface waters as well.

LAND USE

The use of land for renewable and conventional energy development in Pennsylvania has been a contentious issue in the Commonwealth in recent years. The land footprint of energy development varies widely by source and technology. For instance, the Pennsylvania Solar Future Plan[18] notes that the state could produce 10 percent of its power from in-state solar energy using roughly 100,000 acres of land (about 0.3 to 0.4 percent of total land area in Pennsylvania, depending on the solar resource). Producing a similar amount of energy from wind in Pennsylvania would require a somewhat larger footprint, depending on the technology.

Among renewable and low-carbon energy sources, geothermal energy likely has one of the lowest land footprints per unit of energy produced. (See Figure 6.3.[19,20,21]) Geothermal's surface facilities could include local heat pumps, co-generation plants for district heating, or larger power plants associated with a successful EGS reservoir.

Beyond footprint size, for both renewable and non-renewable energy development, stakeholders in Pennsylvania have been concerned about changes to the land and habitat fragmentation. Experiences with wind energy and natural gas development are instructive for the issues that might come up in Pennsylvania in geothermal development. Since the 2000s, Pennsylvania has seen a lot of natural gas and wind energy development—primarily in sparsely populated, highly forested areas. Research has shown that this has resulted in the fragmenting of forest habitats. With natural gas, this fragmentation seems to be due primarily to rights-of-way for pipelines that transport gas from drilling and production sites.[22,23,24] With wind energy, literature suggests that habitat fragmentation happens in part when land is cleared for each wind turbine, as well as from deforestation to build access roads and electrical infrastructure connecting wind farms to the power grid.[25,26,27]

Geothermal energy is expected to have a significantly smaller footprint than wind or gas, and its infrastructure will be different too. But developers can still learn from best practices to reduce habitat impacts. Some can be mitigated by building infrastructure along existing rights-of-way where possible, and by avoiding putting infrastructure in areas with sensitive wildlife populations particularly susceptible to habitat fragmentation. Geothermal developers in Pennsylvania could reduce land use impacts even further by repurposing the state's numerous abandoned oil and gas wells to tap into geothermal energy. In other words, using sites that have already been disturbed.

Solar energy development on agricultural land in Pennsylvania offers another instructive lesson for geothermal. Controversy around large-scale solar on agricultural land in the state has been intense, especially in terms of visibility and the loss of an agricultural way of life.[28,29] The "agrivoltaics" approach, which aims to balance solar development with agricultural use, has faced numerous obstacles, including public opposition and low economic returns.[30] Stakeholders in Pennsylvania continue to struggle with how to maintain agricultural lands and deploy enough solar energy in promising locations.

Given geothermal's much smaller land footprint, the conflicts between agricultural use and geothermal energy could be less severe. Development of geothermal energy on agricultural lands would only require space for well pads, access roads, and electrical interconnections

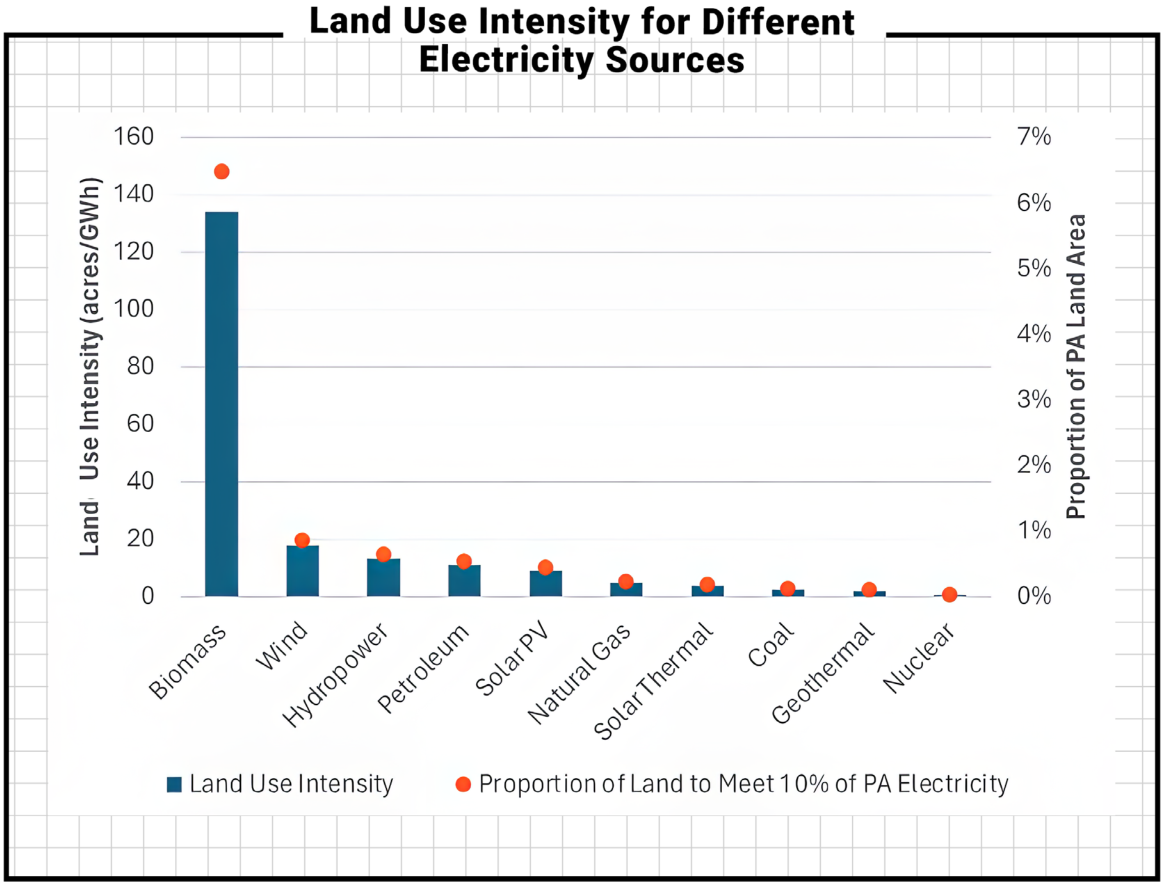


Figure 6.3: The blue bars (left-hand axis) show the land-use intensity of each power generation source. Figures are representative of the entire United States and were not developed specifically for Pennsylvania. The orange dots (right-hand axis) show the proportion of total Pennsylvania land area required for each power generation source to produce 10% of Pennsylvania's annual electricity demand (~145,000 GWh, per EIA). The "biomass" source assumes agricultural land completely dedicated to energy crops. Sources: McDonald, et al. and the 2014 National Climate Assessment. See References 20 and 21.

(if being used for electricity generation). The amount of land taken out of agricultural service for geothermal energy is likely to be lower—on a per-unit energy basis—than for solar.

As with all energy sources, geothermal developers will have to comply with numerous land-use regulations and requirements, including setbacks, buffers, and erosion and sediment controls, which all vary depending on the site. These issues would likely be comparable to those encountered during oil and gas development.

TRAFFIC AND NOISE

Much like in the construction of other industrial facilities, geothermal exploration and production could lead to increased truck traffic on local roads. Surrounding populations could also have to bear an increase in noise. These aren't likely to be any greater than other comparable industrial activities. Noise comes from the process of drilling wells, traffic, construction, and operational equipment such as pumps and compressors. Most noise would likely happen during construction and drilling, though operations can still produce noise levels that may affect nearby residents and wildlife.[31,32] Noise levels from drilling operations and traffic have been raised as major concerns in Pennsylvania communities hosting natural gas development.[33,34]

In response, the natural gas industry has found ways to move people and equipment more efficiently to reduce noise. Geothermal developers could adapt these and other mitigation strategies to build a good relationship with local communities.

AIR EMISSIONS

Air emissions associated with energy production can present concerns for human and environmental health via both local air pollution and contributions to global greenhouse gas levels. Unlike fossil fuel energy, however, the use of geothermal energy involves very low levels of greenhouse gases and local air pollutants. While there have been virtually no emissions analyses specific to Pennsylvania geothermal power plants, and very little analysis of emissions implications of geothermal heat pumps in Pennsylvania,[35] there are clear implications that can be drawn from the literature about what to expect in terms of air pollution and greenhouse gas emissions from geothermal deployment.

The existing literature on life cycle greenhouse gas emissions from geothermal electricity development has found that the emissions intensity of geothermal energy production, although always very low, varies with the type of technology being used. Whereas coal and natural gas power plants (without carbon capture) may have emissions rates of 500 to 1,000 grams of carbon dioxide equivalent per kilowatt-hour (g CO_2e/kWh), a review of studies by the National Renewable Energy Laboratory (NREL) found life cycle greenhouse gas emission rates from geothermal energy to generally range from about 15 to 50g CO_2e/kWh.[36] Flash systems, where high-temperature hydrothermal fluids are "flashed" to steam at the surface to directly drive turbines and produce power, have been found to be on the higher end of the geothermal emissions spectrum. Binary hydrothermal systems, where lower-temperature geothermal fluids are passed through heat exchangers with a secondary fluid rather than directly contacting the heat exchanger, have generally been found to have lower life cycle greenhouse gas impacts. The same is true for binary EGS systems, which are more likely than hydrothermal systems to be deployed for geothermal electricity or district or industrial heating in Pennsylvania. (See Figure 6.4 for emissions comparisons for different power-generation technologies.)

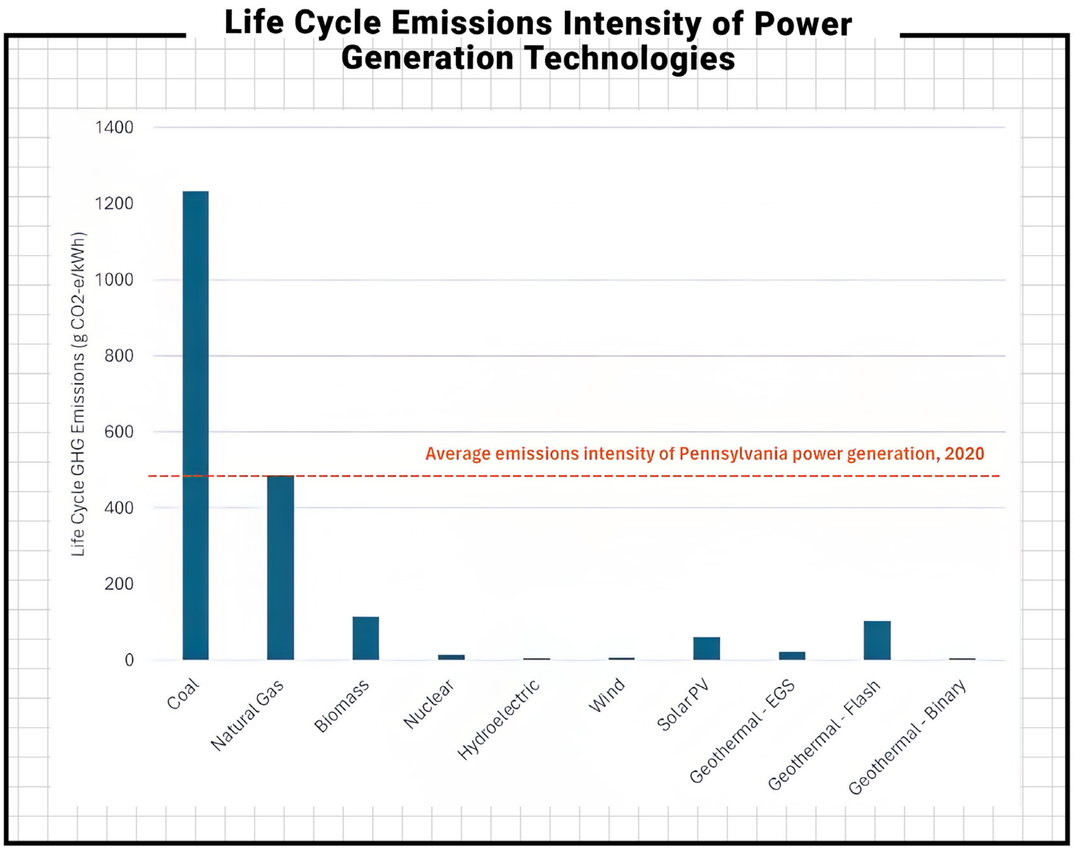
In addition to low levels of emissions, geothermal energy also has low levels of air pollution. The core reason for both is the same: geothermal energy doesn't involve the kinds of combustion-related emissions that accompany the use of coal, oil, or natural gas. In addition, the total energy use needed to recover geothermal energy has been found to be low relative to other power generation technologies.[37] The emissions that do come from geothermal energy deployment tend to be indirect, such as from construction, drilling, and infrastructure (piping, pumps, and so forth);[38] some analyses have found that geothermal energy extraction involves more of this infrastructure-related energy than other low-carbon power sources.[39] Any electricity drawn from the regional power grid would likewise involve some indirect air emissions because Pennsylvania's electricity mix currently involves substantial use of fossil fuels. Still, the overall emissions of geothermal energy will be quite low. What's more, as the power grid decarbonizes and as on-site deployments of renewables and energy storage increase, these indirect emissions will decline.

Some studies have found direct releases of CO_2 from some types of geothermal operations globally.[40,41,42] Dry-steam and flash-steam hydrothermal technologies, for instance, may involve the release of small amounts of greenhouse gases (primarily CO_2) from well discharge in the form of non-condensable gases. These technologies, however, are not ones that would be used in Pennsylvania. Large CO_2 emissions from geothermal power plants have also been noted in a few places globally, but these places feature high levels of carbonate in the rock, which would not be characteristic of Pennsylvania.[43]

Beyond geothermal's own emissions, it is important to recognize that geothermal energy can help avoid or mitigate emissions as it replaces existing or new fossil sources. In addition, repurposing abandoned oil and gas wells in Pennsylvania to tap into geothermal energy could help mitigate the wells' release of fugitive methane emissions.

CONCLUSION

All energy sources and technologies have potential environmental impacts that need to be identified, monitored, and mitigated. Since Pennsylvania has not yet seen large-scale geothermal energy development, this assessment has largely drawn on the experiences of other states and countries, as well as modeling studies and analogues such as Pennsylvania's prolific shale gas production.



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It is worth reiterating that geothermal energy development in Pennsylvania is likely to have relatively low impacts, across multiple measures, as compared with other forms of conventional and renewable energy. Particularly with the kinds of geothermal technologies likely to be deployed in the Commonwealth. Geothermal as an energy source is likely to lead to fewer air emissions, a lower greenhouse gas footprint, and lower pressures on land use and wildlife habitats. Pennsylvania's geology means the Commonwealth is at low risk of induced seismicity and land subsidence. Wastewater management, water use, and traffic and noise will require careful oversight and mitigation during geothermal project siting, development, and assessment, but these are challenges that can be addressed.

Environmental impacts and mitigation measures will inherently be specific to where and how geothermal energy is developed in Pennsylvania—not only the type of system used, but also the surface and subsurface characteristics at the drilling location and the available mechanisms to handle fluids and wastewater. Pennsylvania's geology and site situations are going to be highly variable in different areas of the state. Conducting robust upfront site characterization and gathering field data (ideally using low-impact geophysical techniques or surveys) for next-generation geothermal systems is going to be critical for identifying the most appropriate locations, crafting the lowest-impact industrial practices, and guiding Pennsylvania towards effective and reasonable regulations—and therefore a safe, sustainable, and effective deployment of geothermal energy.

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Chapter 7

Opportunities for Pennsylvanians: Navigating Geothermal for Landowners, Communities, and other Stakeholders

C. Young, M. Clark & L.Ritzer

> ***Successfully deploying geothermal in Pennsylvania for heating, cooling, and power requires engaging valuable stakeholders like labor unions, environmental groups, and energy providers; addressing community concerns; leveraging the state's oil and gas expertise; and fostering innovation via research and federal support. Collaborative efforts can position geothermal as a vital resource for the Commonwealth.***

INTRODUCTION

In the United States, places that have extensive oil and natural gas development—like Pennsylvania—can be attractive locations for geothermal projects.[1] Geothermal energy produced in the Commonwealth could support residential and industrial uses, and some baseload electricity generation. (See chapters 2 and 3). Today, an increased focus on Engineered Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS), as described in Chapter 1, bolsters those opportunities.

Should energy companies decide to establish geothermal projects in the Commonwealth, they will have to engage with a range of stakeholders. This chapter reviews some of the key constituencies affected by and central to geothermal energy development in the Commonwealth. For example, private landowners and governments stand to benefit from geothermal royalties. Government also plays a critical role in shaping the success of geothermal projects through regulatory oversight and policy development. As with all energy development, geothermal projects could have impacts as well as benefits. Pennsylvanians are likely to use past experiences with mineral resource extraction as a frame of reference for geothermal development.[2,3]

Engagement with communities that could be impacted by geothermal development will be necessary to address concerns and bolster public support. Developers should also engage potential advocates (labor unions, environmental groups), potential sources of technical expertise (industries, research universities), and natural gas and electricity providers to explain the benefits of—and to solicit critical support for—geothermal development in Pennsylvania.[4]

Increased geothermal production offers significant opportunities for diverse stakeholders, and by engaging with them all, geothermal developers and state officials could create ongoing economic benefits, particularly in many rural parts of the state.

PRIVATE LANDOWNERS

Private landowners in Pennsylvania may benefit economically from geothermal lease agreements, royalties, and rights-of-way agreements. Given the history of energy development in the state, many landowners are familiar with these sorts of arrangements and should generally understand the potential financial gains they stand to make.[5] With an appropriate level of compensation, landowners could be a catalyst for widespread adoption of geothermal heat and power, providing a reliable source of abundant energy to the state.[6] Engaging landowners as prospective partners should be a primary concern for geothermal developers.

Understanding royalty expectations among land and mineral rights owners is essential to understanding how geothermal energy may develop in the Commonwealth, and how landowners may receive the geothermal industry.[7] Royalties are generally tied to the revenues earned or volumes produced. The amount of royalties depends on a myriad of factors, including plot size, market price, and production levels. Over the past century, owners have been compensated for allowing access to various resources, including coal, natural gas, and oil. Those agreements might be a blueprint for access to heat on private property.[8] (See *Chapter 4: Who Owns the Heat*)

While examples of payments for access to geothermal resources are scant, Pennsylvania's experience with royalties for other energy resources provides insights. For example, when the Pennsylvania shale gas boom began in earnest, economists estimated that royalty payments to landowners in Pennsylvania exceeded $16 million per year and injected significant capital into the economy.[9] Studies conducted in the early years of the boom estimated that the monetary benefits for Pennsylvania property owners via royalties and leases exceeded those of local employment and wages.[10] Payments were so substantial for some owners that Pennsylvanians coined the term *mailbox millionaires*.[11]

To ensure equitable compensation to private owners of shale gas, the Pennsylvania General Assembly enacted the Guaranteed Minimum Royalty Act in 2013. The law protected landowners by setting expectations for compensation associated with oil and gas extraction through a guaranteed royalty rate equal to or greater than 12.5 percent of the value of the oil or gas produced from their land.

While the actual amount of royalties paid to private landowners is not publicly reported, in 2020, the Pennsylvania Independent Fiscal Office (IFO) calculated an estimate of royalties paid to landowners in recent years using the market value of natural gas and assuming a 13.5 percent royalty rate (found to be average;[12] see Table 7.1). Outside of Pennsylvania, studies have found that for each million dollars of natural gas produced, $132,000 in royalty payments was generated.[13]

Other energy projects, such as wind farms, have also generated significant royalty payments for private landowners in Pennsylvania.[14] In the Commonwealth, there are 27 privately operated wind farms, and like natural gas development, wind farms typically compensate property holders for access to the land and the amount of energy produced. While numbers are not readily available for Pennsylvania, an economic study conducted in Texas found that two counties with abundant wind farms generated approximately $11.5 million in royalties annually.[15]

Royalty agreements may prove paramount to the success of geothermal projects on private lands in Pennsylvania.[16,17] Geothermal energy developers and operators should work with landowners to establish equitable compensation agreements that benefit both parties.

Estimated Private Landowner Royalties from Natural Gas in Pennsylvania

Calendar Year	Market Value of Natural Gas	Estimated Royalty Payments
2018	$ 11,554,000,000	$ 1,559,790,000
2019	$ 9,692,000,000	$ 1,301,670,000
2020	$ 4,626,000,000	$ 624,570,000
2021	$ 18,010,000,000	$ 2,431,350,000
2022	$ 36,990,000,000	$ 4,993,650,000
2023	$ 7,064,000,000	$ 953,640,000

Table 7.1: The spike in estimated royalties in 2021 and 2022 was mainly due to a large increase in the price of natural gas caused by geopolitical and economic forces. Pennsylvania Independent Fiscal Office. (2020). Natural Gas Royalties Increase in 2017. http://www.ifo.state.pa.us/download.cfm?file=Resources/Documents/RB%202019%20Natural%20Gas%20Royalties.pdf

That said, while Pennsylvania landowners certainly have experience with energy development, research on geothermal energy projects shows that landowners could use more education to make informed decisions. A dearth of information about geothermal projects and their risks and benefits increases skepticism.[18] Studies suggest that landowners may be more willing to allow energy development if they feel that steps have been taken to reduce negative externalities and if the developer has had experience with such projects in the past.[19] In other words, geothermal developers should pursue efforts to educate landowners about the benefits of development and mitigation of negative externalities.

GOVERNMENTAL ENTITIES

Like private landowners, government agencies could enjoy a range of benefits from geothermal energy development. And they will be key players in charting the future of geothermal energy in the Commonwealth.

Increased revenue for local, state, and federal agencies may be generated through leases and royalties for geothermal development on public land. Lands could include parks, forests, game lands, university properties, and military facilities. In some cases, the landholdings of government agencies may be significant, with the potential to host multiple geothermal energy projects. There are, for example, approximately 2.2 million acres of state forests, 1.5 million acres of state game lands, 283,000 acres of state park lands, and 622,000 acres of federal land in Pennsylvania.[20] (See *Chapter 2: Where to Develop Geothermal.*)

When energy is developed on federal lands, local governments can benefit as well. Today, the Bureau of Land Management manages more than 531 geothermal leases in 11 Western states and Alaska. On average, geothermal leases generate over $12 million in federal royalties each year. Half of that is shared with the states and a quarter with local counties.[21] In 2023, federal geothermal rents, bonus bids, and royalties combined amounted to $25.3 million.[22]

Again, experiences with oil and gas development are instructive. Nationally, an economic study examining taxation of oil and gas production estimated that approximately 10 percent of all revenue from extraction was collected by state and local governments. In Pennsylvania, governmental entities benefited handsomely from royalties via shale gas development. Both the Pennsylvania Game Commission and the Department of Conservation and Natural Resources (DCNR), for example, have received millions of dollars

Estimated State Agency Royalties from Natural Gas in Pennsylvania

Fiscal Year	PA Game Commission	DCNR
2018-19	$ 39,923,902	$ 66,781,972
2019-20	$ 50,554,313	$ 64,945,055
2020-21	$ 54,793,673	$ 57,497,750
2021-22	$ 171,899,459	$ 115,434,485
2022-23	$ 306,864,414	$ 165,288,329
2023-24	$ 82,529,361	$ 65,978,653

Table 7.2: As reported by the Commonwealth. Sources: Pennsylvania Game Commission. (2022). Fiscal 2021-22 Annual Report. https://www.pgc.pa.gov/InformationResources/MediaReportsSurveys/Documents/PGC_Annual_Report_2022_WEB.pdf. And Department of Revenue. (2024). May 2024 - Report of Revenue and Receipts. https://www.pa.gov/content/dam/copapwp-pagov/en/revenue/documents/news-and-statistics/reportsstats/revenuereceipts/documents/2023-24/2024_05_bfmmonthlyreport.pdf

annually from royalties, with payments spiking in fiscal years 2021-22 and 2022-23 due to geopolitical and economic forces, as shown in Table 7.2.

The Commonwealth does not aggregate data on local government royalty payments, but it appears that counties, boroughs, and townships have also received considerable royalty payments. Conversations with officials in Washington County, one of the top gas-producing counties in the state, revealed that land leased for gas development in two county parks generated an estimated $27 million in lease and royalty payments since 2007. Two-thirds of that revenue has been generated since 2012, and the county has used the revenue to develop parks and recreation programs.

In addition to royalties, lease payments, and the like, other mechanisms could also create revenue for state and local governments. For instance, Act 13 of 2012 provided for the imposition of an unconventional gas well fee (sometimes called an impact fee), which has generated millions of dollars for state agencies and municipal governments to use for specific purposes, such as public infrastructure and safety (see Figure 7.1).

The benefits to governments from geothermal energy development go beyond the financial and economic; there are clear environmental and public health gains too. Widespread deployment of geothermal systems would reduce energy-related air emissions. Geothermal projects that repurpose orphaned and abandoned wells could also help state and local governments reduce fugitive methane emissions as well as other economic, environmental, and public health risks.[23,24,25] As Pennsylvania considers its energy initiatives, geothermal energy could be a primary tool in reducing the state's emissions.[26]

Of course, governments are not just passive beneficiaries of energy development. In their regulatory and policy-making capacities, they will also play central roles in shaping the future of geothermal energy development in Pennsylvania. (See *Chapter 4: Who Owns the Heat* and *Chapter 5: Additional Policy and Regulatory Issues*.) Geothermal developers should expect to engage with borough and township authorities, DCNR, the Department of Environmental Protection (DEP), the Public Utility Commission (PUC), the Department of Transportation (PennDOT), and others that will oversee geothermal energy projects and associated infrastructure on private and public lands. Table 7.3 summarizes the oversight functions of unconventional natural gas development in Pennsylvania, illustrating how various governmental entities might be involved in the oversight of geothermal energy development.

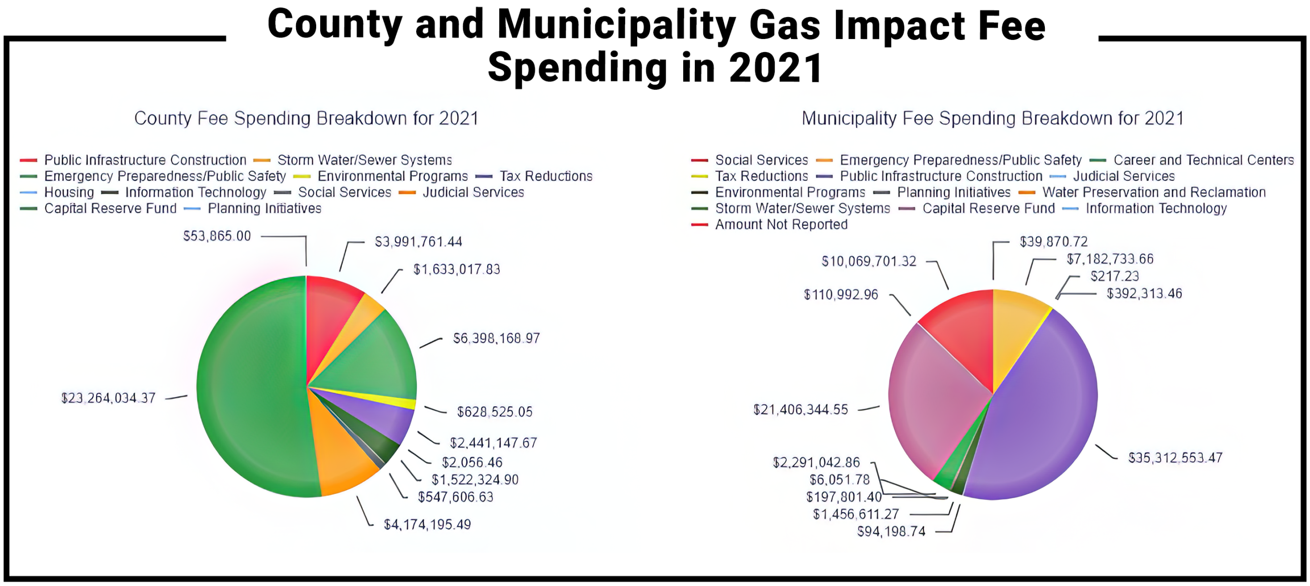


Figure 7.1: Source: Act 13 Public Utility Commission. (n.d.). Disbursements and Impact Fees. Retrieved from https://www.act13-reporting.puc.pa.gov/Modules/PublicReporting/Overview.aspx

IMPACTED COMMUNITIES

As discussed earlier, geothermal energy deployment will present a host of benefits, as well as potential concerns, for the communities where development occurs. The impacts will vary depending on the location, design, and operation of a specific project. As outlined in Chapter 1: Where to Develop Geothermal?, deployment is mostly expected to occur where unconventional natural gas wells already exist. Many of those areas overlap with areas identified for recent federal tax incentives, including Opportunity Zones created as part of the Tax Cuts and Jobs Act signed into law by President Trump, and Energy Communities defined in the Inflation Reduction Act signed by President Biden (see Figure 7.2). These incentives will increase the economic benefits for projects located in these areas.

Assuming development occurs in the areas with the highest potential, geothermal developers should expect to work primarily in rural Pennsylvania communities with small economic bases. Many of these communities face higher unemployment rates and lower wages than their Pittsburgh and Philadelphia Metropolitan Statistical Areas (MSAs) counterparts. Furthermore, as shown in Table 7.5, many counties identified as possible priority areas for geothermal development have experienced significant population loss since 1983.

Geothermal projects could provide a much-needed boost to the local economies in these regions. As noted, geothermal development could increase revenue through royalties, leases, and perhaps something akin to the Act 13 unconventional gas well fee. In addition, geothermal projects could create new jobs and help stabilize wages. Research on economic impacts of renewable energy suggests that investments in hydroelectric, biomass, solar, wind, and other projects have had positive effects on local employment and wages.[27,28] Similar results were observed amidst the shale gas boom, though to a lesser degree.[29]

It is important to remember that these communities have also disproportionately experienced environmental impacts from industry and energy development over the years.[30,31,32,33,34] Many of those impacts may be repeated with geothermal development—noise, dust, traffic during construction, concerns about operations, and other nuisances.[35] Research shows that even the most ardent supporters of shale gas development expressed frustration with dust, traffic, noise, and road damage associated with the industry.[36,37,38] (See *Chapter 6: Environmental Considerations*.)

A recent study of geothermal energy found that negative perceptions of unconventional natural gas development significantly impact perceptions of

Natural Gas Oversight in Pennsylvania

Entity	Local Zoning	Municipal Planning Code	Land Access	Well Drilling Permit	Landowner Notification	Gas Well Bond	Containment Plan	Emergency Response Plan	Waste Disposal Permits	Road Occupancy	Impoundment Permits	Water Use Permits	Wastewater Permits	Stream & Wetlands Permits	Air Emissions	Erosion & Sedimentation	Production & Waste Reports	Inspection & Environmental Compliance	Impact Fees	Pipelines	Electric Connection	Grid Integration (other)
County & Municipality	●	●	●	○	○			○		○		○		○		○				○	○	
DEP				●	●	●	●	●	●		●	●	●	●	●	●	●	●		●		
DCNR			○									○	○	○							○	
Game Commission			○											○							○	
PUC																			●	○	●	●
PennDOT			●							●										○		

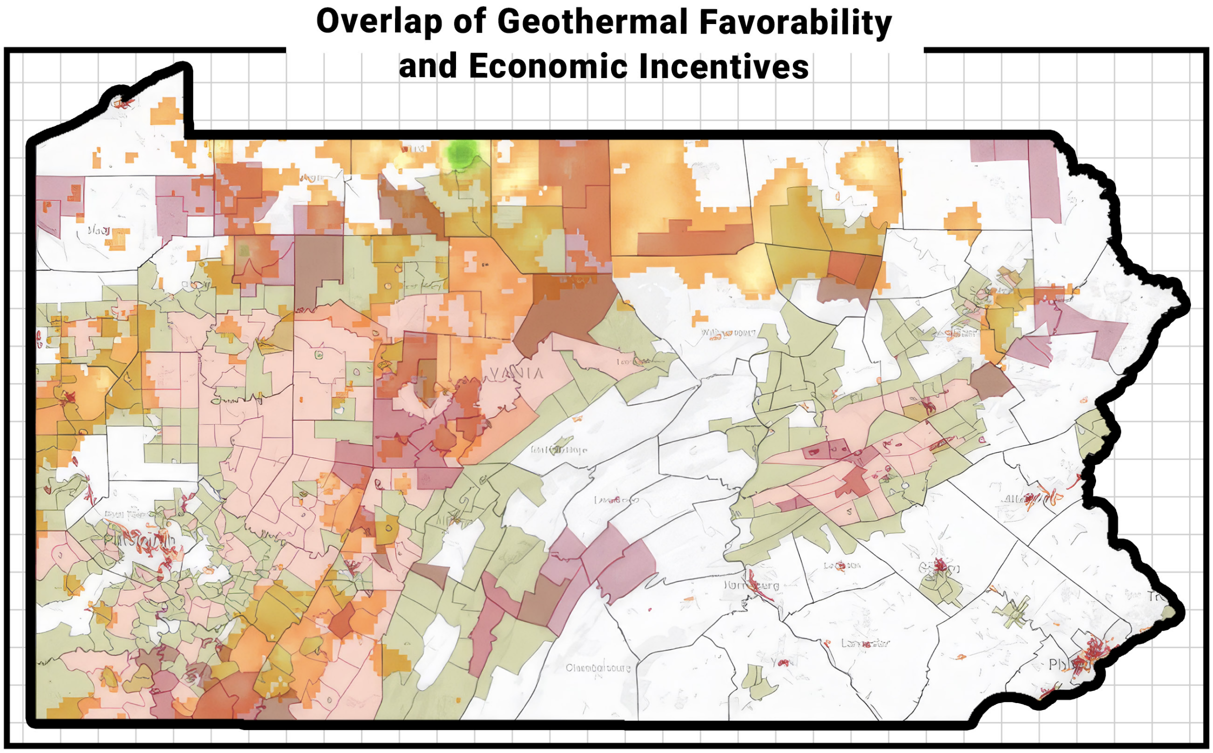
Table 7.3: Solid dots indicate direct involvement of local and state governmental entities, while empty dots indicate indirect involvement. Source: Author interviews with DEP and other state officials

EGS and AGS. However, the study also found a degree of ambivalence to geothermal rather than outright rejection.[39] The findings suggest that communities may be willing to consider new geothermal technologies if they are used appropriately and transparently, with stringent development conditions to minimize environmental risk. Further, most shale communities are considered environmental justice communities,[40] and as such, require special consideration under state and federal guidelines.

To avoid the issues prevalent during the early years of the shale gas boom, geothermal developers should conduct education and outreach campaigns tailored to Pennsylvania's rural communities. As part of the campaign, developers should detail the process of geothermal development, the economic benefits of projects to communities, and how they will mitigate negative externalities.

OTHER KEY STAKEHOLDERS TO ENGAGE

As mentioned, numerous other constituencies could be affected by, be strong advocates for, or benefit from geothermal energy development in Pennsylvania. Geothermal developers will want to engage with labor unions, environmental interests, industries, research institutions, natural gas and electricity providers, and other entities to explain the benefits of potential projects, garner support, and accelerate deployment.



Overlap of Geothermal Favorability and Economic Incentives

Figure 7.2: Pink, maroon, and tan areas show Opportunity Zones and Energy Communities. Yellow, orange, and green show areas capable of reaching 300°F (150°C) within 5km. See figures 2.3, 2.4, and 2.5 for further detail on temperatures. Source: GeoMap

Potential Advocates

The geothermal industry can benefit from partnering with labor unions, a skilled and motivated workforce and a powerful advocate for a supportive policy environment.[41] Geothermal energy projects require significant labor throughout construction, operation, and maintenance phases. The Bureau of Labor Statistics (BLS) and Geothermal Energy Association estimate that a 50-megawatt (MW) geothermal plant requires between 697 and 862 workers for completion, including jobs in construction management, engineering, geology, and hydrology.[42] BLS data indicates that union membership for the geothermal labor force could range from 4.9 to 20.8 percent, based on the oil and natural gas extraction and utilities sectors, respectively.[43] In addition to increased opportunities, studies have found that laborers benefit from increased wages from renewable energy projects. One study found that installation of a large wind farm was associated with a 2 percent permanent increase in wages.[44] Another study found that net-zero energy transitions could lead to approximately $200 billion in wages over the next decade and another $200 billion or more by 2050.[45] Given these potential benefits, unions could be strong advocates for policies that support the growth of the geothermal sector. For example, as detailed in *Chapter 5: Additional Policy and Regulatory issues*, states like New York and Maryland recently passed legislation, with wide support from organized labor, that allows gas utilities to operate thermal energy networks (TENs). In Pennsylvania, unions recently helped advocate for the Commonwealth to become a hydrogen hub under the federal Bipartisan Infrastructure Law of 2021.[46]

Environmental advocates are another valuable constituency. While some may need reassurance about mitigation of potential negative impacts, the environmental community could be strong advocates for an always-on source of clean energy. They may also welcome the reuse of abandoned oil and gas wells in Pennsylvania because it represents an opportunity to

Population Change since 1983 in Counties with Potential for Geothermal Development

County	Population Change (%)
Allegheny	-13.2
Armstrong	-16.3
Beaver	-16.8
Bradford	-4.1
Butler	32.8
Clarion	-14.0
Crawford	-8.4
Erie	-5.0
Fayette	-20.0
Forest	30.6
Greene	-15.6
Jefferson	-9.4
Lawrence	-18.9
McKean	-20.8
Mercer	-13.8
Potter	-7.7
Susquehanna	0.0
Tioga	2.1
Venango	-22.9
Warren	-21.2
Washington	-2.7
Westmoreland	-9.2

Table 7.5: Source: (*United States Census Bureau, 2022*)

mitigate fugitive methane emissions and reduce the need for new wells (minimizing the associated impacts of drilling and exploration), while decreasing the overall carbon footprint of energy production.[47] Incentivizing utilities to adopt TENs would further reduce fugitive methane emissions from otherwise leaking distribution networks. Environmental justice and environmental advocates may also be supportive of more widespread industrial use of geothermal, which would likely improve air pollution, as geothermal heat produces significantly less pollution than fossil fuel combustion. (See *Chapter 2: Where to Develop Geothermal* and *Chapter 6: Environmental Considerations* for more.)

Other non-profit non-governmental organizations (NGOs), such as ones focused on sustainable economic development, could likewise find geothermal development in the Commonwealth to be aligned with their missions. For example, repurposing abandoned wells for geothermal energy can help create job opportunities in the renewable energy sector and contribute to the growth of the green economy.[48] As noted, geothermal production can also help stimulate economic growth and improve the living standards of local communities.[49] A range of NGOs could be helpful advocates for geothermal energy deployment.

Potential Sources of Technical Expertise and Innovation

The Commonwealth's extensive experience with resource extraction and energy projects means there are a lot of stakeholders in the region with a wealth of relevant technical expertise who are equipped and eager to facilitate geothermal development. (See Figure 7.3.)

Pennsylvania's oil and gas industry, for instance, with its estimated 40,000 workers across specialties, is poised to be a major stakeholder in geothermal development. The existing knowledge bases in well design, drilling, reservoir detection, hydraulic fracturing, and fluids and water management, are all transferable to geothermal. Geologists, drillers, and landmen can plan and build next-generation geothermal wells with minimal retraining. Information and technologies currently owned and used by the oil and gas industry can not only help reduce costs and risks, especially in the early stages of geothermal development, but also serve as a foundation on which

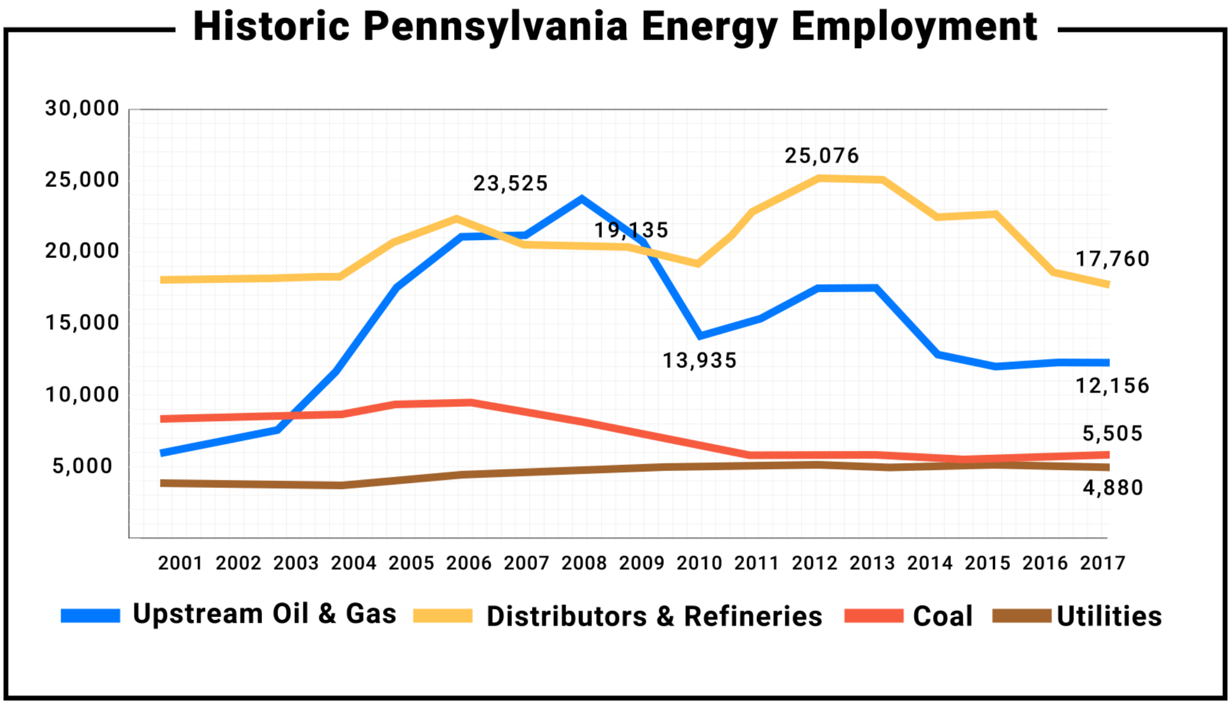


Figure 7.3: Number of workers. Excludes transportation fuel retailing. Source: Bureau of Labor Statistics (BLS), Quarterly Census of Employment and Wages. Source: Bureau of Labor Statistics (BLS), Quarterly Census of Employment and Wages

future geothermal-specific research can be built. There are Pennsylvania-based companies already actively engaged in geothermal development. For example, CNX Resources, a prominent natural gas driller and operator based in Canonsburg, is currently conducting a preliminary investigation for a potential geothermal pilot project. Atlas Copco Secoroc LLC, an oil and gas services company based in Fort Loudon, received $1 million from the Department of Energy (DOE) in 2011 to perform technical research to “enable drilling at high temperatures encountered in deep geothermal wells.”[50] Today the company is applying air compressor technology to drilling applications for faster completion.[51] And a number of Pennsylvania entities recently submitted a proposal for a DOE grant for EGS pilot projects.

Add to all this: Utility workers and pipefitters can install and repair thermal energy networks in the same rights of way and with similar tools and techniques as used for natural gas (see Natural Gas and Electricity Providers below). Process engineers can design, develop, and maintain direct use systems. (See Chapter 3: Geothermal Direct-Use Opportunities.) Next-generation geothermal presents immediately applicable job opportunities requiring near-identical skills and expertise for tens of thousands of Pennsylvania workers.

Pennsylvania’s 300-plus colleges and universities, six of which are designated as having high research activity, also share in the Commonwealth’s rich energy history and have conducted important and impactful research relevant to geothermal. Some of these universities boast multi-disciplinary research capabilities, spanning from complex technical and engineering capacities to regulatory and policy work. Many of these schools have formed centers or other initiatives dedicated to emerging energy technologies, including geothermal energy. Some are already involved in projects that could have an impact on geothermal development. Penn State University’s Renewable Thermal Energy Working Group, University of Pennsylvania's Kleinman Center for Energy Policy, Lehigh University's Energy Research Center, and Carnegie Mellon University's Wilton E. Scott Institute for Energy Innovation are all either engaged in or are suited to begin working in the geothermal sector. As well, many of the Commonwealth's universities, including Temple University and the University of Pittsburgh, are home to professors whose work is dedicated to geothermal development.

Federal agencies, such as the National Energy Technology Laboratory (NETL), which has an office in South Park, PA, will also play a critical role in steering the development of geothermal development. In the West, NETL is a partner with the Energy and Geoscience Institute at the University of Utah and the Geothermal Technologies Office (within the DOE's Office of Energy Efficiency and Renewable Energy) to develop enhanced geothermal systems at the Frontier Observatory for Research in Geothermal Energy (FORGE) in Utah. In Pennsylvania, NETL could potentially help fund research projects, facilitate public-private partnerships, and provide technical expertise to overcome the scientific and engineering challenges associated with next-generation geothermal energy development.

Natural Gas and Electricity Providers

As of this writing, several Pennsylvania natural gas distribution companies, including the municipally owned Philadelphia Gas Works, are exploring installation of or conversion to utility-scale geothermal district heating and cooling networks.[52] While common in the western United States and Europe, and even on some Pennsylvania university campuses (such as Lehigh University), geothermal district heating and cooling networks at utility scale would be relatively novel in the Commonwealth and region. Natural gas providers could be key allies in the Commonwealth, as they have been in New York and Maryland.

As shown in *Chapter 2: Where to Develop Geothermal*, some locations in Pennsylvania could also host geothermal electricity generation projects, which means electricity providers also have a stake in how geothermal development proceeds in the Commonwealth. Recent studies suggest that current technologies could provide up to 15 MW of capacity per geothermal well to local electricity supplies.[53] Utilities in Pennsylvania do not own generation; rather, utilities and competitive electricity suppliers procure generation to supply to customers. That makes electricity providers potential customers for geothermal project developers. However, geothermal electricity costs may need to come down to achieve widespread interest from providers. If subsidies and other incentives were offered for projects, the deployment of geothermal could increase by more than 20 percent.[54] (Policy support is addressed in detail in *Chapter 5: Additional Policy and Regulatory Issues.*) Electricity generation from geothermal projects might also require new transmission and distribution infrastructure (e.g., poles and wires) and integration into existing infrastructure,[55,56] which means engagement with distribution utilities, transmission operators, and PUC officials.

CONCLUSION

Pennsylvania could be an attractive choice for geothermal energy production. Development will depend on geothermal developers' engagements with an array of key stakeholders. Education and outreach efforts are needed for private landowners, governmental entities, impacted communities, and potential advocates—to explain the potential economic, environmental, and other benefits of geothermal development, as well as the measures that will be taken to mitigate negative externalities. Geothermal developers will also benefit from engaging with industries and institutions that have extensive technical expertise, to gain from their experience and accelerate the deployment and innovation of geothermal technologies. Coordinating with natural gas and electricity providers, too, will help ensure there is interest and infrastructure to support deploying geothermal energy for local heating, cooling, and power. By engaging with all these important stakeholders, a range of Pennsylvanians can reap the benefits of geothermal energy in the Commonwealth.

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Abbreviations List

AAPG: American Association of Petroleum Geologists

AEIA: Alternative Energy Investment Act

AEPS: Alternative Energy Portfolio Standard

AGS: Advanced Geothermal Systems

ATES: Aquifer Thermal Energy Storage

BHT: Bottom Hole Temperature

BLS: Bureau of Labor Statistics

BTES: Borehole Thermal Energy Storage

BTU: British Thermal Unit

CHP: Combined Heat and Power

CHS: Conventional Hydrothermal Systems

CLGS: Closed Loop Geothermal Systems

CWTs: Centralized Waste Treatment Facilities

DCNR: Department of Conservation and Natural Resources

DEP: Department of Environmental Protection

DLE: Direct Lithium Extraction

DOE: United States Department of Energy

EGS: Enhanced or Engineered Geothermal Systems

EIA: Energy Information Administration

EPA: Environmental Protection Agency

EPO: Energy Program Office at DEP

FORGE: Frontier Observatory for Research in Geothermal Energy

g CO_2e/kWh: Grams of Carbon Dioxide Equivalent per Kilowatt-Hour

GES: Geothermal Energy Storage Systems

GPFA-AB: Geothermal Play Fairway Analysis- Appalachian Basin

GSHPs: Ground Source (Geothermal) Heat Pumps

IEA: International Energy Agency

IFO: Pennsylvania Independent Fiscal Office

IRA: Inflation Reduction Act

IRENA: International Renewable Energy Agency

mD: Millidarcies

MECS: Manufacturing Energy Consumption Survey

MSAs: Metropolitan Statistical Areas

MTES: Mine Thermal Energy Storage

MW: Megawatt

NETL: National Energy Technology Laboratory

NGOs: Non-Governmental Organizations

NREL: National Renewable Energy Laboratory

ORC: Organic Rankine Cycle

PACER: Pennsylvania Carbon Emissions Reduction Act

PEDA: Pennsylvania Energy Development Authority

PennDOT: Pennsylvania Department of Transportation

PJM: Regionally administered grid operator

POWER: Pennsylvania Opportunities with Energy Reliability

PRESS: Pennsylvania Reliable Energy Sustainability Standard

PUC: Public Utility Commission

RGGI: Regional Greenhouse Gas Initiative

RISE PA: Reducing Industrial Sector Emissions in Pennsylvania

SMU: Southern Methodist University

sCO_2: Supercritical Carbon Dioxide

SHR: Super Hot Rock

TBtu: Trillion British Thermal Units

TDS: Total Dissolved Solids

TENORM: Technologically Enhanced Naturally Occurring Radioactive Materials

TENs: Thermal Energy Networks

UTES: Underground Thermal Energy Storage

WWTPs: Wastewater Treatment Plants