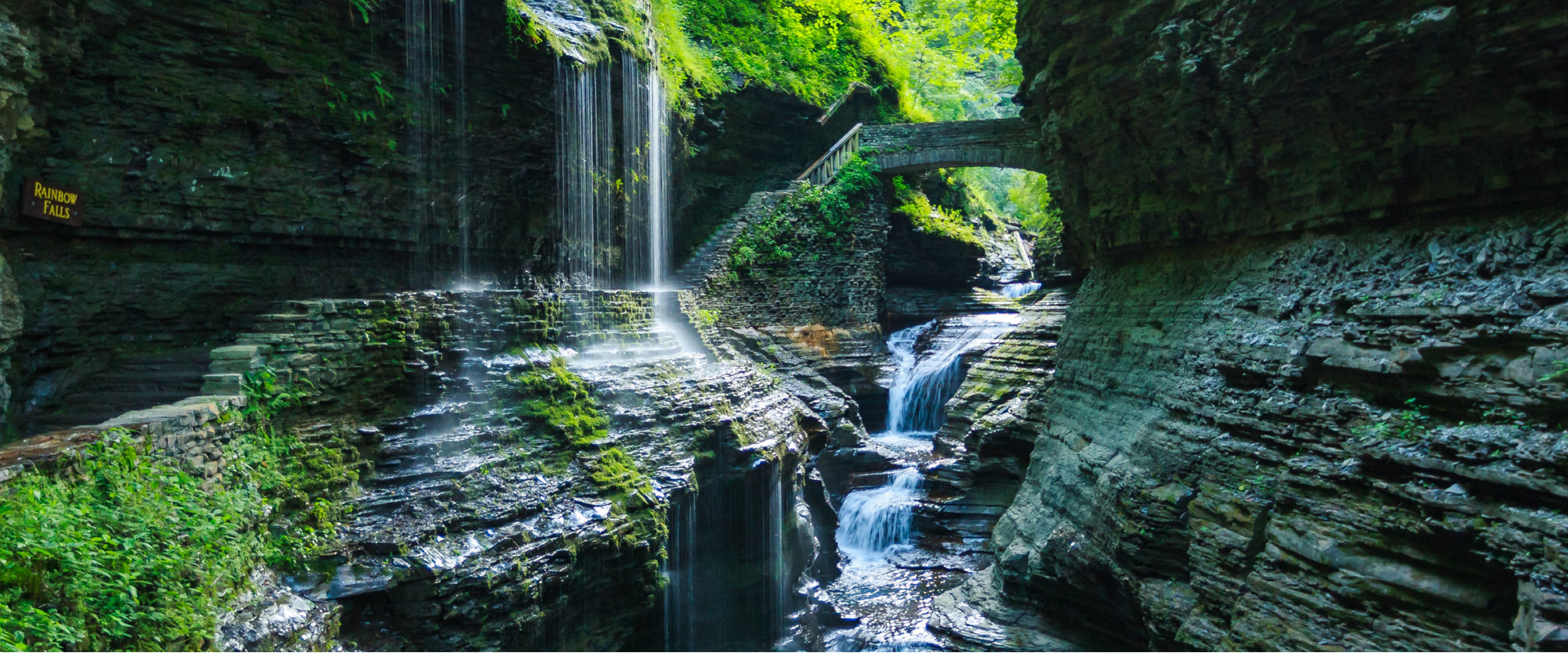


Chapter 6

# 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

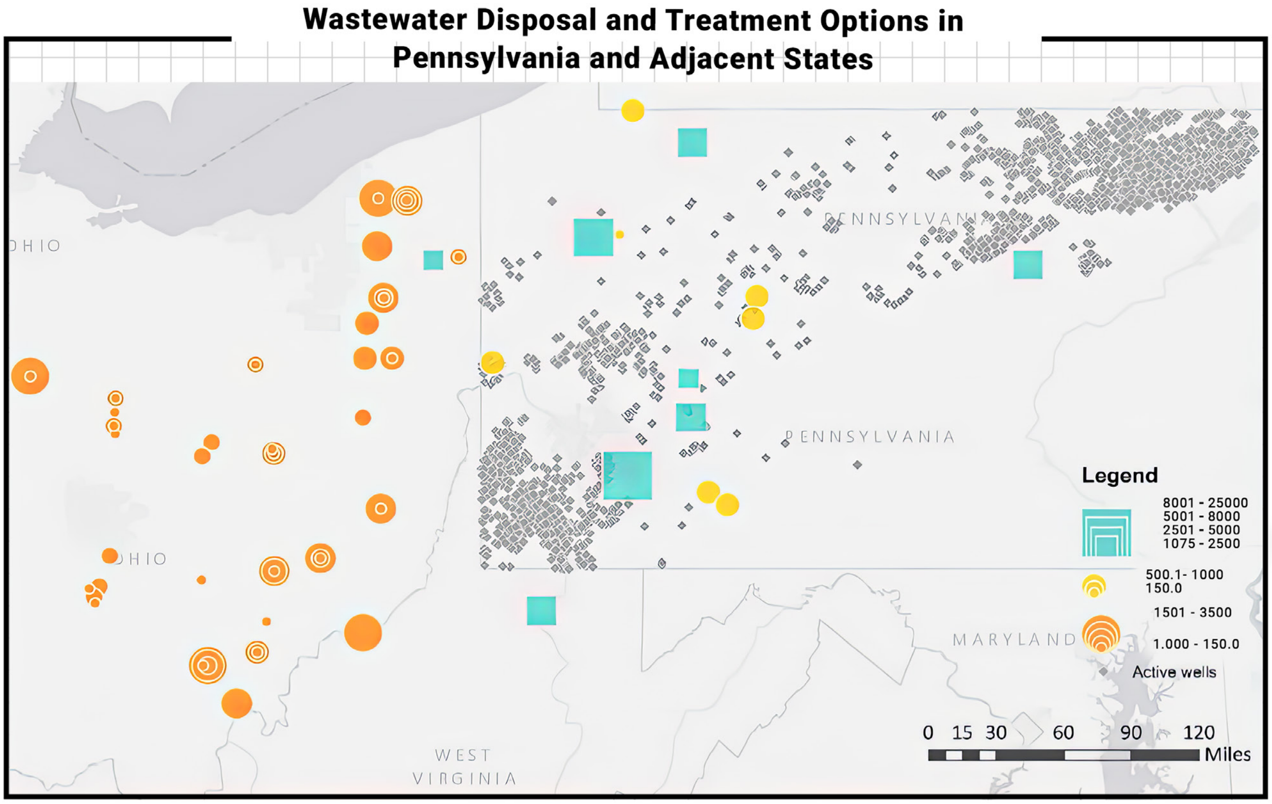


**Figure 6.1:** The size of the markers is proportionate to the wastewater disposal capacity at a site, in barrels per day (bbl/day). Blue squares correspond to CWT facilities. Yellow circles are dedicated wastewater disposal wells in Pennsylvania. Orange circles are dedicated wastewater disposal wells 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—

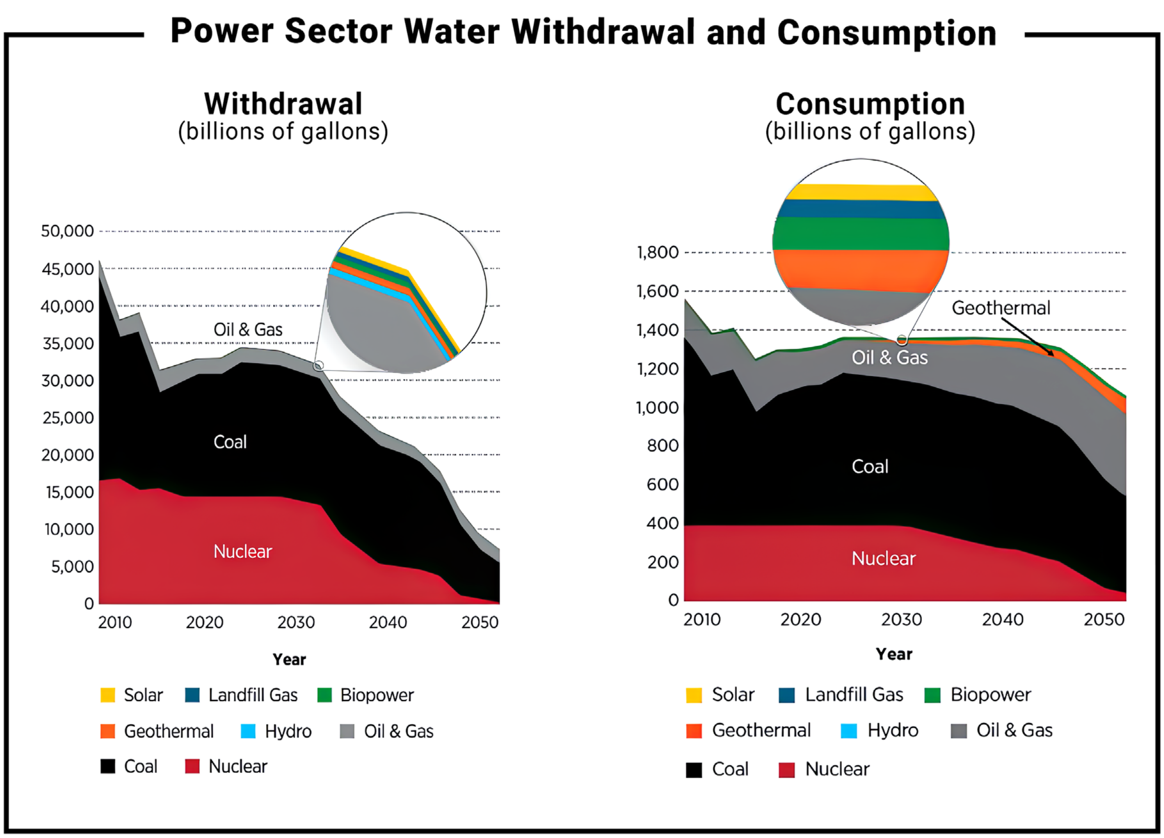


**Figure 6.2:** Water withdrawal and consumption impacts in billions of gallons (1 gallon=3.8 liters) over time and by energy type. Source: *The Future of Geothermal Energy in Texas: The Coming Century of Growth & Prosperity in the Lone Star State*, 2023. University of Texas at Austin Energy Institute.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

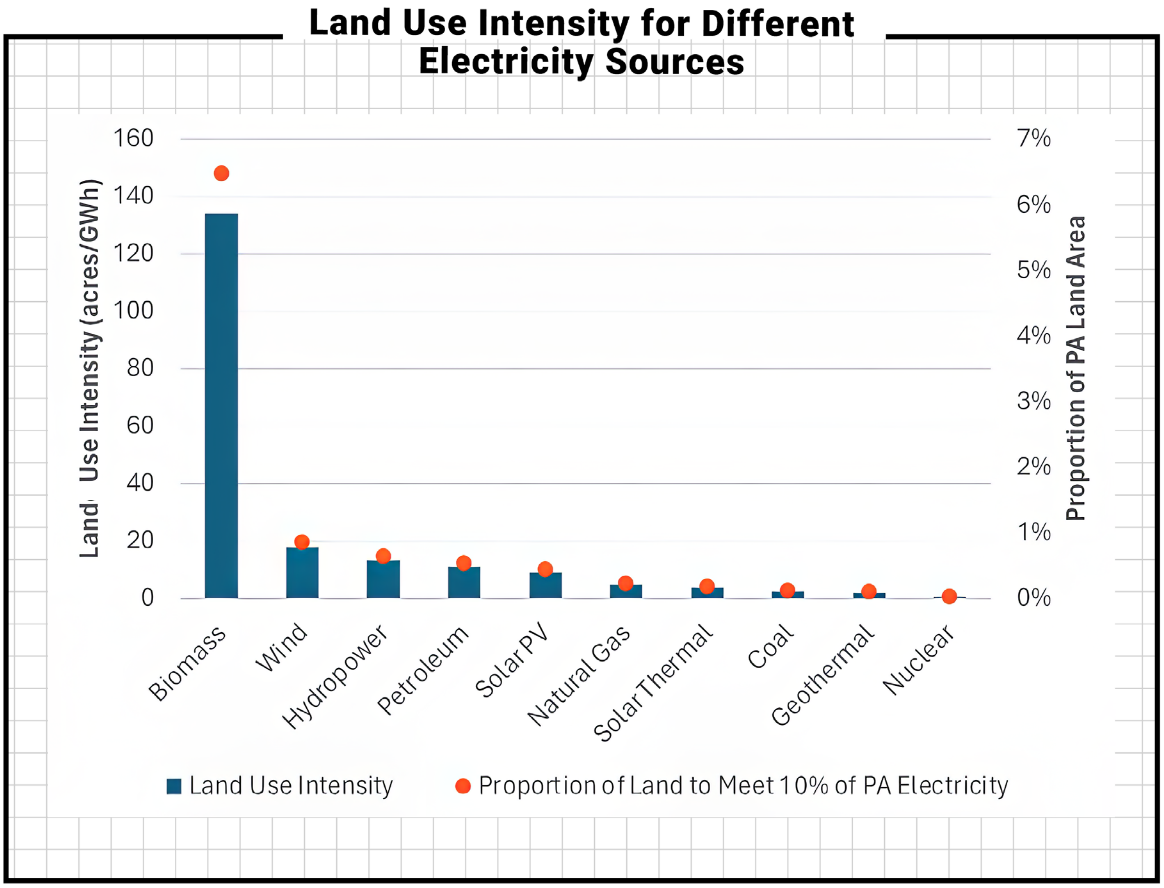


**Figure 6.3:** The blue bars (left-hand axis) show the land-use intensity of each power generation source. Figures are representative of the entire United States and were not developed specifically for Pennsylvania. The orange dots (right-hand axis) show the proportion of total Pennsylvania land area 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 $CO_2$e/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 $CO_2$e/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.

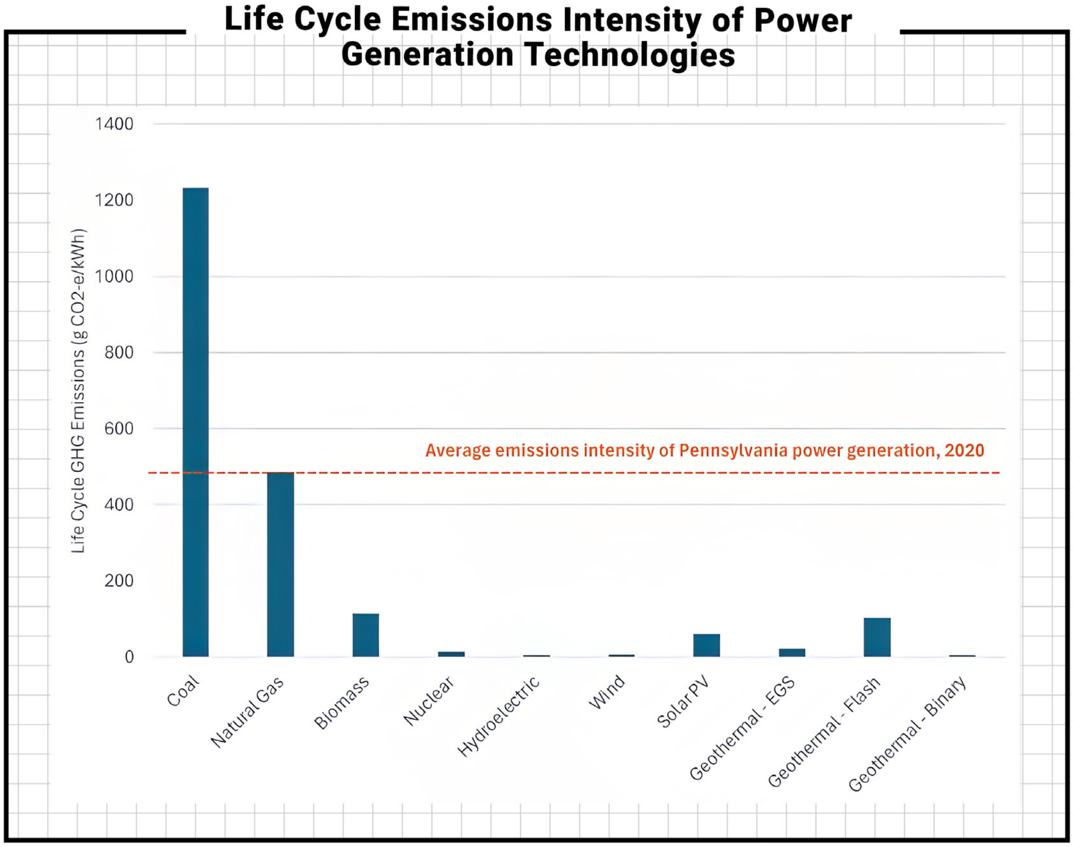


**Figure 6.4:** Sources: Sullivan, et al. (2010). Life-Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems(No. ANL/ESD/10-5), 201. And Pennsylvania Department of Environmental Protection. (2023). Pennsylvania Greenhouse Gas Inventory Report; 2023. https://files.dep.state.pa.us/Energy/Office%20of%20Energy%20and%20Technology/OETDPortalFiles/ClimateChange/FINAL_2023_GHG_Inventory_Report_12.13.23.pdf.

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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