Chapter 1

An Introduction to Next-Generation Geothermal

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

OVERVIEW

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

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

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

APPLICATIONS FOR GEOTHERMAL ENERGY

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

Geothermal Electricity Generation

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

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

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

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

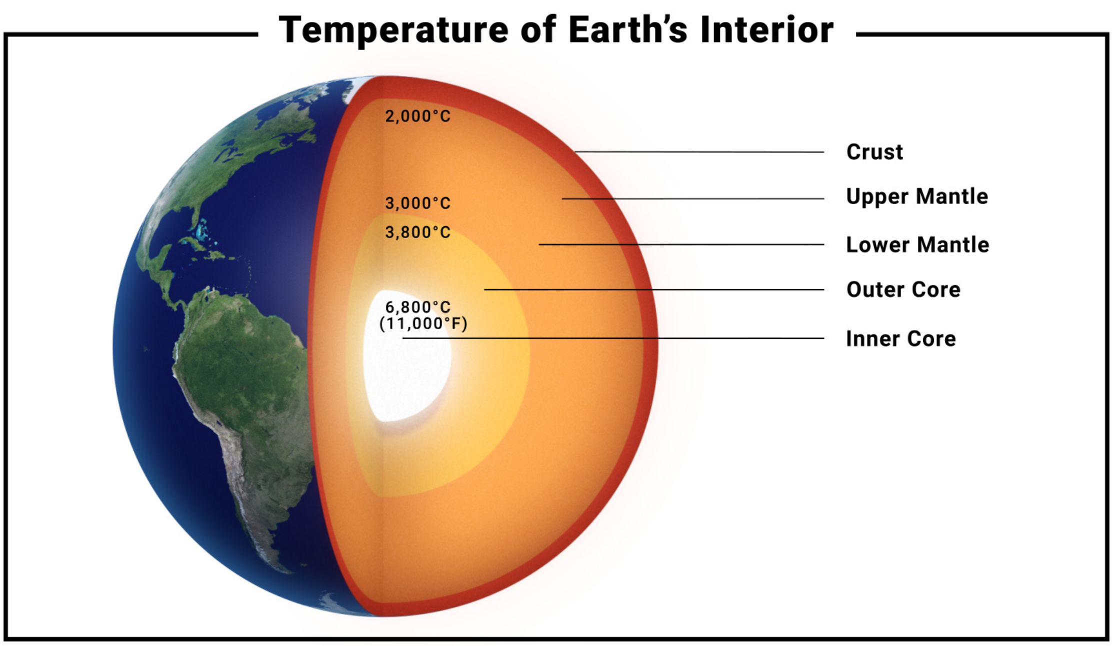

Figure 1.1 The core of the earth exceeds the temperature of the surface of the sun. Because the crust of Earth is an excellent insulator, enough heat is trapped beneath us to power the world hundreds of times over.

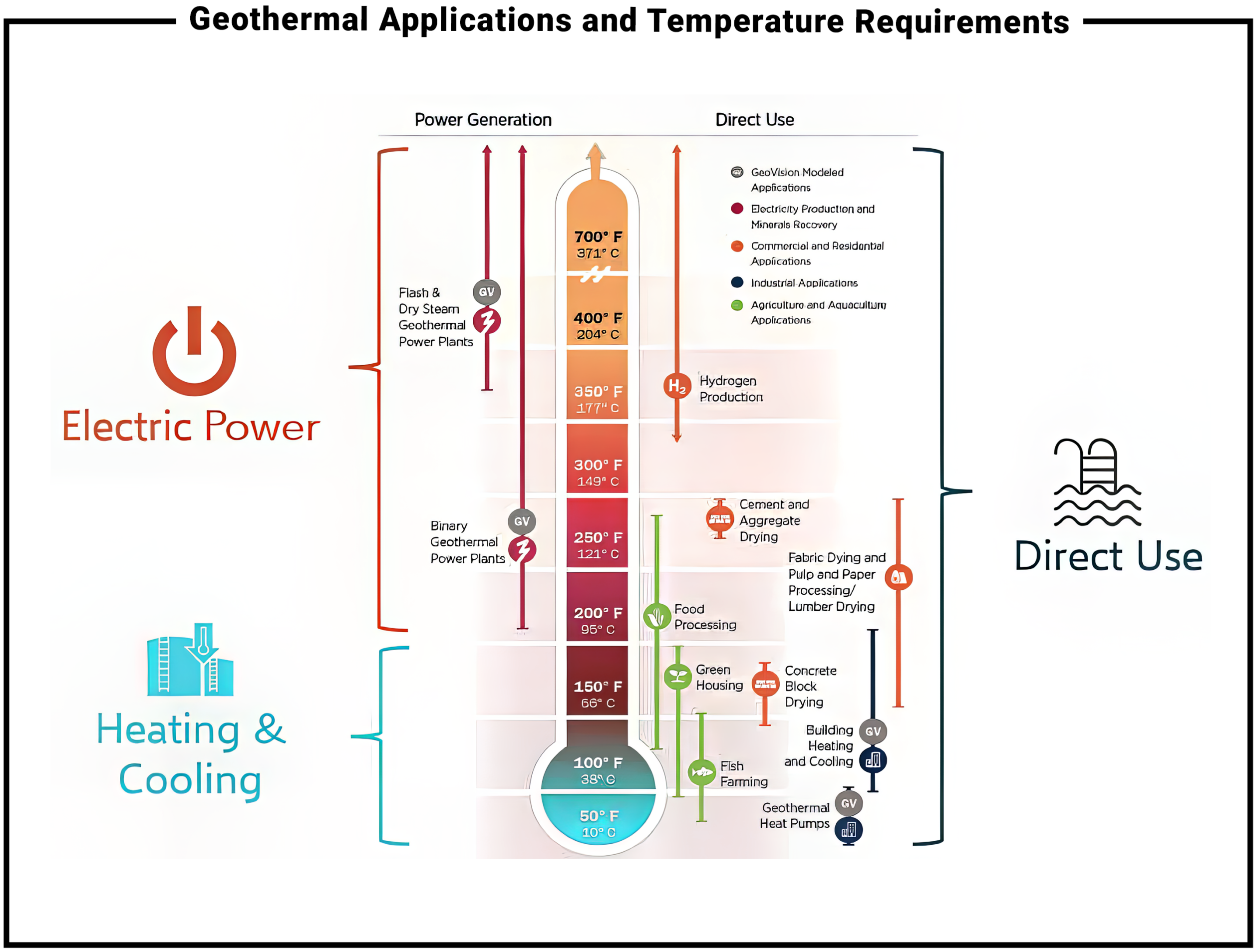

Figure 1.2: Source: *Porse, S. (2021, August 2-6). Geothermal Energy Overview and Opportunities for Collaboration [Conference presentation]. Energy Exchange, Georgia World Congress Center, Atlanta, GA, United States.*

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

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

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

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

Geothermal Heating and Cooling for the Built Environment

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

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

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

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

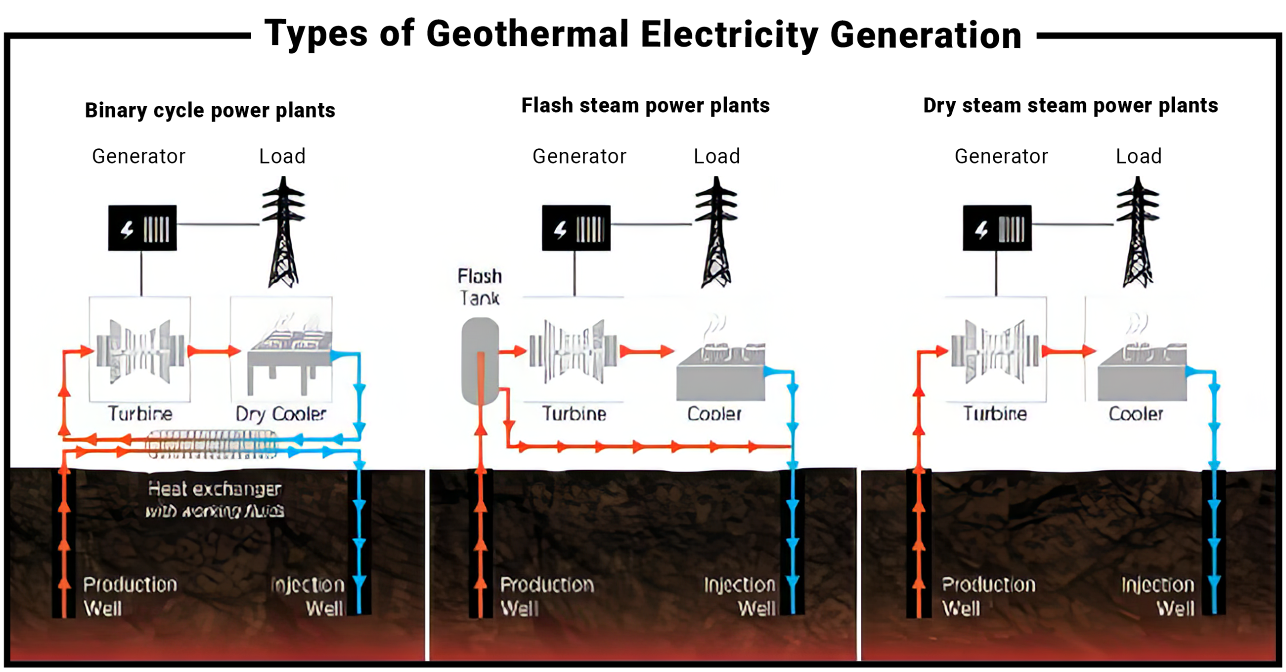

Figure 1.3: Source: Adapted from *U.S. Department of Energy (2019)*. Geovision: Harnessing the Heat Beneath Our Feet. https://www.energy.gov/eere/geothermal/geovision

Industrial Process Temperatures and Heat Pump Technologies

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

Technology Readiness Level (TRL) of heat pumps:

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

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

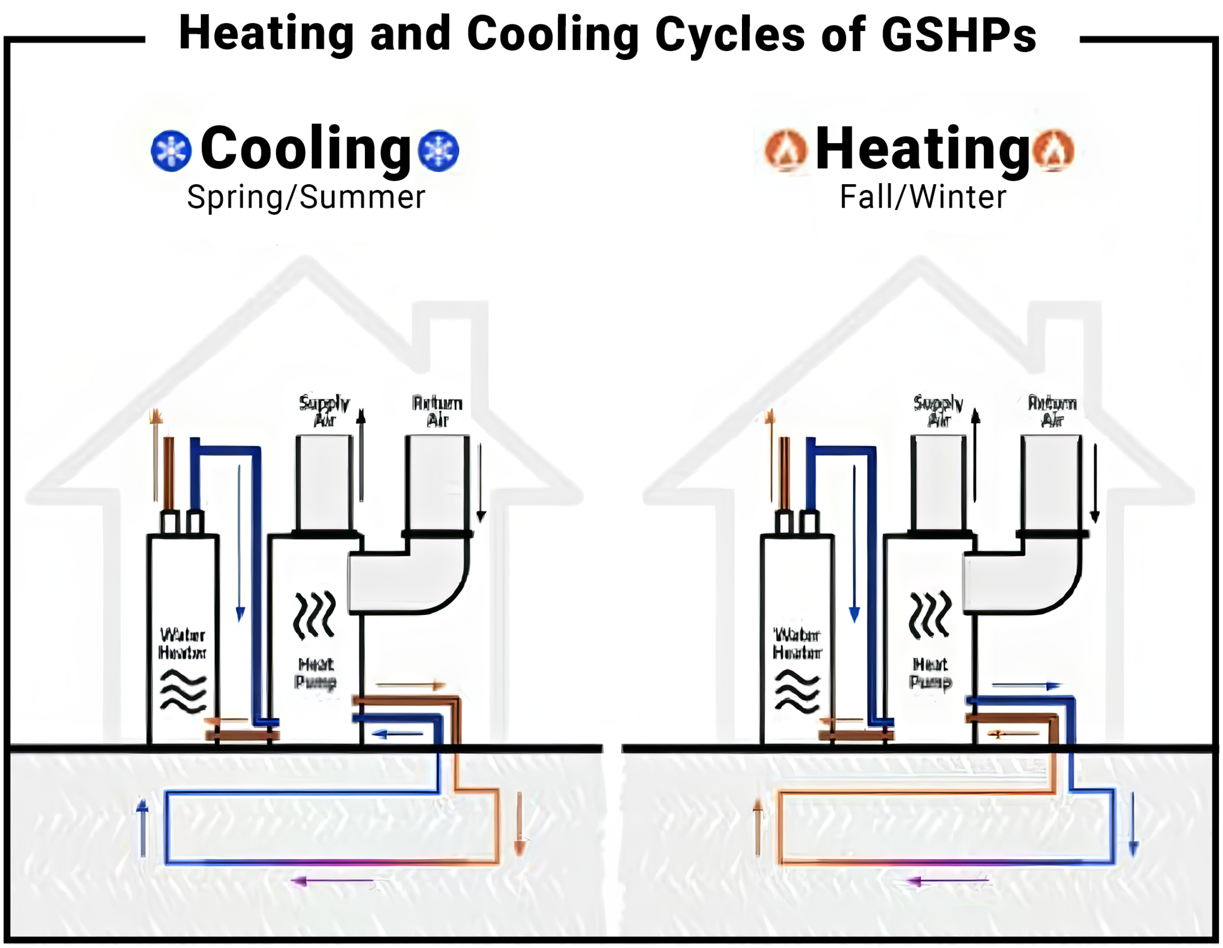

Figure 1.4: Source: Beard, J. C., & Jones, B. A. (Eds.). (2023). The future of geothermal in Texas: The coming century of growth and prosperity in the Lone Star State. Energy Institute, University of Texas at Austin. https://doi.org/10.26153/tsw/44084. Adapted from U.S. Department of Energy - DOE. (2019).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

Industrial Process Heat

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

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

Geothermal Energy Storage

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

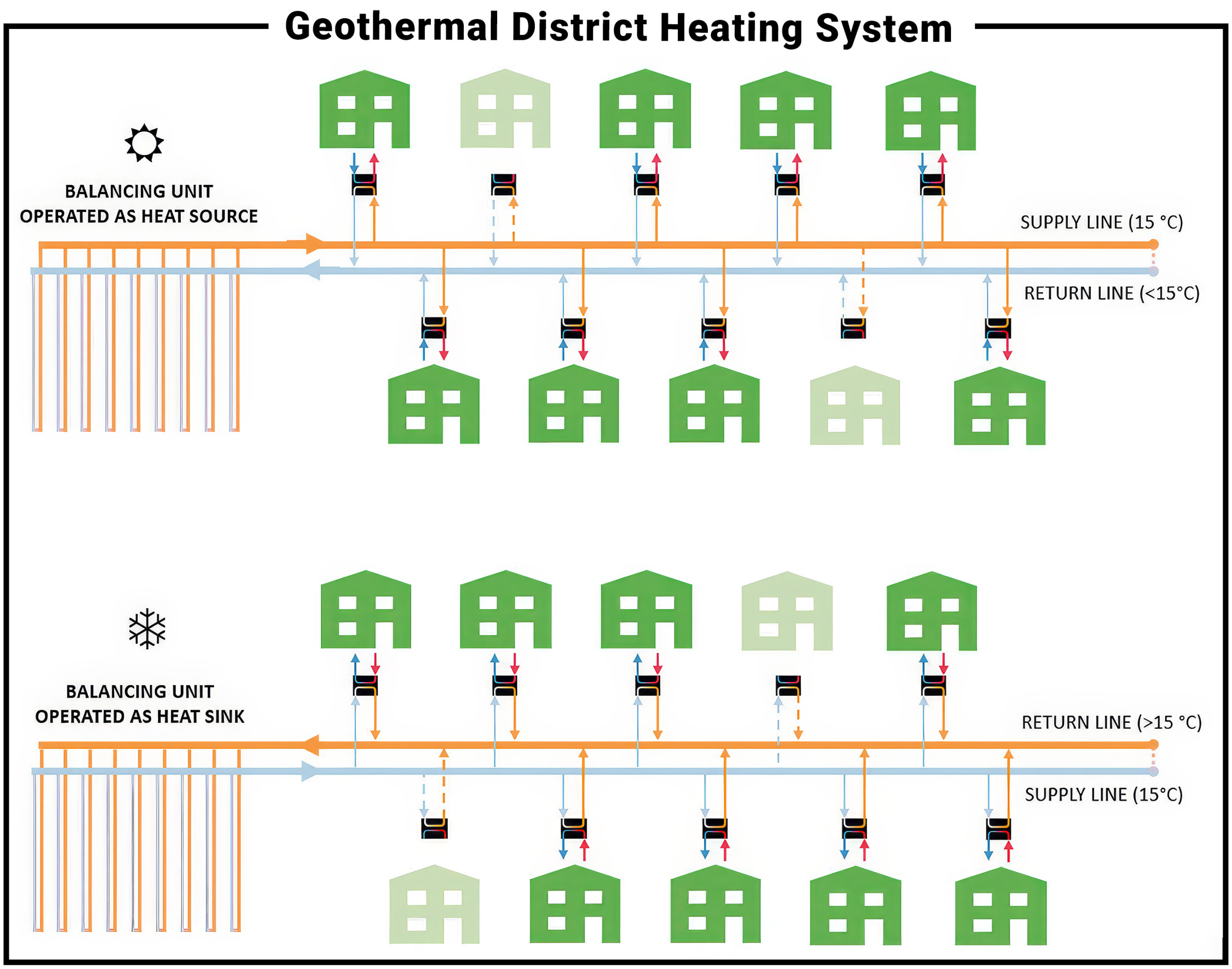

Figure 1.5: García-Céspedes, J.; Herms, I.; Arnó, G.; de Felipe, J.J. Fifth Generation District Heating and Cooling Networks Based on Shallow Geothermal Energy: A review and Possible Solutions for Mediterranean Europe. Energies 2023, 16, 147. https://doi.org/10.3390/en16010147

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

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

Critical Minerals Extraction

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

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

BENEFITS OF GEOTHERMAL

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

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

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

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

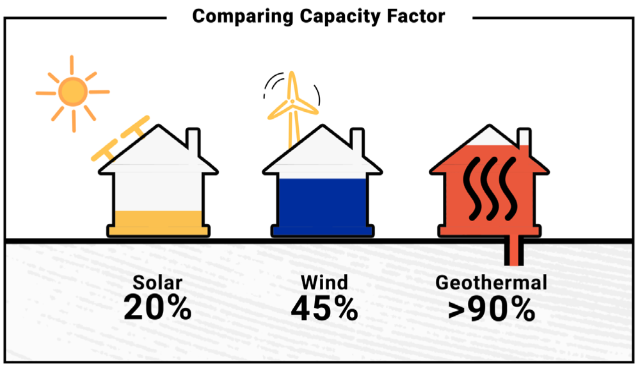

Figure 1.6: Capacity factor is the percentage of time that a plant is generating electricity. Source: Adapted from EIA, 2014.

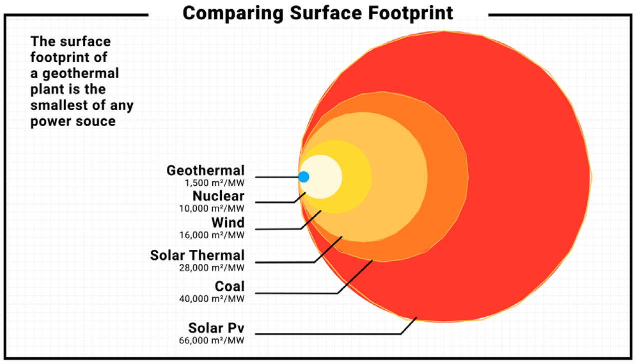

Figure 1.7: The project surface footprint, acre for acre for one gigawatt of generating capacity, is smallest with geothermal compared to other clean sources and coal. Source: Adapted from Lovering et al., 2022 and NREL.

THE EVOLUTION OF GEOTHERMAL: FROM CONSTRAINTS TO POSSIBILITIES

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

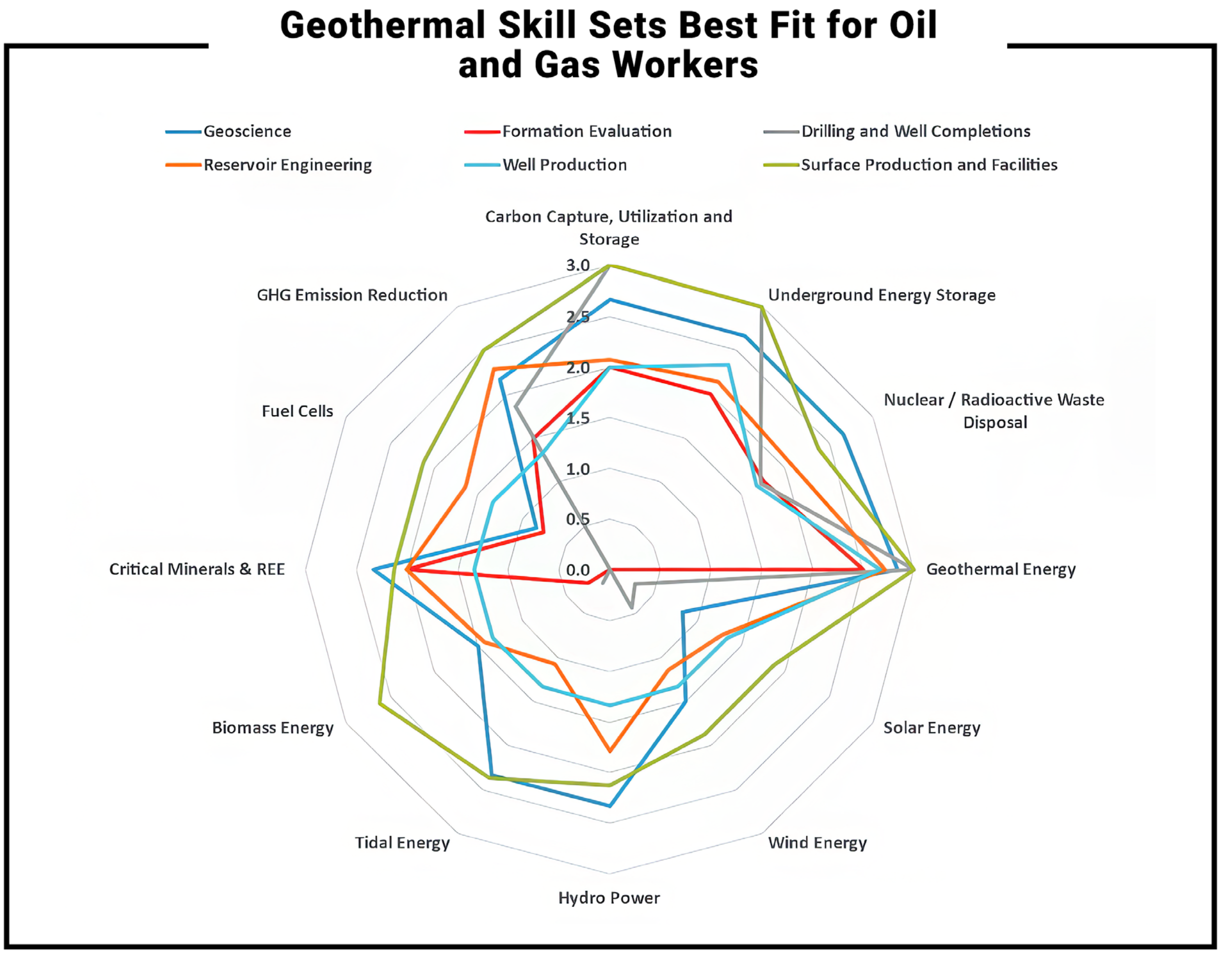

Figure 1.8: As shown, geothermal ranks highest when considering the potential impact of transferring oil and gas skills into other energy transition and low-carbon technologies. Source: Tayyib, D., Ekeoma, P. I., Offor, C. P., Adetula, O., Okoroafor, J., Egbe, T. I., and E. R. Okoroafor. "Oil and Gas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

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

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

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

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

Engineered Geothermal Systems (EGS)

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

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

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

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

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

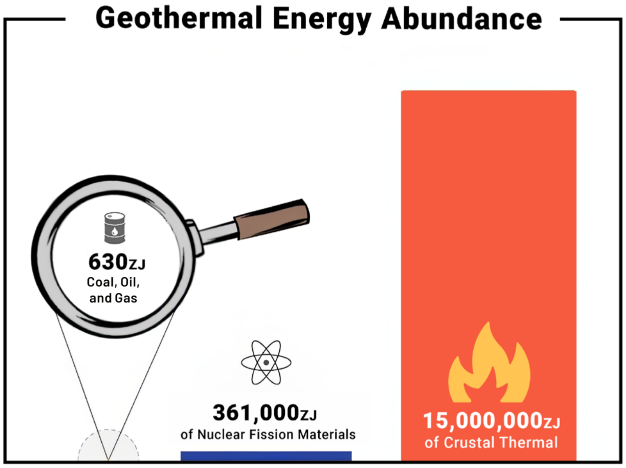

Figure 1.9: Comparison of total heat energy in Earth's crust, compared to fissionable materials and fossil fuels. Note that total fossil fuels, when compared with crustal thermal energy, is the equivalent of less than one pixel at the bottom of the graphic, shown magnified to illustrate scale. Measurements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

Advanced Geothermal Systems (AGS) or Closed-Loop

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

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

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

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

Super Hot Rock (SHR)

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

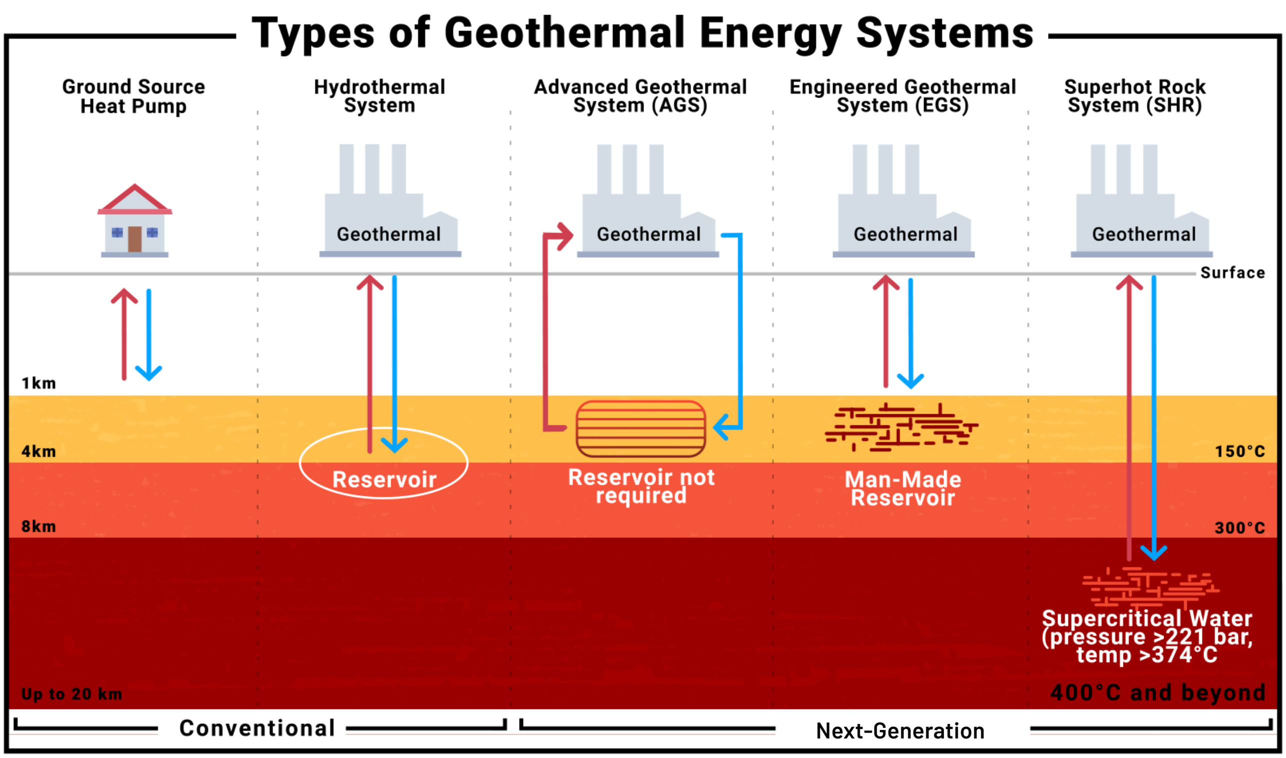

Figure 1.10: Except for Ground Source Heat Pump, images depict geothermal electricity generation. GSHP shows building heating; the arrows would reverse for building cooling. Source: Adapted from S&P Global Commodity Insights. (2024) Next-generation technologies set the scene for accelerated geothermal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

GEOTHERMAL GEOLOGY AND HEAT FLOW

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

Conduction, Advection, Convection, and Radiation

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

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

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

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

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

Geology and Energy Extraction

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

Convection-dominated:

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

Conduction-dominated:

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

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

Comparison of Existing and Emerging Geothermal Technologies and Concepts

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

Table 1.2

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

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

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