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# Investigating the Geothermal Potential of Baltimore

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# Executive Summary

Heating and cooling of commercial and residential buildings account for about a quarter of all energy consumption in the U.S., most coming from fossil fuels including natural gas, fuel oil, kerosene, and propane. With the need to dramatically reduce harmful emissions to limit an increase in global temperatures, the development of sustainable, affordable sources of energy is more urgent than ever. Baltimore, like many cities across the globe, is dependent on fossil fuels, which are finite and highly polluting. We must consider alternative sources and strategies, if we want to preserve and protect our planet and power our future.

The Earth's core is 6,000 degrees Celsius, the same temperature as the sun, and that heat is available 24 hours a day. In order to access the geothermal heat, circulating water, permeable hot rock, and an economical and feasible method to transfer the heat from underground are required. The geothermal heat that is brought to the surface can be used for heating or generating electricity. While small, local residential geothermal systems are being installed in Baltimore and across the eastern half of the country, our half of the U.S. has yet to see geothermal energy installations of the scope and scale with the capacity to heat and power an entire district. There are innovative geothermal projects in development in Massachusetts and New York, places that would generally be considered unlikely locations for geothermal extraction. The 2021 U.S. bipartisan infrastructure bill gives a boost to innovation by dedicating $84 million to improving enhanced geothermal systems.

This report describes the science and engineering behind geothermal energy production and explains how the geology of the eastern United States and, more specifically, the geology of central Maryland affect the potential for geothermal energy production in our region. The report finds:

- More than 60 geothermal plants operate in the U.S. today, using steam heat to power turbines and providing nearly 4 GW of electricity or the equivalent of powering more than 1 million homes. But the plants tend to be concentrated in areas where sufficiently hot rocks are in the shallow subsurface.

- Continual improvements and innovations in geothermal technology — drilling, deep well pumps and engineered fracturing of rocks — will make it possible to extract heat from deeper regions of the crust almost everywhere.

- The lack of major hot springs in Maryland reflects a low potential for easily accessing geothermal energy for power generation or district heating in the state. In the specific instance of Baltimore, calculations indicate that rock at a depth of greater than about 4.5 km are at a sufficient temperature for electricity production using a binary geothermal electricity power plant. In order to determine the accurate depth of the sufficiently hot rocks, however, a test well is required.
- Commercial levels of geothermal energy production, for power production or district heating, require more complex systems than what is needed for small, residential systems. Large-scale geothermal energy extraction requires land in an appropriate location, environmental permits, large quantities of water, drilling, pumping, surface power plant and distribution piping system, and/or connection to electric grid systems.
- Assuming favorable geologic conditions at a depth of 5 km, rough estimates for the costs of two average geothermal plants in the Baltimore area are calculated for: 1) direct use of heat; and 2) electricity generation. The capital costs are estimated to be $22.97 million for the direct heat, and $52.41 million for power generation. At current costs of electricity, the amount generated per year might generate $4 million in revenues; however, with natural gas costs expected to escalate rapidly, the payback might be quicker.
- Model results indicate that the conceptual geothermal system would be economical for at least six to seven years of power generation, after which time the temperature of the extracted water drops below 150 degrees Celsius. Subsequently, it might be possible to repurpose the system for direct use.
- Advancements in the field of geothermal energy may enable deeper drilling with less costs, enabling better accounting for capital costs, water treatment, pipeline corrosion, leakage control, and payback.
- Drilling a relatively deep pilot test well would be the best first step. The economic model shows that a test well in a geologic setting similar to that of Baltimore to a depth of approximately 3 km will cost a minimum of $5.3 million. This pilot well will allow a much better understanding of the thermal potential of the deeper rock formations and an assessment of the environmental aspects of the geothermal plant installation.

# The Objective

The objective of this report is to provide a preliminary assessment of the geothermal energy resources in Baltimore and throughout Maryland that may be used for district heating and power generation. The overall goal is to provide an in-depth understanding regarding the availability and use of geothermal energy, which is an excellent source of baseload power, unlike other renewable sources.

Geothermal energy production involves the transfer of Earth's innate heat into circulating waters, which are then brought to the surface and used for heating or generating electricity. The most critical component is an abundance of rock and water above a temperature of about 150 C (~300 F).

A map (see Figure 1), provided by the Geothermal Laboratory Office of the National Renewable Energy Laboratory (NREL), shows the general availability of geothermal resources in the United States. In particular, this map shows the hydrothermal sites (see yellow dots) within the country as well as (in the nature of the colors) the favorability or potential for deeper enhanced geothermal systems (EGS, described on p. 9). In general, the potential for geothermal energy in the western half of the United States is remarkably higher than in the eastern half, indicating that adequately hot rocks for extracting geothermal energy are significantly closer to the surface in the western part of the country. It further suggests that extracting geothermal energy may be a challenge in the eastern portion of the United States. That said, there are small-scale, local residential geothermal systems that have been widely installed in the eastern half of the country. This amounts to absorbing heat from the ground via an appropriate fluid circulating in a closed loop of pipe, and then capturing this heat via a heat exchanger, similar to a heat pump. Although similar in principle, this is much different in scale than the physical process considered in this report. Nevertheless, there are several regions in the eastern half of the country that present anomalously warm geothermal areas potentially useful for generating electrical energy; these regions are in West Virginia, New Hampshire, and Pennsylvania, but there may be other, smaller areas that are undiscovered.

Whereas the geothermal potential is different from one place to another, heat is essentially available everywhere at deeper locations in Earth's crust. Accessing this depth and having an abundance of hot water, however, might not be economically viable. At first glance, Maryland and Baltimore, in particular, are not among the areas with high potential for readily available geothermal energy. Many European countries with small potential for shallow geothermal energy comparable to that of Maryland are exploring unconventional methods for extracting this clean renewable energy (such as very deep drillings and improving high-efficiency heat exchangers). Thus, in order to appreciate the potential of this energy in Maryland and Baltimore, a closer review of this information is necessary to assess the viability of local geothermal energy.

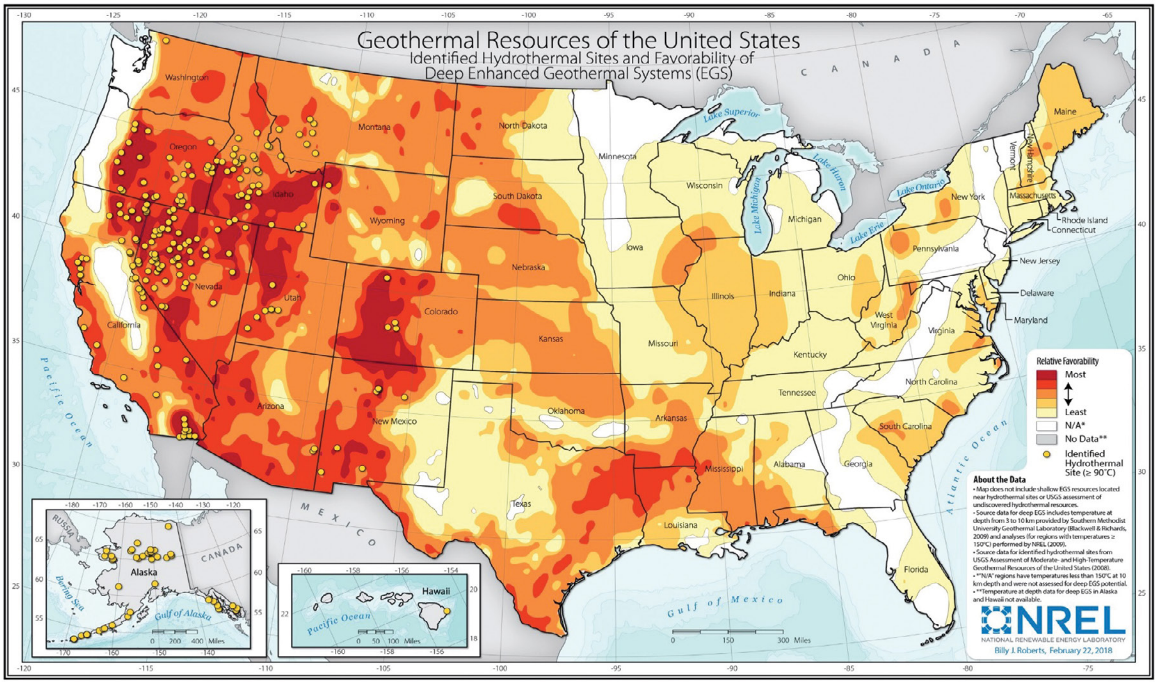


**Figure 1.** *Map of geothermal resources in the United States generated by NREL.*

In this report, a first-order analysis of the potential of employing geothermal energy for producing heat and electricity is presented. The source material for this analysis includes information published in peer-reviewed scientific literature, books, U.S. Department of Energy reports, conference papers, and reports by the USGS (U.S. Geological Survey) and NREL, among others. First, a brief background on geothermal energy, the variety of geothermal energy usage, and the types of reservoirs is presented. Second, the geologic setting of Maryland and Baltimore is briefly described. This is followed by a demonstration of how to use these available data, in concert with an analytic model, to calculate a thermal profile beneath Baltimore. A section is also included describing a possible design and performance of a geothermal system for Baltimore. Last, an economic model is described illustrating the cost of installation of a geothermal system for district heating and electrical energy production.

# Geothermal Energy

Geothermal energy comes from the natural heat of the Earth, available as an indigenous source of energy. This energy is generated mainly from primordial heat and the decay of radioactive elements in Earth's interior. Primordial heat is the massive amount of heat created ~4.5 billion years during Earth's formation. Emissions from the decay of long-lived radioactive elements (Th, U, and K) lead to the release of enormous heat, and thus, the deeper regions of Earth are very hot. Going downward, for example, the relatively short distance of, say, 40 kilometers—less than the distance between Baltimore and Washington, D.C.—the temperature increases to almost 1,000 C (~1,850 F); the rocks there are red hot. (In fact, the center of Earth is the same temperature as the surface of the sun, about 7,000 C). This also leads to heating of the rocks in the uppermost parts of Earth's crust, which heats any available water existing in the porous zones. Some of this hot geothermal water moves upward through faults, joints, and cracks, and leaks out at the surface, producing hot springs or geysers. In most cases, however, the heated water is not very abundant and remains trapped in cracks and porous rocks deep underground to form a geothermal reservoir.

As mentioned already, going downward, the temperature typically increases by 20 C to 50 C per kilometer (but may be lower and can be significantly higher). Heat flows upward and obeys Fourier Law:

$$q = k\,(\Delta T/\Delta L) \quad \textbf{(1)}$$

which also can be written as:

$$T = (\Delta L * q / k) + T_0 \quad \textbf{(2)}$$

Where q is the background heat flow and k is the thermal conductivity of the rock, ($\Delta T/\Delta L$) is the thermal gradient that represents the rate of temperature change ($\Delta T$) in the interior of the Earth over a distance downward of $\Delta L$. $T_0$ and T are the temperatures at the surface and at depth. The average background heat flux from Earth is ~87 $mW/m^2$ (milliwatts per square meter), with the oceanic crust being warmer and the continental crust being colder.

Since ancient times, the heat of hot springs has been used for bathing and warming the environment. Attempts to harness geothermal energy to produce electric power date back to the beginning of the 20th century. In 1904, the first experimental electric power generator was operated at Larderello, Italy, using natural geothermal steam that seeped to the surface via rock fractures. In 1913, the first geothermal power plant was completed.

In a number of other countries, including the United States, attempts to develop geothermal energy for power production were made in the early 1920s. Geothermal energy development has since increased dramatically, and as of 2019, the United States has become the world leader with about 25% of the total global online capacity, equivalent to 3.7 GW (gigawatts) of geothermal energy.

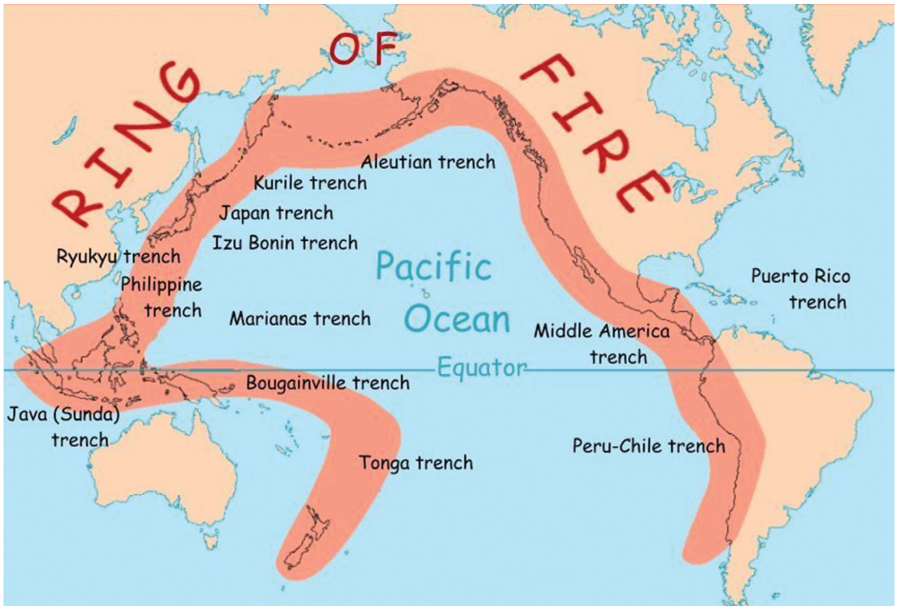


**Figure 2.** *A map that demonstrates the Ring of Fire, a vast region along plate boundaries with high thermal states. From National Geographic Society.*

## Geothermal Resources and Important Factors

Whereas geothermal heat is a universal energy, a geophysical factor known as the geothermal gradient plays an important role in determining whether a region is suitable for extraction of such energy. As emphasized already, the geothermal gradient measures the rate at which the temperature increases with increasing depth, and it is different for various regions of the Earth. For example, the average geothermal gradient in France is 33 C/km, while in Iceland the gradient can reach as high as 80-100 C/km.

Geothermal energy resources are concentrated to a large extent along geologic plate boundaries and are typically associated with recent volcanism. These regions demonstrate higher thermal gradients and cover approximately 10% of Earth's surface. The most outstanding geothermal zone is the Pacific Ring of Fire, shown in Figure 2, which is a region of strong volcanism bordering the Pacific Ocean. Moreover, there are large amounts of geothermal energy stored in the crust far from these volcanic regions. A vast amount of energy exists, for example, in hot sedimentary aquifers, which are often distant from volcanic regions and tectonic plate boundaries.

As mentioned at the outset, an abundance of hot water is a critical feature necessary for successful geothermal energy production. This potential abundance of water is controlled by the porosity and permeability of rock (see Figure 3). Porosity is the void space within rocks that can hold fluids, such as air and water, and permeability measures the ability of a porous material to allow fluids to pass through it. Rocks have a wide range of permeability values, which are most often in the range of $10^{-7}$ – $10^{-19}$ $m^2$ (smaller values are for low-permeable rocks). These physical characteristics of rocks are typically determined via laboratory work on extracted cores, but they are also sometimes measured by performing pumping tests in wells. Subsurface rocks usually do not have a uniform permeability and porosity structure, and these parameters within one geologic layer might change. For economically viable geothermal energy production, high porosity and permeability are desirable. Any rock with porosity above 10% and permeability of $10^{-14}$ $m^2$ or more would be ideal for geothermal energy extraction. In many cases, since rocks commonly have very small permeability values, an artificial stimulation method, akin to fracturing, is used to enhance the rock permeability to more desirable values.

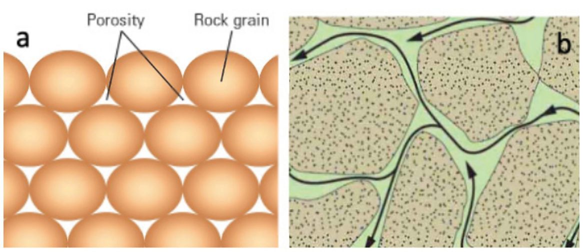


**Figure 3.** *Schematics that show porosity and permeability of rocks. Image from Department of Mine and Petroleum.*

Geothermal energy, as mentioned earlier, is technically available almost everywhere on Earth in various forms. The challenge is designing a means of economically harvesting this energy. Although very deep—and very expensive—geothermal wells such as Orka in Iceland (~4500 m) also exist, as of now the majority of these extra-deep geothermal fields/wells are used only for research purposes. Most geothermal wells for successful economic energy extraction are relatively shallow (less than 2 km). The main reason for targeting such depths is drilling limitations and large expenses for such drilling (See Conclusions for more discussions).

Along these lines, based on the thermodynamic and hydrologic properties of a region, geothermal resources are divided into several types:

**VAPOR-DOMINATED AND LIQUID-DOMINATED SYSTEMS:** If the pore space in the near-surface region of the reservoir is mainly filled with steam, the geothermal system is vapor-dominated. In liquid-dominated systems, the void space of the hot subsurface rock is mainly filled with a circulating fluid (water or brine) that transports the heat of the rock from deep regions to shallow regions via natural circulation. Vapor-dominated systems, or dry steam fields, are relatively rare. The Geysers geothermal field in Northern California is a vapor-dominated system. Liquid-dominated resource types are far more abundant than vapor-dominated ones.

**HOT DRY ROCK SYSTEMS:** Independent of any hydrothermal fluid convection, the subsurface temperatures increase with depth. Thus, it is realistic to assume that more heat is stored in the rock matrix than in the convecting or advecting of water. Since porosity generally decreases with depth, at great depth, there might be insufficient water in the rock to transfer heat for power production. Systems in which rock at depth are at a high enough temperature for geothermal power production (e.g., Malin et al.) but lack sufficient permeability to allow adequate fluid flow to transfer heat are *hot dry rock* (the rocks are "dry" in the sense of power production but generally have water in their pore space).

In the past few decades, new methods have been developed for artificially inducing or manufacturing fractures in hot dry rocks. This engineering process is done by a variety of methods, among which hydraulic stimulation or fracking is the most common approach. These new fractures generate a porosity and permeability adequate for fluid circulation. Subsequently, cold waters are pumped into these hot geothermal reservoirs using an injection well and forced under pressure to flow where, at some distance the heated water is extracted using one or more production wells. The heated water is then inputted to a conversion unit (or a generator) to produce electricity. The resulting cooled water, having given up its thermal energy, is then again reinjected into the subsurface fractured rock system. This method of extracting geothermal energy (see Figure 4) from hot dry rock is known as an enhanced geothermal system (EGS).

**GEOPRESSURED SYSTEMS:** Geopressured resources are those geothermal reservoirs significantly above hydrostatic pressure — with a pressure comparable to lithostatic pressure (i.e., direct weight of the overlaying layers of rock). These resources are located in highly pressurized formations such as shale or sandstone, where compaction occurs. These highly pressurized layers typically contain very high-temperature fluids (water or brine), up to 204 C (400 F). The thermal energy of these resources can be used directly in a steam-driven generator to produce electricity. In the U.S., favorable geopressured reservoirs are mostly found along the Gulf Coast.

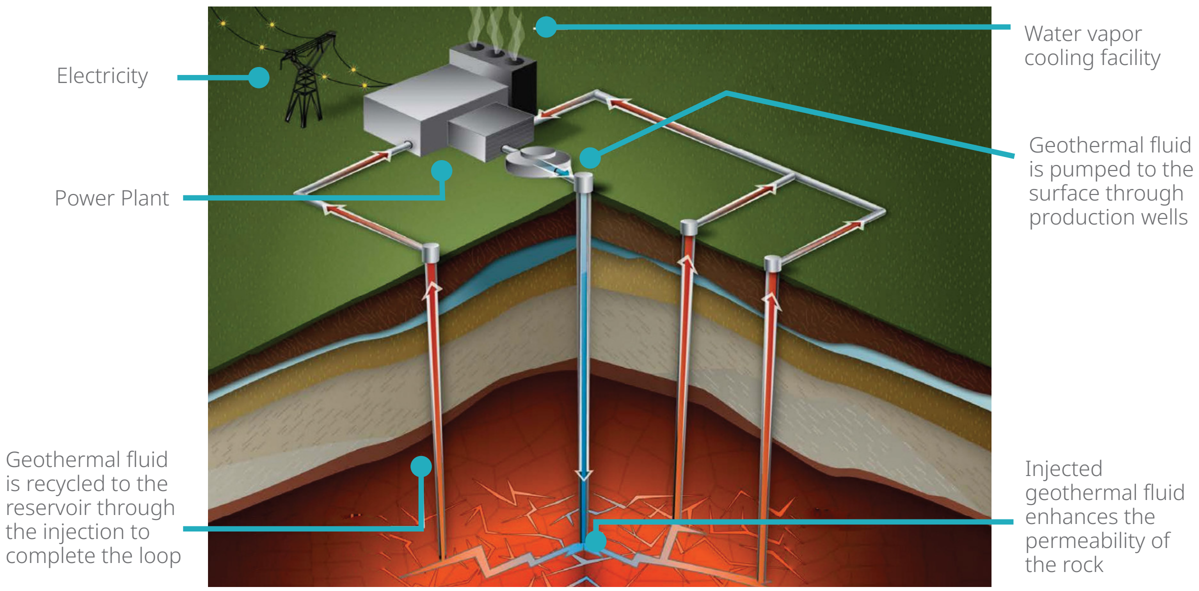


Figure 4. *A schematic of an EGS geothermal system that entails an injection well and three extraction wells. This type of geothermal plant can be installed in hot dry rock, sedimentary aquifers, or geopressured resources. Figure from the Department of Energy.*

**HOT SEDIMENTARY AQUIFERS:**
Hot sedimentary aquifers are available in many locations and can provide a rechargeable source of heat for geothermal energy production. The geothermal energy stored in sedimentary aquifers has been used for district heating in the Netherlands and Germany for decades. Unlike conventional EGS systems installed in hot dry rock, where production temperatures drop below economic levels (~150 C) relatively quickly, geothermal systems installed in hot sedimentary aquifers may have a greater longevity due to a constant flow of hot water that recharges the geothermal system. Extracting electricity via the geothermal energy stored in hot sedimentary aquifers are in its initial stages, and the U.S.—with numerous hot sedimentary aquifers—has a great potential for extracting such energy.

# Types of Geothermal Energy Based on the Temperature

The temperature of geothermal reservoirs determines whether it can be used for space heating or for electricity production. Table 1 demonstrates how the temperature of the geothermal system determines the geothermal use. In the present investigation, we will use the data in Table 1 to determine the depth to which drilling is needed for extracting geothermal energy in the Baltimore area.

**DIRECT USE (SPACE HEATING):**
So far, the most common application of geothermal energy has been as a supply of thermal energy. Since the majority of easily accessible geothermal reservoirs have low temperature, they are not economically

**Table 1: Summary of the usage of extracted geothermal energy based on the reservoir temperature.**

| Reservoir Temperature | Reservoir (Fluid or Steam) | Application |
|---|---|---|
| **High Temperature, >220 C** | Water and/or Steam | Power Generation & Direct Use |
| **Intermediate Temperature, 100-220 C** | Water | Power Generation & Direct Use |
| **Low Temperature, 80-150 C** | Water | Direct Use |

suitable for power generation. The most well-known and probably the most economical district heating system is installed in Reykjavik, Iceland, whereas the oldest and largest geothermal district heating system in the U.S. is near Boise, Idaho. In these systems, the geothermal water is pumped directly from the well to a pipeline, and then it is directly circulated for consumer uses. Although these systems are quite efficient for district heating, the thermal energy cannot be transported economically more than a few tens of kilometers without significant temperature decrease.

**POWER GENERATION:** The principle of electrical energy production using the thermal energy of hot subsurface fluids is similar to steam driven turbines. In such systems, high temperature fluid or steam drives a turbine, directly spinning the blades and ultimately generating electricity. Afterward, when the fluid has cooled, it is reinjected in the subsurface to be heated again for reuse. Based on working principles and the temperature of extracted fluids, geothermal plants can be divided into three groups as illustrated by Figure 5.

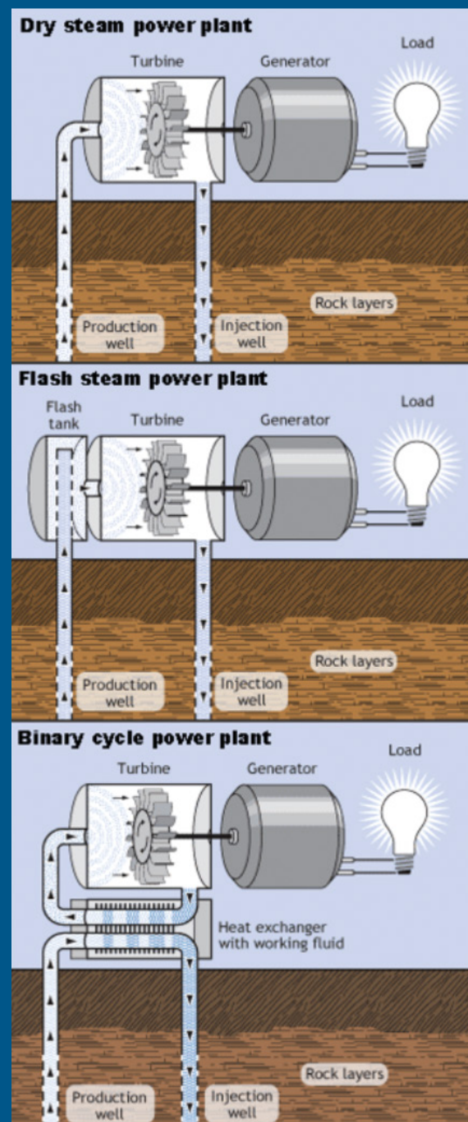


**Figure 5.** *The three basic types of geothermal power plants. Figures from U.S. Department of Energy.*

- **Dry Steam:** This is the first and oldest type of geothermal plant, in which dry steam from an underground reservoir is used directly to drive a turbine generator. The reservoirs containing such high temperature fluid are relatively rare.
- **Flash Steam:** For a flash steam plant, hot water at high pressure is pumped into lower pressure tanks, allowing the water to spontaneously flash or vaporize into steam, which then drives turbines. Flash steam plants typically require a fluid with a temperature of more than 182 C. Currently, this is the most common type of plant operating in the world.
- **Binary Cycle:** Binary cycle plants are the most modern form of geothermal plants, using water of relatively lower

temperatures, typically less than 175 C (see Table 1). The high temperature geothermal fluid is used to vaporize a working fluid, typically an organic fluid with a low boiling temperature. The steam resulting from evaporation of working fluid is then used to turn a turbine. Similarly, the cooled water from the heat exchanger is reinjected into the geothermal reservoir to be reused.

# Geology of Maryland and Baltimore

After analyzing the thermal state of the crust of the areas of Maryland and Baltimore, we provide estimates of the possible temperatures of the available thermal energy along with the design of a geothermal plant. But first, it is essential to appreciate the basic geology of this region.

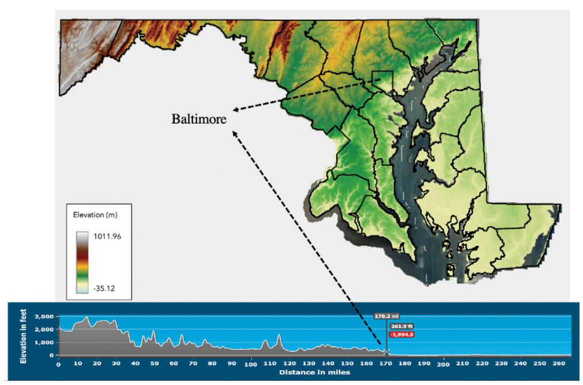


*Figure 6. Topographic regions of Maryland with the location of Baltimore marked. The elevation is high in the western part of the state, and drops markedly traveling eastward. This information is from the Maryland Geological Survey*

**GEOLOGY OF MARYLAND:** Traveling from west to east across the state of Maryland, there are dramatic changes in the geological structure and the topography. Western Maryland is characterized by the high elevations of the Appalachian Mountains; the middle of the state is characterized by the urbanized landscapes and lower elevations of Baltimore; and finally, the Eastern Shore is characterized by the smooth low elevations with expanses of marshland. Figure 6 & 7 illustrates these topographic divisions of Maryland along with an east-west topographic profile passing through Baltimore.

Maryland is adjacent to the Atlantic continental shelf, and the land is formed of five distinct physiographic provinces: (1) the Coastal Plain Province; (2) the Piedmont Plateau Province; (3) the Blue Ridge Province; (4) the Ridge and Valley Province; and (5) the Appalachian Plateaus Province. These regions are shown in Figure 7.

- **The Coastal Plain Province:** This is the youngest province, covering 50% of the state and consisting of a nearly horizontal, southeastwardly sloping wedge of sediments over 8,000 feet thick. The sediments are primarily unconsolidated (such as clays, gravels, etc.); their formation age is 100 million years (Ma) near Baltimore, and younger closer to the Atlantic Ocean. These sediments dip very gently eastward at less than 1 degree inclination (Figure 6 & 7).
- **The Piedmont Plateau Province:** This region covers about 25% of the state and contains some of the state's oldest rocks, dating between 500 million and 1.1 billion years old. The rocks of this province are

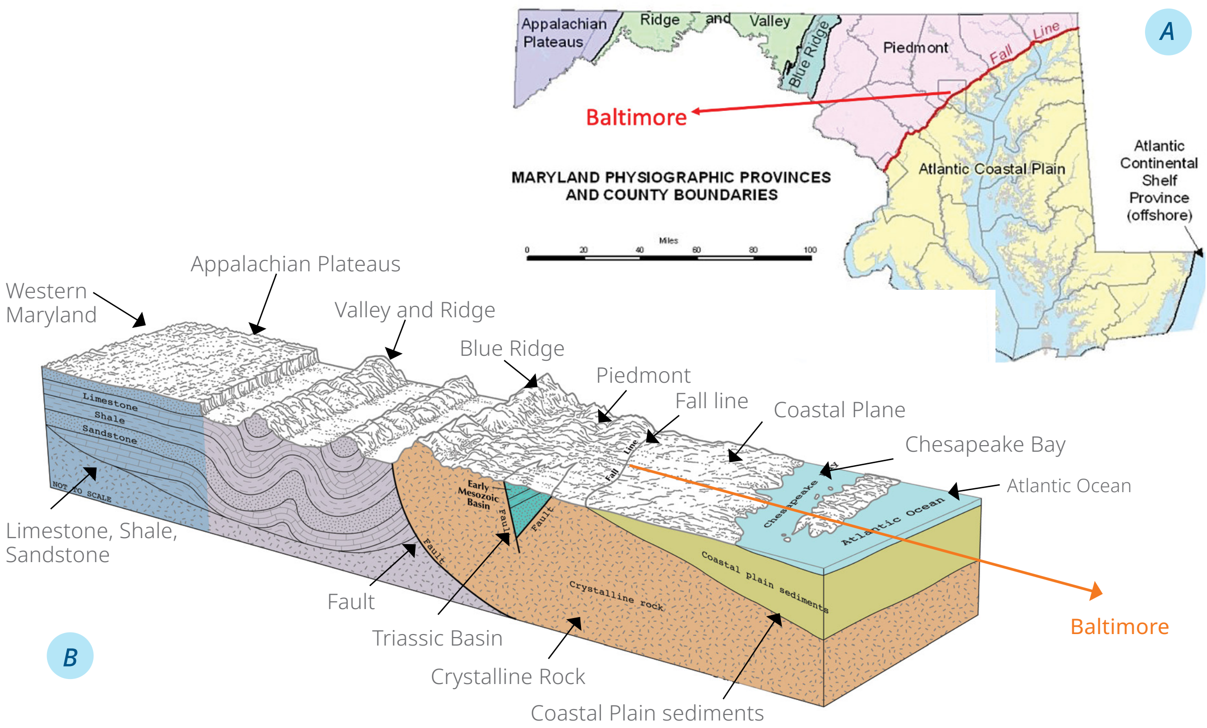


**Figure 7.** *A geographical map showing the extent of geologic provinces of Maryland (a). The subsurface cross-section demonstartes the layers beneath these geologic provinces of Maryland (b). The location of Baltimore is marked on each figure. Figures from Maryland Geologic Survey.*

primarily igneous, metamorphic, and some sedimentary, and have been extremely deformed during extensive continental collision tectonics. Here, there are several magmatic intrusions of granite and pegmatites. Previous geologic studies used deep drilling and determined that the sedimentary rocks of both the Piedmont and Coastal Plain are underlain by metamorphic and igneous rocks.

- **The Blue Ridge Province:** The smallest province, which covers only 5% of the state, is defined by Catoctin Mountain and South Mountain to the east and west, respectively. In this province, due to a long process of erosion, 1.1-billion-year-old rock is exposed in the center while younger rocks of volcanic and sedimentary origin are overlying.

- **The Ridge and Valley Province:** This province covers 10% of the state and contains intensely folded and faulted sedimentary rocks. Various sedimentary rocks of this region (e.g., conglomerates, sandstones, siltstones, shales, and limestones) range in age from 544 million to 300 million years old, belonging to the Cambrian, Ordovician, Silurian, Devonian and Pennsylvanian period. These rocks were initially formed flat, but due to tectonic processes, they have subsequently been tightly folded into anticlines and synclines (hills and dales in geological terms).

- **The Appalachian Plateaus Province:** This province is the westernmost portion of Maryland and covers 10% of the state. The bedrock of this region is mainly sedimentary rock (e.g., shale, siltstone, and sandstone) of Devonian age, and comparable to that of the Ridge and Valley Province. The bedrocks are gently folded and have generated elongated anticlines. A large amount of the Maryland natural gas fields is found in this province.

**GEOLOGY OF BALTIMORE:** The city of Baltimore is located at the transition between the Coastal Plain and Piedmont Plateau provinces, known as the Fall Line because it is marked by falls in rivers. As a result, the geology of the city has some of the characteristics of each of these two provinces (see Figure 7a, b). An examination of the geologic maps of the Baltimore area shows that the uppermost part of the crust (<500 ft) is a combination of unconsolidated rocks (such as gravel, sand, etc.), whereas further below are undifferentiated crystalline rocks and metamorphic rocks. Figure 7b shows a geologic cross-section or model of the crust beneath the surface of Maryland, where the location of Baltimore is also designated. As mentioned earlier, going eastward and toward the coastal plain, the subsurface layers dip or slant very gently eastward, and, unlike central Maryland, are not folded.

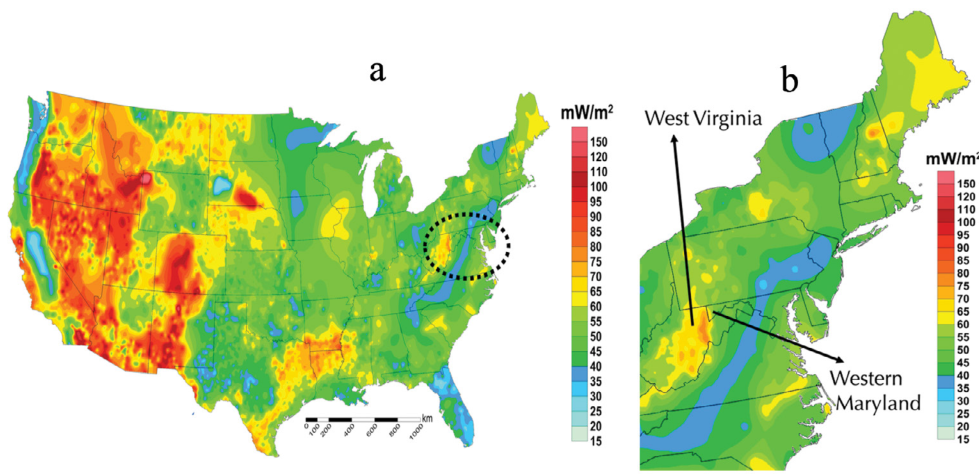


Figure 8. *(a) Heat flow map of the United States on which Maryland and the surrounding states are marked by an oval. (b) A magnified view of a heat flow map of the Eastern Shore that shows a prominent thermal anomaly at the border of Maryland and West Virginia. The map is reproduced from the Geothermal Lab at Southern Methodist University (SMU).*

# Thermal State of Maryland and Baltimore

Previous geophysical/geological studies have shown that there are no major hot springs in Maryland. This reflects a low potential for easily accessing geothermal energy for direct use in the state. This is primarily due to the low temperature of the rock in the shallow crust. There is a small region in the westernmost part of Maryland, as shown in Figure 8 (a, b), that may have some potential for geothermal energy, and which may be geologically related to a geothermal anomaly in West Virginia.

As evident from equation (2) presented earlier (page 6), in order to obtain a good estimate of subsurface temperatures, two main physical parameters are required: the background heat flow and the thermal conductivity of the rocks. Numerous previous works have investigated the geophysical characteristics of the eastern United States via drilling and have constrained the background heat flow. Maryland has a varying background heat flow, with the highest being on the western borders and the coolest in the center and east. The average background heat flow in the Coastal Plain and the Piedmont Plateau is 48 ± 0.8 mW/m$^2$, which is much less than the global average (~67 mW/m$^2$) for continental regions.

The Baltimore city area has only one drilling site, and the measured background heat flow in that well is ~49.8 mW/m$^2$, which is similar to the average value of the Coastal Plain and the Piedmont Plateau. This well, at 282 m deep, is a typical depth for a heat-flow determination but relatively shallow in terms of depth for geothermal use temperature. The well shows a basal temperature of 16.4 C.

Based on previous experimental works, the thermal conductivity of rocks mainly falls between 0.5 and 7 W/m K (Watts per meter kelvin). Unconsolidated rocks such as gravel have a lower thermal conductivities, whereas sedimentary, volcanic, and metamorphic rocks have higher values. Given that the subsurface rocks beneath the Coastal Plain and the Piedmont Plateau are sedimentary, metamorphic and volcanic, an average value for the thermal conductivity of subsurface rocks beneath the two provinces is estimated to be in the range of 1.5-4 W/m K. A similar range of thermal conductivities is estimated for the rocks beneath the city of Baltimore and surrounding areas. Based on these initial estimates, the subsurface temperatures at greater depths has been calculated using equation (2), assuming conductive heat flow with no water flow and no heat sources.

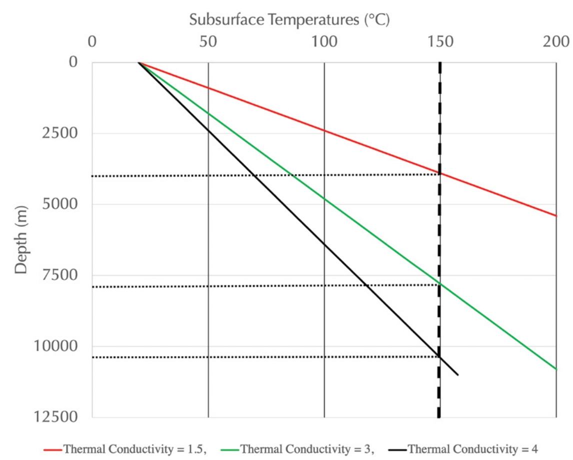


Figure 9. *The plot of estimated subsurface temperatures beneath Baltimore and surrounding areas. The background heat flow is assumed to be 50 mW/m$^2$, while the thermal conductivity values are 1.5, 3, and 4 W/m K. The bold dashed vertical line designates the temperature of 150 C, whereas the horizontal dotted lines show the depths to that temperature for different thermal conductivities.*

Figure 9 gives some estimates of the temperature increase beneath Baltimore for various values of thermal conductivity and a background heat flow of 50 mW/m$^2$. This estimation technique is similar to the regional temperature estimation performed by the Geothermal Laboratory at SMU (see Figure 10) at depth 6.5 km. Figure 9 also shows the threshold of 150 C above which the rock temperature is suitable for power generation. Based on a combination of Figures 8-10, in order to reach a subsurface region sufficiently hot for producing electricity using geothermal energy, a minimum depth for drilling would be >4.5 km. This is the most desirable scenario where the thermal conductivity of subsurface rock is 1.5 W/m K. The geothermal energy using temperature of shallower rocks might be suitable for direct use. It should be noted that an average thermal conductivity of 1.5 W/m K is a very low estimate for the upper 5 km of sedimentary, volcanic and metamorphic rocks beneath Baltimore and adjacent areas. Bottom hole temperature is strongly a function of the background heat flux and thermal conductivity. For instance, if the average thermal conductivity of subsurface rock is larger (e.g., 3 W/m K), the depth for extracting geothermal energy would be > 7 km (see equation 2). This depth is significantly deeper than the drilling depth of current active geothermal plants.

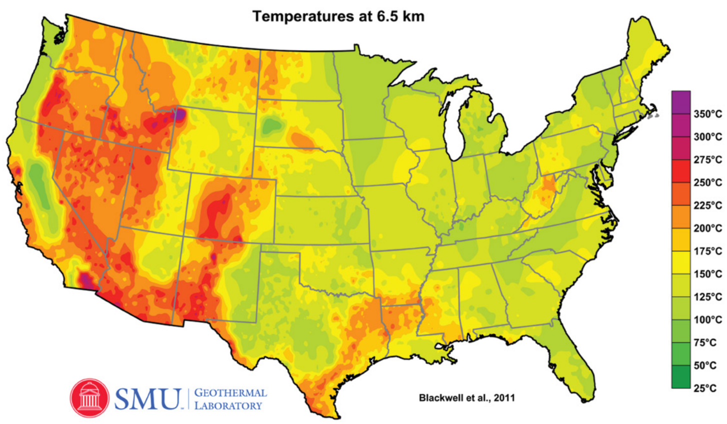


Figure 10. *A map showing rock temperatures at 6.5 km. Figure from Blackwell et al, 2011.*

# Extracting Geothermal Energy

**HEAT PUMPS:** Geothermal heat pumps (also known as ground source, earth-coupled, etc.) take advantage of a relatively constant temperature of the very shallow subsurface and have been used since the 1940s. Although atmospheric temperatures in the U.S. vary strongly from one place to another, the subsurface temperature a few feet below the surface remains much more constant (~10-20 C). Residential geothermal heat pumps take advantage of this constant subsurface temperature and use a geothermal heat exchanger to provide heat in winter and cool air in summer (see Figure 11). That is, a special fluid is pumped through the pipes, absorbing or giving up heat, which is then used in a heat pump-like system; no naturally occurring water is used. There are several types of residential geothermal systems (such as horizontal, vertical, pond/lake, etc.), and the reports of Department of Energy show that, as of 2020, more than 50,000 geothermal heat pumps

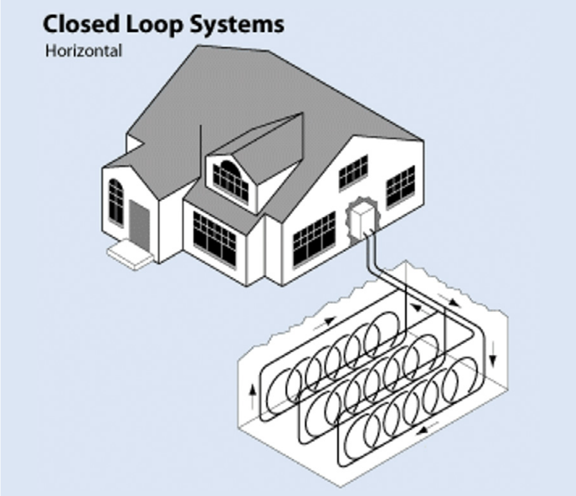


Figure 11. *A schematic showing a residential closed-loop geothermal heat pump system. The ground loop is the interface with the earth through which heat is either gained or lost during the operation of the heat pump. Figure from the U.S. Department of Energy.*

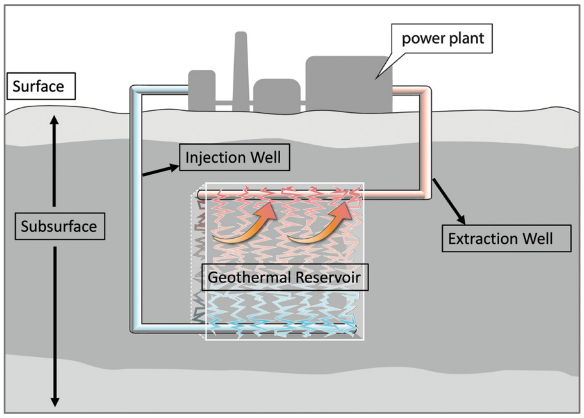


Figure 12. *A schematic showing a conventional enhanced geothermal system with an artificially built reservoir, injection and extraction wells, and power plant (or conversion unit). These components are normally the most expensive elements of any geothermal plant. In this system, the cold water is pumped into the geothermal reservoir (artificially made reservoir) and becomes heated due to exposure to hot rocks. The heated water is then collected using an extraction well and transferred to a conversion unit to produce electricity. The processed cold water will be reinjected to the reservoir to continue the cycle. https://pages.jh.edu/mkarimi1/*

are installed in the U.S. Financial models show that using geothermal heatpumps reduces energy consumption by up to 60%, and the relatively high initial investment can be recouped in five to 10 years. If properly installed, heat pumps are great energy saving devices for various moderate heating/cooling uses and are suitable for use in many regions including Baltimore area.

## LARGE SCALE GEOTHERMAL SYSTEM:

A commercial level of geothermal energy production, for power production or large-scale direct use, requires a more complicated setting. Large-scale geothermal energy extraction needs several requirements such as land in a desirable location, several environmental permits, a large amount of water, piping, drilling, pumping, a surface power plant, and connection to electric grid systems (see Figure 12). Typically, drilling is the first step in building a system for harvesting geothermal energy. If there is insufficient permeability to pump sufficient fluid, then permeability may be increased by hydraulic fracturing. As a result, a series of fractures are produced artificially using hydraulic stimulation technique. The overall objective of the drilling and stimulation is to establish a functioning man-made geothermal reservoir large enough to contain enough energy for harvesting. The stimulated region allows the movement of water in the hot rock and extraction of heat at depth. In such geothermal systems, cold water is injected into the geothermal reservoir through an injection well, and heated water is collected using an extraction well. Collectively, the drilling, stimulation, and pumping of water establish a plumbing network at a depth from which hot water is extracted, its heat is removed, and then, once cooled, water is reintroduced back into the system at depth.

The extracted heated water is processed in a surface power plant, converting heat into electricity. The produced electrical energy can then be added to the electric grid system. In cases where geothermal energy is used for district heating, the installed system should not be too far from consumers (less than a few kilometers), because as the distance increases, the water temperature drops dramatically. Figure 12 is a schematic illustration that demonstrates a geothermal system and several of its components.

In the specific instance of Baltimore, calculations show that sufficiently hot subsurface rock is at a depth of greater than about 4.5 km. A test well, however, is needed to accurately determine the actual depth of the required temperature. Geologic examinations indicate that at this depth, the local rocks are undifferentiated, massive crystalline rocks, which are generally tight and relatively impermeable. To alleviate this condition and make these hot rocks conducive to producing hot water, the rocks must first be pervasively fractured, enhancing the permeability and manufacturing pathways (also known as geothermal reservoir) for the artificially introduced water to move throughout the target rocks. As previously discussed, geothermal systems of this kind are called EGS, and methods of working in such systems have been studied extensively and are an ongoing subject of intense interest to the U.S. Department of Energy.

## A Possible Project Design and Numerical Modeling

This initial geologic investigation shows that several kilometers beneath the surface of Baltimore, adequately hot rocks might be available for geothermal energy extraction after sufficient stimulation. To test this possibility, we have used state-of-the-art numerical modeling methods, the Comsol Multiphysics numerical package, to simulate the geothermal energy extraction under these given geological conditions. Such a geothermal system should be a conventional EGS, meaning that it would entail manufacturing a man-made geothermal reservoir at a depth (>4.5 km or deeper) where the temperatures are sufficiently high for power generation.

In this conceptual model, the artificially produced reservoir has a volume of ~160 million cubic meters and an initial temperature of ~155 C. Other important parameters of this numerical model are listed in Table 2. The details of the simulation are thoroughly described in our previously published studies (e.g., Hilpert et al.; Karimi and Marsh). Figure 13 shows the numerical modeling domain, while Figure 14 demonstrates the temperature of extracted water over time. The plotted water temperature versus time is of utmost importance, as it determines the efficiency and longevity of the system. Economic investments for geothermal plant construction are only accepted if

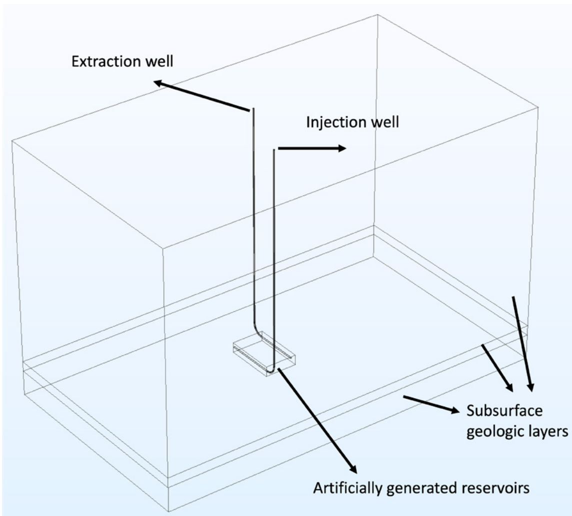


**Figure 13.** *The domain of numerical modeling for an idealized EGS geothermal system installed in the Baltimore area. The geophysical characteristics of the model such as density values, thermal state, depth of the reservoir, etc. are those specifically for the Baltimore area.*

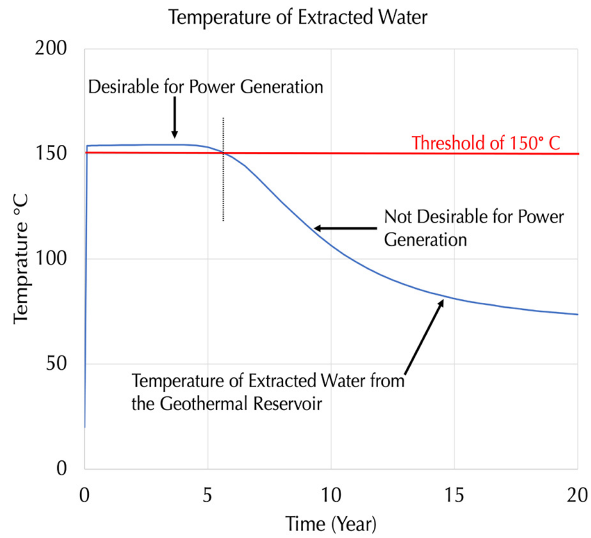


**Figure 14.** *Results of the numerical modeling showing the temperature of extracted water versus time. The threshold of 150 C is marked on the plot, and the extracted water temperature above that would be suitable for power generation. This study shows that the proposed geothermal system is capable of producing economic level of energy for electrical power production six to seven years. Afterward, the temperature of extracted water drops below 150 C, which is not suitable for power generation.*

the system is highly productive with a long life cycle. Based on the standards of the Department of Energy, if the extracted water temperature of a geothermal plant is above 150 C, it is suitable for power generation, whereas water at lower temperatures is suitable for direct use.

The simulation results indicate that the conceptual geothermal system modeled here for Baltimore would be economical for at least six to seven years of power generation (see Figure 14). The duration of efficient energy production has a crucial role in determining whether the construction of such a geothermal plant is economical or not. After this period, the temperature of the extracted water drops below 150 C, which is not suitable for power generation.

Subsequently, it might be possible to repurpose the system for direct use.We also emphasize that this conceptual model is mainly based on the most favorable geophysical conditions, which in reality might not be available. The efficiency and longevity of geothermal plants can be improved by enhancing various critical characteristics of the system, such as the volume of artificially built reservoir, the depth of reservoir, the geometry of wells, etc. The financial model for building two geothermal systems (district heating and power generation) is described in the next section.

**Table 2. An overview of a few parameters used for finite element modeling of the possible geothermal plant in Baltimore shown in this section. Some parameters are physical characteristics (such as density, specific heat, permeability, and porosity), while others are engineering components (such as flow rate).**

| Property | Value | Unit |
|---|---|---|
| Depth to Sufficiently Hot Rock [1] | 5 | km |
| Volume of the Reservoir [2] | 1.6E8 | $m^3$ |
| Lengths of Reservoir | 1, 0.8 | km |
| Thickness of Reservoir | 0.2 | km |
| Porosity | 10 | % |
| Permeability of Rocks | $10^{-17}$ | $m^2$ |
| Permeability of Stimulated Rock (Artificial Reservoir) | $10^{-14}$ | $m^2$ |
| Flow Rate [3] | 100 | kg/s |
| Density of Rock Matrix | 2500 | $kg/m^3$ |
| Reservoir Temperature [4] | 155 | °C |
| Injection Temperature [5] | 20 | °C |
| Thermal Conductivity of Subsurface Rocks | 1.8 | W/m K |
| Specific Heat of Porous Rocks | 1200 | J/kg K |

*Descriptions of these parameters can be found on the next page.*

**The Description of the Marked Parameters:**

| | |
|---|---|
| **1.** | The depth below which the temperature of rock is hot enough for extraction of geothermal energy. Based on the standard of the Department of Energy, the minimum temperature of rock should be 150 C. Typical geothermal reservoirs are in depth of <2 km, and thus the conceptual design presented here is anomalously deep. |
| **2.** | The volume of artificially stimulated rock at depth, also known as geothermal reservoir. |
| **3.** | As mentioned earlier, to produce power using a geothermal system, cold water must be pumped to the sufficiently hot subsurface. To produce an economic level of energy, a minimum flow rate of 100 kg/s of water should be pumped to the geothermal reservoir. The amount of flow rate for district heating is less and on the order of tens of kg/s. Considering that the depth of the presented geothermal model is anomalously deep, a very large pumping power is required for moving the water to/from the geothermal reservoir. As a result, a large portion of the energy produced might be used for pumping. |
| **4.** | The temperature of the stimulated rock (or geothermal reservoir) to which the cold water is being pumped. |
| **5.** | The temperature of the cold water that is pumped to the subsurface using the injection well. |

# Economic Model

To determine whether a geothermal plant installation is economically viable, several financial parameters must be considered. Most important is assessing the cost of building the system and its longevity, and whether in that time frame the investment could be returned. To do so, any economic model must take into account numerous parameters of the geothermal system above and below the ground. Among these components, some of the most important factors are:

1. **Reservoir Geometry and Depth:** The shape of the man-made reservoir and its depth.
2. **Reservoir Temperature:** The temperature is typically dictated by the depth and thermal gradient of the region. Reservoir temperature plays a vital role in the efficiency of the system.
3. **Length of Injection and Extraction Wells:** The length of two boreholes that connect the surface to the geothermal reservoir. Typically, geothermal reservoirs have at least one injection well through which cold water is injected to the geothermal reservoir, and at least an extraction (or production) well that collects the heated water. The length of these two wells is dictated by the depth of the reservoir.
4. **Wellbore Diameter:** The diameter of the wells (injection and extraction) through which water is pumped to/from the reservoir. The cross-section of wells is circular, and as the diameter becomes larger, the cost for drilling that well increases accordingly. Typically, the wellbore diameter of geothermal wells is in the range of 6-12 inches.
5. **Flow rate and Pumping:** For a geothermal system to work properly, water should circulate in and out of geothermal reservoir. For this circulation to happen, two pumps for injection and extractions are required. For direct use, the flow rate (the amount of water that is pumped per second) of water is smaller, and for power production the flow rate is larger.
6. **Injection/Extraction Temperatures:** The temperature of water that is injected into and collected from a geothermal reservoir.
7. **Conversion Unit:** The surface equipment that collects hot water and converts it to electric energy.

Drilling to depths of several kilometers is very expensive, and any changes in assumed reservoir depth can drastically change the outcome of the economic model.

Recently, NREL and the Department of Energy have produced an economic model named GEOPHIRES, which provides the best estimate of the cost of geothermal energy extraction in systems of this type. This model provides many financial details regarding a geothermal system such as capital and operation and maintenance costs, drilling costs, and overall levelized cost of energy of a geothermal plant, among others. For more information regarding the economic model, see the publication by Becker and McCabe (2019).

In this report, rough estimates for the costs of two average geothermal plants in Baltimore area are calculated: 1) for direct-use; and 2) for power generation. Some of the model inputs along with the results of the economic models are given in Tables 3 and 4. Analysis of the costs shows that the most expensive part of the expenses is for drilling. Generally drilling is costly, and as the depth increases, the cost for drilling to that depth increases as well. Furthermore, drilling a well in a metamorphic or an igneous rock is generally more expensive because the rock is harder. Additionally, the diameter of wells plays a significant role in determining the cost of drilling. Thus, while drilling cost is a function of numerous parameters, an average cost of drilling geothermal wells is in the order of $1.5-2 million per km. For the case of Baltimore, where the hot rocks are deep, the cost for drilling to these rocks is estimated to be high, almost half of the entire cost.

**DIRECT USE RESULTS:** The financial analyses show that a geothermal system for direct use in Baltimore with the specification listed in Tables 3 would cost around $23 million. The exploration stage, during which a test well is drilled to evaluate the possibility of building the geothermal plant, costs $5.33 million. The exploration stage is typically the very first stage of any geothermal system and determines the answer for a go/no-go decision. The major share of the cost is for drilling, which is about $11 million (also known as wellfield cost) and covers two vertical wells of injection/extraction that extend to the depth of at least 3 km beneath the surface. The cost for stimulation is ~$1.51 million, during which stage the subsurface rocks will be fractured using hydraulic techniques (see p. 17-18 for more details). The surface plant and field gathering system costs are $3.85 million and $1.31 million, respectively; these costs cover the installation of a heat exchanger, a distribution center, pumps, and surface piping that delivers heated water to buildings. The annual cost for overall maintenance of the system is around $0.5 million per year and entails cost of water, pumping energy, supervising of the operation of all components of the system, etc.

In the presented models, pumping of water (injection and extraction) occur 24/7, however it can be conducted according to a desired pumping rate and energy needs. If this geothermal system works for five hours/day, 5x3600x35 = 630,000 kg of water should be pumped, which is one-quarter of the amount of water in an Olympic-size pool. This budget also covers land lease and acquiring various environmental permits, receiving of which is dependent on the local government of each region. For instance, construction of a geothermal plant might not be feasible in the middle of a large city because it requires leased land, and it may impact geologic layers beneath the surface. The economic model estimates an average of 9.14 MW (megawatt) of thermal energy for the output of such a geothermal system. If a typical house uses 15,000 kWh of thermal energy annually, then the geothermal plan would provide heating for more than 600 houses per year. In the state of Maryland, and in particular in the city of Baltimore, there are infrastructures for transferring heat and energy, including piping, pumps, etc. In the case of using geothermal energy for district heating, more detailed consultations are required to determine how much of the existing infrastructures can be repurposed for geothermal energy.

**POWER GENERATION RESULTS:** The economic model shows that the minimum cost of building a functioning geothermal system for electric power generation would be around \$52.41 million (see Table 4). The exploration expenses of this geothermal system is larger than the previous geothermal system because it must reach deeper regions and costs \$9.97 million. The subsurface plumbing structure of the geothermal system, most prominently drilling, costs about \$23.5 million, while the cost for rock stimulation is \$1.51 million. The drilling cost of this geothermal system is significantly larger than for the direct use because the rocks with sufficiently high temperature are in the deeper region. The power plant (for converting the extracted heat to electricity) and field gathering system costs are \$14.47 million and \$2.89 million, respectively. This budget covers the expenses of surface pipes, a heat exchanger, the power plant structure, and the connection to the local electric grid. The annual cost for overall maintenance of the system is around \$1.13 million per year and entails cost of water, pumping energy (which is about three times higher than the previous system), supervising of the operation of all components of the system, etc. Similar to the previous geothermal system, this system also needs injection/extraction of water. If this geothermal system works for five hours/day, 5x3600x100 = 1,800,000 kg of water should be pumped, which is about three-quarters of the amount of water in an Olympic-size pool. Similar to the budget of the previous system, this budget (\$52.41 million) also covers acquiring a land lease and various environmental permits, etc. The generated power of 4 MW of clean energy is equivalent to taking ~1,500 cars off the streets. Further, according to the published analyses, each MW of clean power can provide energy for 180-250 houses per year. As a result, this geothermal power can provide power for up to 1,000 houses per year.

A renewable power production of 4 MW will lower the carbon footprint by at least 5,000 tons every year, and as such, the proposed geothermal system can play a vital role in the overall plan of carbon reduction.

As is evident in Tables 3 and 4, the cost for installing a geothermal system for direct use is lower, which is due to two main reasons: First, direct-use geothermal systems require a relatively lower rock temperature of > 80 C, which means drilling to a shallower depth ( as opposed to deep drilling needed for electricity production). Second, the aboveground equipment for direct use is less expensive and less complicated than electrical power production.

To determine whether building a geothermal system (for district heating and/or power generation) is feasible, a detailed analysis of these economic results is required. First, whereas the economic model determines the annual O&M (operation and maintenance) cost, it does not determine the pumping power requirements. However, a typical 4.5 MW geothermal power plant has about 1-1.5 MW of parasitic loss. Since sufficiently hot rocks below Baltimore are in significantly deep regions, the pumping power for injecting/extracting water might be very high. In fact, a large portion of the produced energy might be used for pumping power, which is essentially an energy loss. As a result, the net produced energy might be much smaller than the simulated power. Second, the initial investment for construction of a geothermal system for producing electricity in Baltimore is about $52 million, and its longevity is about six to seven years. The initial investment and longevity of the geothermal system for district heating are $23 million and ~20 years, respectively.

This report further provides first-order estimates on the number of houses whose power can be supplied by these geothermal systems. To make a go/no-go decision, it should be determined whether such an initial investment could yield profit in the duration of power production. If gas prices increase as predicted in the next decade or so (5-10x) and the price of electricity rises (2-3x), then the motivation to invest in such geothermal plants may increase remarkably.

**Table 3. A few of the input parameters for the economic model (left column) versus the calculated results of costs, average heat generation, etc. (right column). Here, the cost of building a geothermal system for direct use is modeled.**

| Input Values | | Output Values | |
|---|---|---|---|
| **Reservoir depth (km)** [1] | 3 | **Average Net Heat Production** [6] | 9.14 MWth |
| **# of Injection Well** | 1 | **Total Capital Cost** [7] | 22.97 M$ |
| **# of Extraction Well** | 1 | **Wellfield Cost** [8] | 10.97 M$ |
| **Flow Rate (kg/s)** [2] | 35 | **Surface Plant Cost** [9] | 3.85 M$ |
| **Average Thermal Gradient, C/km** [3] | 30 | **Exploration Cost** [10] | 5.33 M$ |
| **Well Diameter, inch** [4] | 8 | **Field Gathering System Cost** [11] | 1.31 M$ |
| **Reservoir Heat Capacity (J/kg K)** | 1000 | **Stimulation Cost** [12] | 1.51 M$ |
| **Porosity, %** [5] | 10 | **Total M&O Cost** [13] | >0.55 M$/year |

*Descriptions of these parameters can be found on the next page.*

**The Description of the Marked Parameters:**

| | |
|---|---|
| **1.** | The depth to sufficiently hot rock for extracting geothermal energy for power generation. Typically, geothermal reservoirs are in shallower depth (less than 2 km). |
| **2.** | The amount of water that should be pumped in and out of the reservoir per second. When the geothermal plant is for district heating, the amount of pumped water can be in the range of 10-50 kg/second, while for electric production, the rate of water is more than 100 kg/s. |
| **3.** | The rate at which the temperature increases below the surface. |
| **4.** | The diameter of wells that inject/extract water. This is a typical value that is used in many geothermal wells. |
| **5.** | This is a typical value of porosity for rocks at depth. |
| **6.** | The amount of thermal energy that is produced using this geothermal system. |
| **7.** | The total cost of building the geothermal system considering all the expenses. |
| **8.** | The cost of drilling wells and producing a plumbing network in the subsurface. |
| **9.** | The cost of construction of a heat exchanger, distributer, piping, etc. |
| **10.** | The cost of a pilot test well to test the viability of geothermal energy extraction. |
| **11.** | The cost of constructing a pipe network for delivering the extracted heated water. |
| **12.** | The cost of the process of hydraulic fracture that enhances the rock permeability. |
| **13.** | The cost of pumping water (injection/extraction), maintenance of the system, supervision, etc. |

**Table 4. A few of the input parameters for the economic model (left column), versus the calculated results of costs, average power generation, etc. (right column). Here, the cost of building a geothermal system for power generation is modeled.**

| Input Values | | Output Values | |
|---|---|---|---|
| Reservoir depth (km) [1] | 5 | Average Net Electric Generation [3] | 4.0 MWe |
| # of Injection Well | 1 | Total Capital Cost [4] | 52.41 M$ |
| # of Extraction Well | 1 | Wellfield Cost [5] | 23.58 M$ |
| Flow Rate (kg/s) | 100 | Surface Plant Cost [6] | 14.47 M$ |
| Average Thermal Gradient, C/km | 30 | Exploration Cost [7] | 9.97 M$ |
| Well Diameter, in | 8 | Field Gathering System Cost [8] | 2.89 M$ |
| Reservoir Heat Capacity (J/kg K) | 1000 | Stimulation Cost [9] | 1.51 M$ |
| Porosity, % | 10 | Total M&O Cost [10] | >1.13 M$/year |

*Descriptions of these parameters can be found on the next page.*

**The Description of the Marked Parameters:**

| | |
|---|---|
| **1.** | The depth to sufficiently hot rock for extracting geothermal energy for power generation. Typically, geothermal reservoirs are in shallower depth (less than 2 km). |
| **2.** | The amount of water that should be pumped in and out of the reservoir per second. |
| **3.** | The amount of electric energy that is produced using this geothermal system. |
| **4.** | The total cost of building the geothermal system considering all the expenses. |
| **5.** | The cost of drilling wells and producing a plumbing network in the subsurface. |
| **6.** | The cost of construction of a conversion unit that converts the heat to electricity. |
| **7.** | The cost of a pilot test well to test the viability of geothermal energy for power generation. |
| **8.** | The cost of constructing a system to connect the produced energy to a local electric grid, etc. |
| **9.** | The cost of the process of hydraulic fracturing that enhances the rock permeability. |
| **10.** | The cost of pumping water (injection/extraction), maintenance of the system, supervision, etc. |

# Conclusions

The current report provides a first-order estimate on the potential for geothermal energy production in Maryland in general, and more specifically in the immediate area of the city of Baltimore itself. This investigation has used all available data to characterize the thermal state of the Earth's crust in the Baltimore region. The geothermal data for Baltimore is based on one well drilled in the 1980s. This well was only 300 m deep and did not completely penetrate through the underlying volcanic and metamorphic bedrocks. Although it provides some information, this is not sufficient to draw firm conclusions about the geothermal potential of the Baltimore area.

At present, and with the current available data, as for most cities along the East Coast, the possibility of harnessing geothermal energy in any straightforward and economical fashion is unlikely. However, in order to have a more accurate understanding and appraisal of the geothermal potential of Maryland/Baltimore, at least one deep test well (> 2 km) is required. This pilot well will allow a much better understanding of the thermal potential of the deeper rock formations and allow an assessment of the environmental aspects of the geothermal plant installation. The economic model shows that a test well in a geologic setting similar to that of Baltimore will cost a minimum of $5.3 million (see Table 3). Such a pilot exploratory well is necessary to have a firm and fundamental knowledge of the geothermal energy potential beneath the area of Baltimore. A geothermal system can only be installed if the various tests associated with the bottom hole temperature, economic model, geochemistry analysis, and permeability/porosity, among others, prove to be satisfactory. Recently a novel technique has been developed for mapping the permeability field known as Fracture Seismic Imaging (FSI). Using this method would also yield useful information regarding the subsurface rocks beneath the Baltimore city. Additionally, in-depth analyses and in-situ examinations of successful geothermal systems installed in various regions, such as Iceland or Boise (Idaho), would be immensely beneficial.

As stated earlier in this report, the main obstacle of extracting geothermal energy is drilling to very deep regions where adequately hot rocks are located. Deep drilling is technologically challenging and very expensive, and collectively makes geothermal energy a less attractive renewable energy for the East Coast. However, this issue seems to have a solution in the near future. Recently, newly established companies, more prominently Quaise, proposed methods for drilling very deep wells for extracting geothermal energy in an economical way. Such proposed wells would have the ability of reaching a depth of 20 km and a temperature of up to 500 C—more than adequate for producing clean renewable geothermal energy anywhere on Earth. These companies estimate a decade for their proposed technique to be commercially available.

As of 2020, nuclear energy and natural gas supplied 79% of the energy needs of Maryland, while renewable sources generated around 11% of the state's power (two-fifths of which came from hydropower). Currently in the state of Maryland, other sources of energy production are more economical than geothermal power plants. For instance, construction of a coal power plant and a gas power plant for electricity generation of the same magnitude (4 MW) cost ~$15 million and ~$10 million respectively, which is significantly cheaper than a geothermal system modeled here. This, however, is poised to change. The financial studies predict 5-10x rise in gas price in the next decade or so, which can be translated to 2-3x rise in electricity prices. Although the presented geothermal models in this study may not be economically feasible now, when deep drilling to reach very hot rocks becomes a reality, clean abundant geothermal energy might well become the sole provider of baseload power energy anywhere, including Baltimore. To prepare for such a day, drilling a relatively deep pilot test well would be a first step.

## About the Authors

Dr. Saman Karimi is a Research Scientist at Johns Hopkins University with broad interests in Earth and Planetary Sciences. Part of his research is geared toward enhancing the efficiency of geothermal systems, while other part is focused on better understanding the thermal and structural evolution of planetary bodies.

Dr. Bruce Marsh, Professor Emeritus, has been at Johns Hopkins University since 1974. He is an expert on the physics and chemistry of planetary magmatic processes including geothermal energy, an elected Fellow of the American Geophysical Union, Geological Society of America, Mineralogical Society of America, and the Royal Astronomical Society.

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