Part I

The Basics of Geothermal

Chapter 1

Geothermal 101: An Overview of Technologies and Applications

Project InnerSpace

Because it is hot everywhere underground, and thanks to technological developments from the oil and gas industry, we can access underground heat in significantly more locations than was historically possible. The potential for geothermal development across a variety of applications and use cases is now truly global.

Geothermal is a naturally occurring, ubiquitous, and clean energy source. About 4,000 miles from the planet's crust, the core of the Earth is roughly as hot as the surface of the sun. (See **Figure 1.1**). Geothermal heat is present across the entire planet—on dry land and on the ocean floor—and offers enough potential energy to power the whole world thousands of times over.

These resources have been exploited for centuries: In the 19th century, people started using heat from the Earth for industrial processes like heating and cooling buildings and generating electricity. The first documented instance of geothermal electricity generation was in Larderello, Italy, in 1904.[1]

But throughout history, these conventional hydrothermal systems have been geographically limited. They require specific subsurface conditions—sufficient heat, water, and rock permeability—which are typically found in tectonically active regions such as Iceland and the western United States.[2] 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 such as a geyser or hot spring.[3] The need for these specific conditions severely restricted geothermal's broader global use, as few locations met these natural requirements.

Today, geothermal energy provides only 0.5% of global electricity.[4] Adoption of this energy is much higher in (primarily) volcanic regions, where geothermal resources—those conventional hydrothermal systems—are uniquely close to the surface. Conventional hydrothermal systems account for 46% of electricity in Kenya, 33% in Nicaragua, and 30% in Iceland.[5] New Mexico is one of seven states in the nation with a utility-scale hydrothermal power facility in operation,[6] the Lightning Dock Geothermal facility in Hidalgo County, in the southwest part of the state. (The plant's first customer was the state's public utility, Public Service Company of New Mexico [PNM].[7])

But now, geothermal energy can be produced from many more locations too. How?

Because it is hot everywhere underground, and thanks to technological developments from the oil and gas sector, we can now access that heat almost everywhere. Geothermal projects that use these technologies are referred to as *next-generation geothermal*. These new approaches—such as engineered geothermal systems and advanced geothermal systems—are expanding the future of geothermal energy beyond all previous geographical limitations. (See "The Evolution of Geothermal: From Constraints to Possibilities" for more on these approaches.) These technologies take many forms: directional drilling, deeper drilling, techniques that create additional pore space for fluid flow, more efficient drill bits, or the introduction of fluids into subsurface areas where they may not naturally be present.

Geothermal has the advantage of being a 24/7/365, clean baseload energy source. Unlike wind and solar, it is always on. Unlike natural gas and coal, it has no emissions or fuel costs. And unlike nuclear power, there is no need to dispose of radioactive material.

In general, the hotter the geothermal resource, the more efficient these next generation geothermal power plants will be at producing electricity. The more efficient the production, the lower the cost. As shown in **Figure 1.2**, geothermal electricity generation is possible with fluid temperatures as low as 200°F (approximately 93°C) using "binary" cycle power plants (in other words, two fluid cycles). Flash steam and dry steam electric turbines (see **Figure 1.3**) can be used when the fluid temperature rises above 350°F (approximately 180°C).[8] And some higher-temperature installations have started using novel binary-type configurations.

A report published in 2024 by the International Energy Agency (IEA) says "the potential for geothermal is now truly global," and next-generation geothermal systems have the technical potential "to meet global electricity demand 140-times over."[9] That analysis also notes that by 2035, geothermal could be highly competitive with solar photovoltaics and wind when paired with battery storage.

TEMPERATURE OF THE EARTH'S INTERIOR

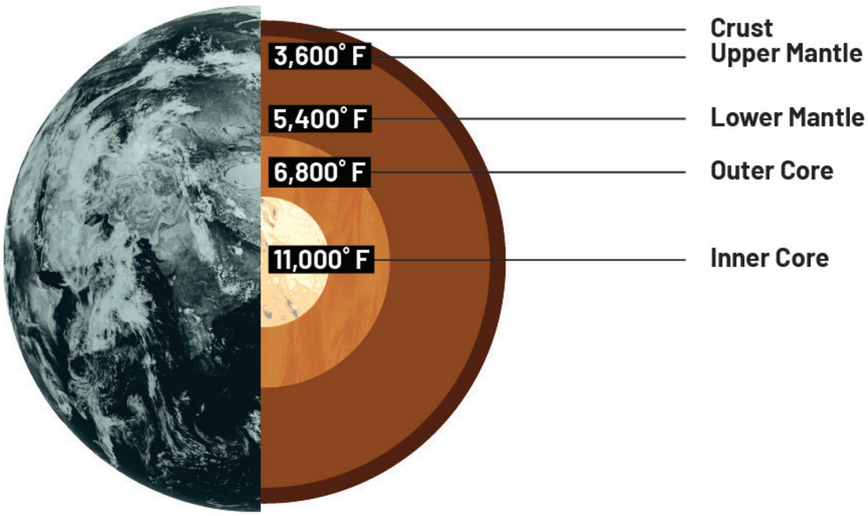

Figure 1.1: The core of the Earth exceeds the temperature of the surface of the sun. Because the crust of Earth is an excellent insulator, enough heat is trapped beneath us to power the world hundreds of times over. Source: Project Innerspace

GEOTHERMAL APPLICATIONS AND TEMPERATURE REQUIREMENTS

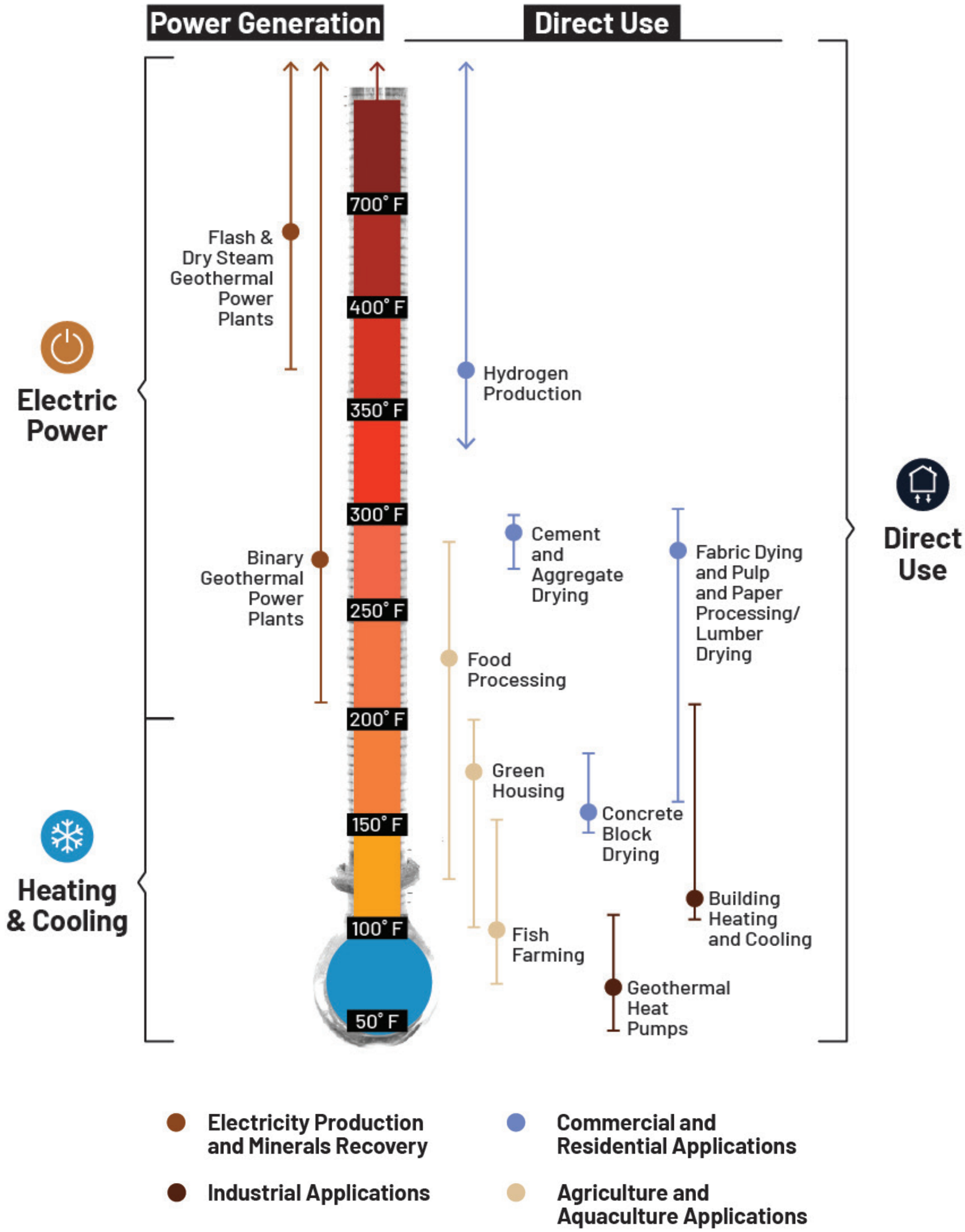

Figure 1.2: Geothermal energy can be used for generating electricity, heating and cooling homes, or manufacturing processes. There are also new and emerging applications such as geothermal energy storage, where the subsurface serves as an earthen battery, and geothermal critical minerals extraction for rare elements. Adapted from Porse, S. (2021, August 2-6). *Geothermal energy overview and opportunities for collaboration*. Energy Exchange, Georgia World Congress Center, Atlanta, GA, United States.

TYPES OF GEOTHERMAL ELECTRICITY GENERATION

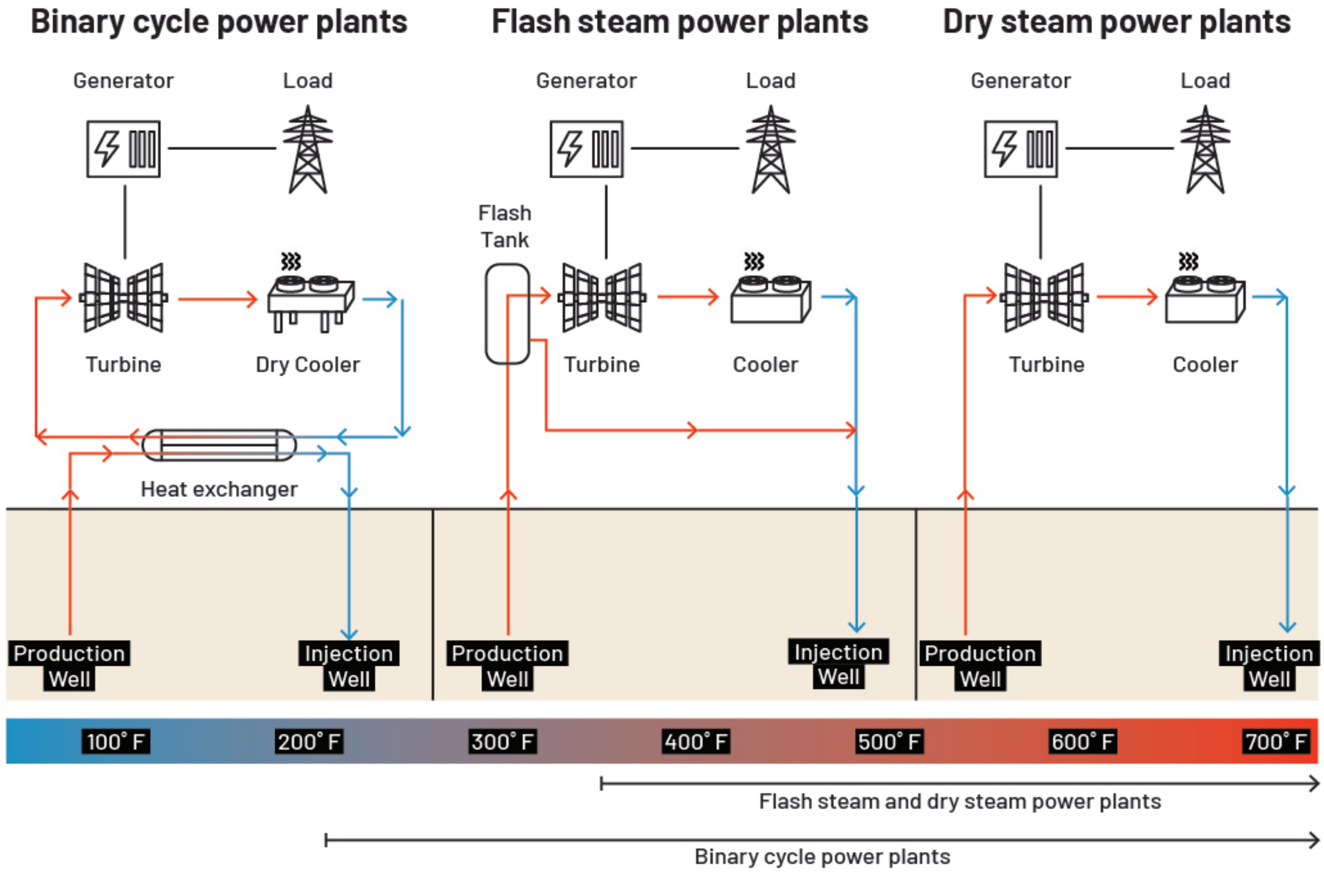

Figure 1.3: There are three primary configurations for generating electricity using geothermal: binary, flash steam, or dry steam. In general with these new technologies, the hotter the underground geothermal resource—whether conventional hydrothermal or next-generation geothermal—the more efficient the surface equipment will be at producing electricity. Binary geothermal electricity generation is possible with fluid temperatures as low as 200°F (about 95°C). Flash and dry steam geothermal electric turbines can be used when fluid temperature rises above ~360°F (182°C). Source: *The Future of Geothermal in Texas: The Coming Century of Growth and Prosperity in the Lone Star State.* https://energy.utexas.edu/research/geothermal-texas

Globally, heat energy makes up about half of all energy consumption and contributes to about 40% of energy-related emissions.[10] To put it another way: Clean geothermal can address almost half of the world's energy demand. Until recently, this opportunity has been almost entirely overlooked.

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

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.[11] The rest is produced from other sources, like burning biomass, or via the electrification of heat—meaning electricity that is produced using solar, wind, or other fuels and then converted back into heat. (For instance, electric strip heaters.)

INDUSTRIAL PROCESS TEMPERATURES AND HEAT PUMP TECHNOLOGIES

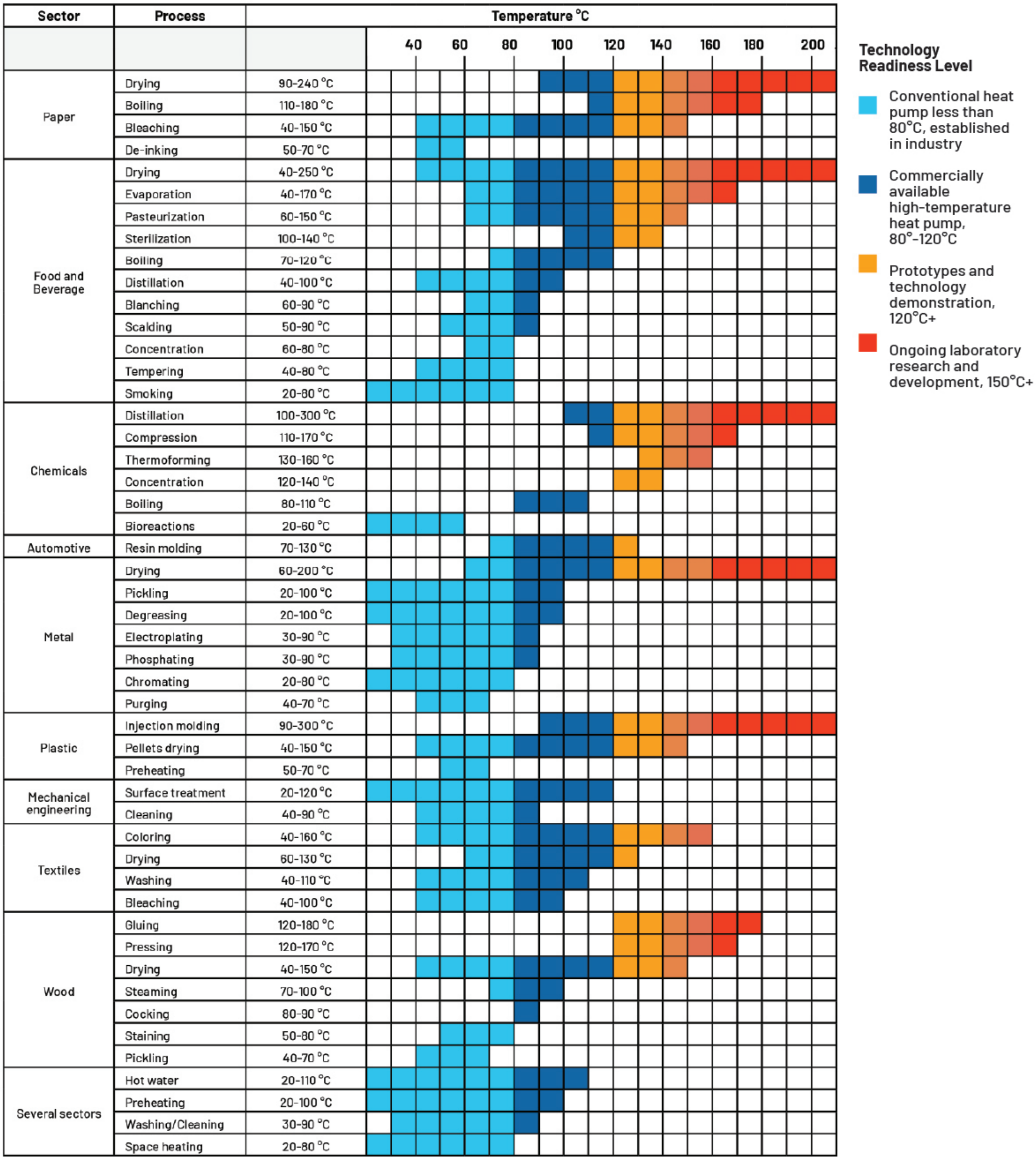

Figure 1.4: Rough technology readiness levels of high-temperature heat pumps as of mid-2023. Geothermal can enable industrial processes without heat pumps; however, combining the two technologies may prove even more useful. High-temperature industrial heat pumps above 100°C have seen significant advances in recent years. Source: Arpagus, C., et al. (2023). *Industrial heat pumps: Technology readiness, economic conditions, and sustainable refrigerants*. American Council for an Energy-Efficient Economy (ACEEE). https://www.aceee.org/sites/default/files/pdfs/IHP_Workshops_2023/Cordin_Arpagaus_-_OST.pdf

HEATING AND COOLING WITH GROUND SOURCE HEAT PUMPS

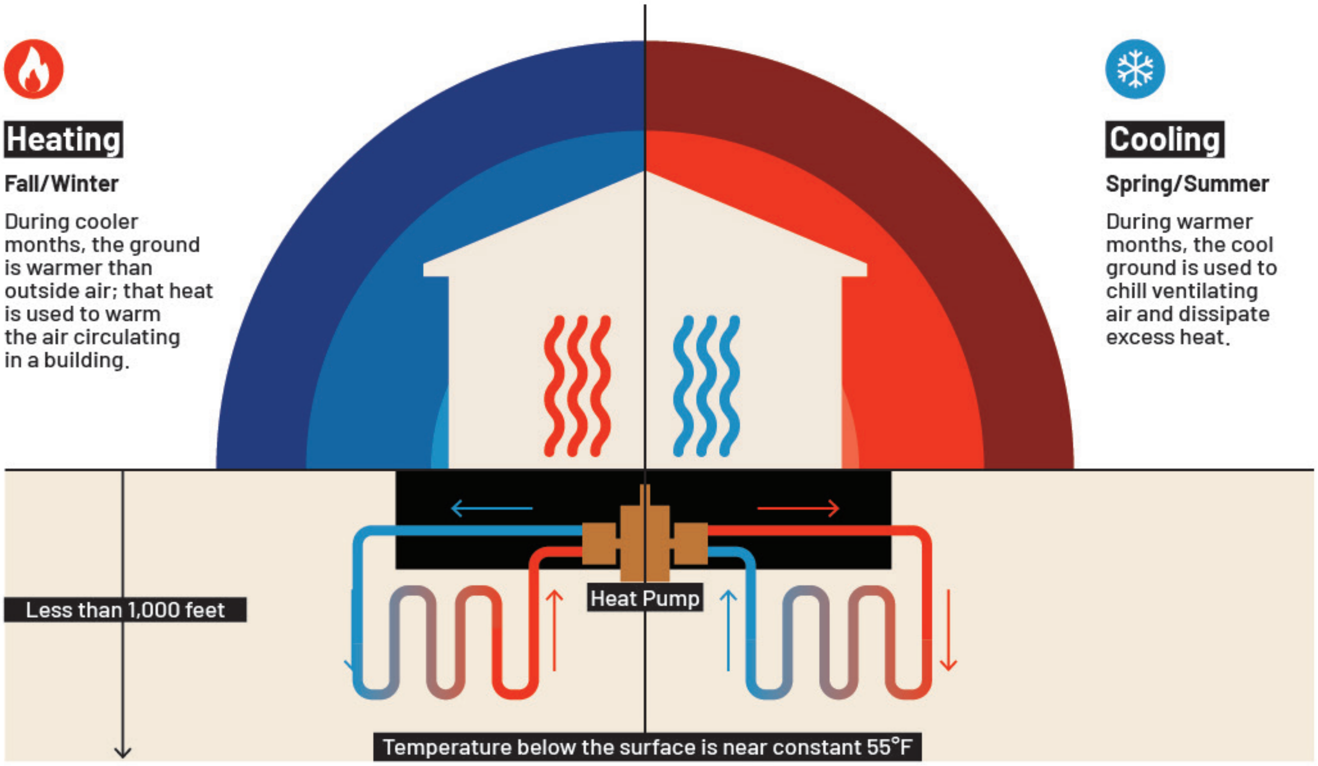

Figure 1.5: The constant temperature of the ground helps improve the efficiency of ground source heat pumps. Adapted from Beard, J. C. and Jones, B. A. (Eds.). (2023). Source: *The future of geothermal in Texas: The coming century of growth and prosperity in the Lone Star State*. Energy Institute, University of Texas at Austin. https://doi.org/10.26153/tsw/44084.

In the United States, the heating and cooling of buildings consumes about half of all energy use in both residential and commercial sectors.[12] That figure is higher in the residential sector in Europe.[13] The good news is that geothermal technologies that can help meet this demand already exist: ground-source heat pumps (geothermal heat pumps) and geothermal district heating. See Chapter 4, "Geothermal Heating and Cooling," for more information about these technologies and their deployment in New Mexico.

Industrial process 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 more than half of total energy use and contributes the majority of the sector's emissions.[14]

All building heating and cooling (heating, ventilating, and air-conditioning; HVAC) and 30% of heat used for manufacturing processes worldwide use temperatures below 300°F (about 150°C).[15] In many parts of the world, geothermally derived heat at this temperature is currently comparable in cost with coal, biomass, solar, and wind. The IEA report estimates that next-generation geothermal could economically satisfy 35% of all global industrial thermal demand for processes requiring temperatures below 390°F (about 200°C). The use of next-generation geothermal could thus save about 750 megatons of carbon dioxide (CO_2) emissions—equivalent to the annual emissions of Canada, the world's 12th-largest emitter.[16]

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

GEOTHERMAL DISTRICT HEATING SYSTEM

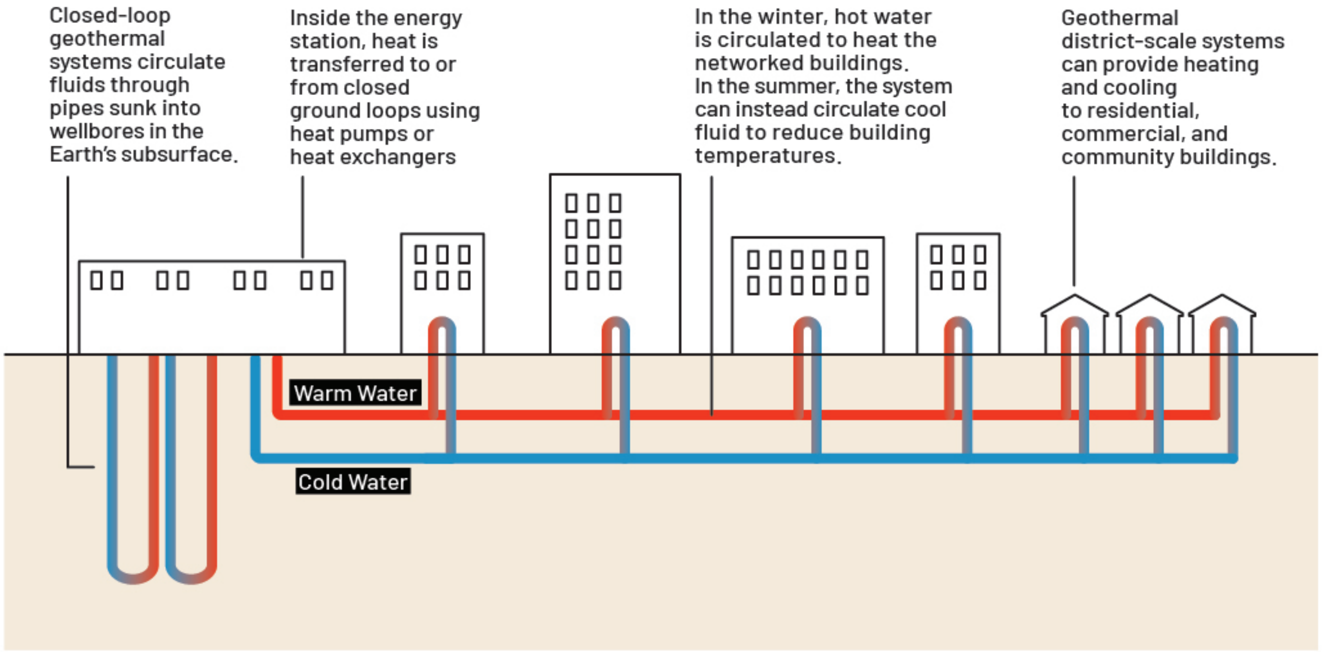

Figure 1.6: District heating system fluid is typically brought to the surface at a target temperature of around 70°F *(21°C). That fluid is then passed through a heat pump to provide hot water in the winter for heating and cold water in the summer for cooling. This style of heating and cooling can be more than twice as efficient as traditional HVAC systems because the thermal load is shared between buildings. Adapted from U.S. Department of Energy. *Geothermal district heating & cooling*. https://www.energy.gov/eere/geothermal/geothermal-district-heating-cooling

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COMPARING CAPACITY FACTOR

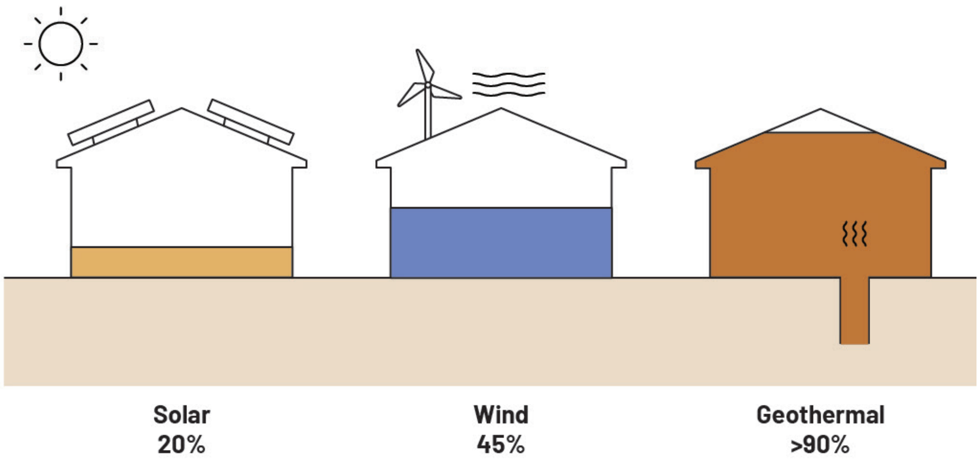

Figure 1.7: Capacity factor is the percentage of time that a power plant is generating electricity in a given day. Adapted from EIA, 2014.

electrons flowing onto the grid from intermittent energy sources such as wind and solar—which are only available when the sun shines or the wind blows—concerns about having power when it is needed have brought the need for energy storage to the forefront.[17] Today, hydroelectric storage provides most global energy storage capacity [18], and recent years have seen a significant expansion in the deployment of batteries for energy storage. A new approach—underground thermal energy storage, 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 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, or 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 clean energy and a domestic lithium source—could lower lithium extraction's environmental impact compared with traditional mining and improve the economics of a geothermal project.

At a conventional hydrothermal site 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 would restrict fluid flow. Today, direct lithium extraction 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 has estimated that the Salton Sea contains enough battery-grade lithium to "satisfy more than one-third of the worldwide demand."[19]

COMPARING SURFACE FOOTPRINT

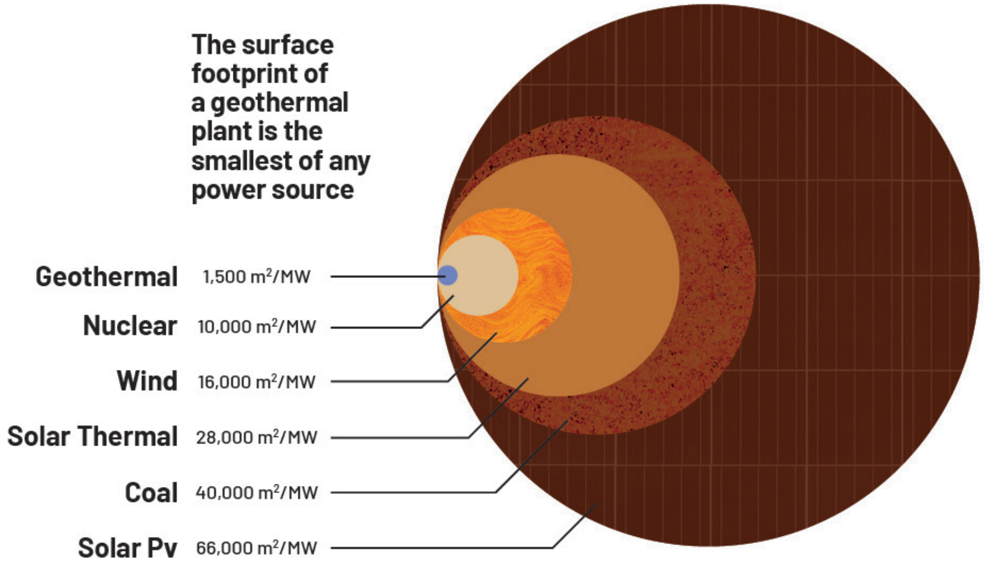

Figure 1.8: The project surface footprint, acre for acre for 1 gigawatt of generating capacity, is smallest for geothermal compared with other renewables and coal. Source: Adapted from Lovering et al., 2022 and NREL.

TRANSFERABLE SKILL SETS FROM THE OIL AND GAS INDUSTRY

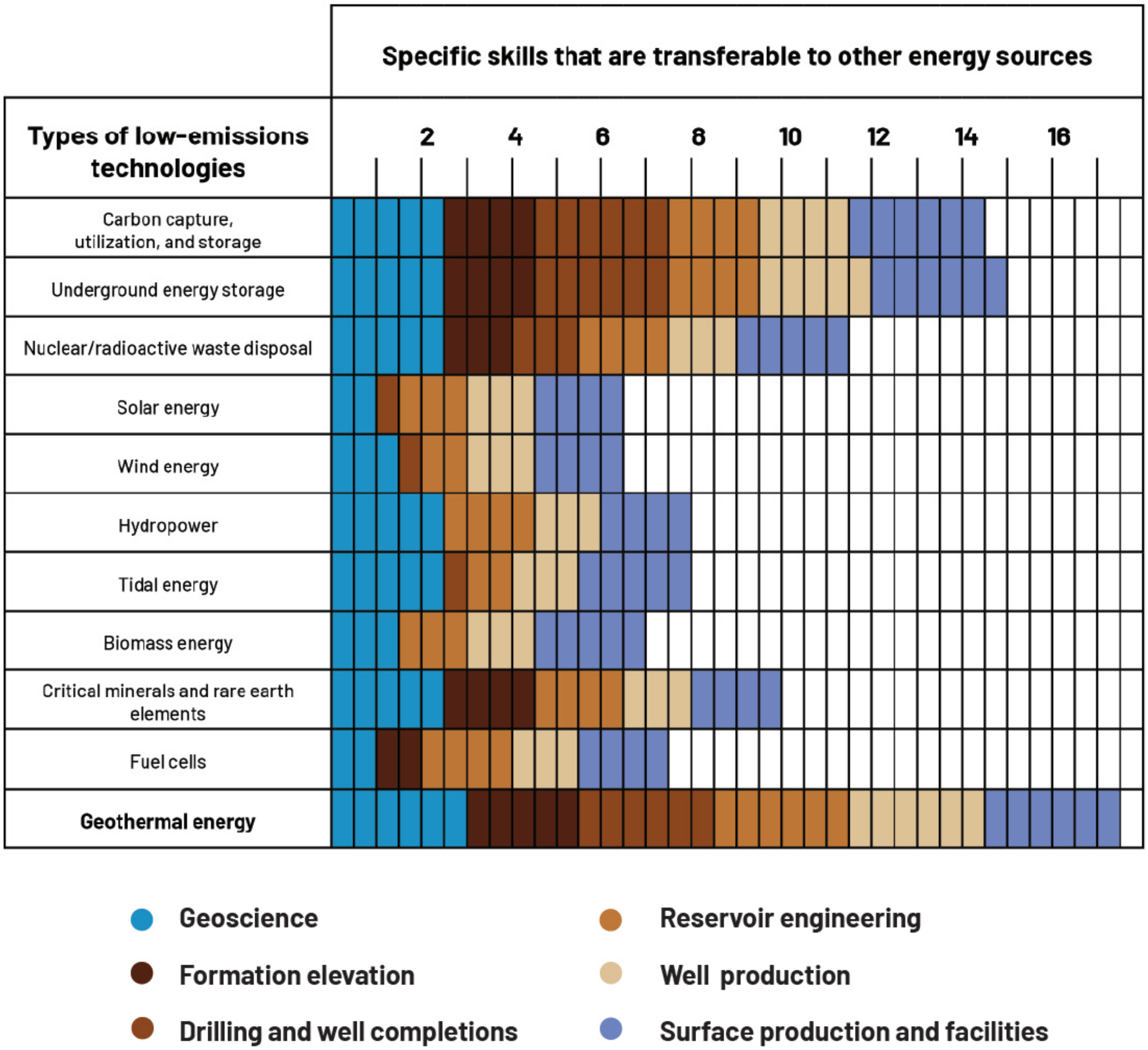

Figure 1.9: REE= rare earth elements. As shown, geothermal ranks highest when considering the potential impact of transferring oil and gas skills into other energy transition and low-carbon technologies. Source: Tayyib, D., Ekeoma, P. I., Offor, C. P., Adetula, O., Okoroafor, J., Egbe, T. I., and E. R. Okoroafor. *Oil and Gas Skills for Low-Carbon Energy Technologies*. Society of Petroleum Engineers Annual Technical Conference and Exhibition, San Antonio, Texas, United States, 2023: https://doi.org/10.2118/214815-MS

THE EVOLUTION OF GEOTHERMAL: FROM CONSTRAINTS TO POSSIBILITIES

As shown in **Figure 1.10**, the Earth's crust contains more potential thermal energy than is present in all fossil fuels and natural nuclear fissile materials combined. The challenge, then, is how to identify the areas and technologies that can tap into that potential energy most efficiently and economically.

Figure 1.11 summarizes the latest geothermal extraction technologies. The following sections describe these technologies in greater detail.

Engineered geothermal system (EGS): This kind of system uses both directional drilling and hydraulic fracturing to create artificial permeability, allowing for the use of geothermal energy far beyond 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.

Although EGS was conceived as early as the 1970s,[20] its scalability has only been 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 is designed to reuse fluids, so the same liquid flows continuously through hot rock in a convective loop.

EGS generally targets shallow hot-rock formations with few natural fractures and limited natural permeability to minimize uncontrolled fluid loss. Well depths can vary depending on where sufficient temperatures and appropriate stress conditions are found.[21]

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 Energy and its Project

HOW ABUNDANT IS GEOTHERMAL ENERGY?

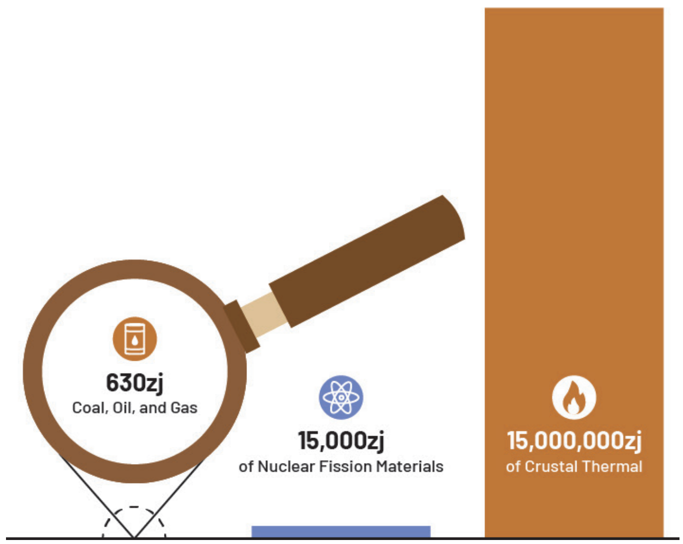

Figure 1.10: Comparison of total heat energy in Earth's crust, compared to fissionable materials and fossil fuels. Note that total fossil fuels, when compared with crustal thermal energy, is the equivalent of less than one pixel at the bottom of the graphic, shown magnified to illustrate scale. Measurements 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.

Red demonstration. Along with advances in tech, EGS is also being scaled for use in industrial-size projects. Fervo recently secured a 400 MW Power Purchase Agreement to construct a first-of-its-kind EGS power plant in Utah that will target approximately 350°F (about 175°C) hot rock.[22]

Advanced geothermal system (AGS): 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 in a "closed loop."

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

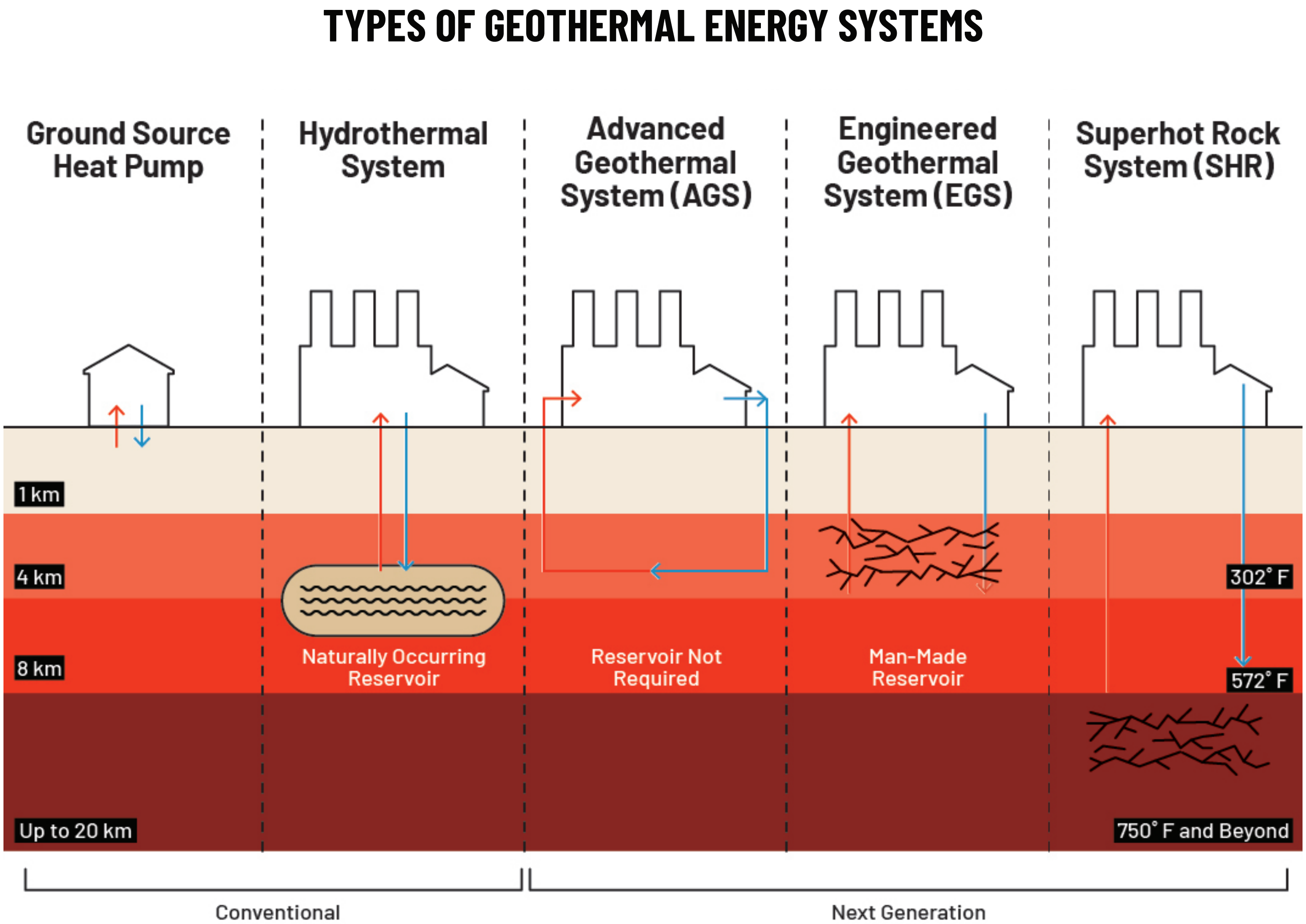

Figure 1.11: Geothermal electricity generation and industrial direct use. Ground source heat pumps shows building heating; the arrows and fluid flow would reverse for building cooling. Adapted from D'avack, F., & Omar, M. (2024, January 11). *Infographic: Next-generation technologies set the scene for accelerated geothermal growth*. S&P Global. 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

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

AGS can be developed in virtually any geological condition with sufficient subsurface heat. While an 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.

Superhot rock (SHR): SHR is a type of next-generation geothermal that targets 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.[23]

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, as well as 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 the following 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 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 has a significant impact 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 described interact to contribute to geothermal energy extraction under three common geological settings:

Convection-Dominated

1. Geologically open geothermal systems: In these systems, water circulates freely (e.g., the Great Basin in the United States). These systems are typically targeted for power generation and open-loop heat.

Conduction-Dominated

2. Geologically closed systems, with limited porosity/ permeability: Water does not flow naturally in these systems, and geothermal energy extraction requires engineered "enhancements" (e.g., hydraulic fracturing).

3. 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**
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 Requirements	Natural hot aquifers in porous rock formations	Typically, sedimentary aquifers but can be used near conventional geothermal systems such as Iceland	No special geology; suitable for almost any location
Temperature Range	302°F-662°F (150°C - 350°C)	Generally, around 176°F-212°F (80°C-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 feet to 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 Advantages	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 center 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

Figure 1.12

	New Geographies, Applications, and Technologies		
	Superhot Rock	**Sedimentary Geothermal System**	**Engineered Geothermal System**
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	Recirculates same fluid (water or otherwise) through fractures in hot rock
Reservoir Type	Open, targeting superhot rock	Open, with naturally porous and permeable rock acting as the reservoir for fluid flow	Open to reservoir with engineered fractures
Geological Requirements	High temperatures (above 703°F/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	703°F/373°C + (targeting supercritical steam)	Can vary (from low ~ 68°F/20°C to > 392°F /200°C)	Typically, 302°F /150°C - 572 °F/300°C
Drilling Depth	Significant depth (potentially 10+ kilometers)	Variable depth range, from 500 meters to 8,000 meters	Typically < 3,000 meters, as high pressure and high drilling would incur additional costs
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 < 3,000 meters and does not contain natural fractures that will increase uncertainty and potential fluid losses
Environmental Impact	High-impact drilling; needs tech improvements for feasibility	Typically low	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, United Kingdom; Paris	Department of Energy's FORGE project, Fervo's Project Red in Utah
Primary Advantages	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 research and development 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 System	**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 Requirements	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 (> 212°F/100°C) to achieve competitive heat extraction	Utilizes both the shallow natural ground temperature (~55°F/13°C) for cooling purposes and the deep ground temperature 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 between 10 feet and 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 impact; relies on pressure management for safe thermal storage
Examples of Use	Various closed-loop designs in development, technologies such as Eavor-Loop and GreenFire Energy's 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, borehole thermal energy storage, and aquifer thermal energy storage
Primary Advantages	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 optimize data center cooling	Provides energy storage to balance renewable power and support grid stability
Challenges	Expensive drilling costs; reduced heat transfer area compared with 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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