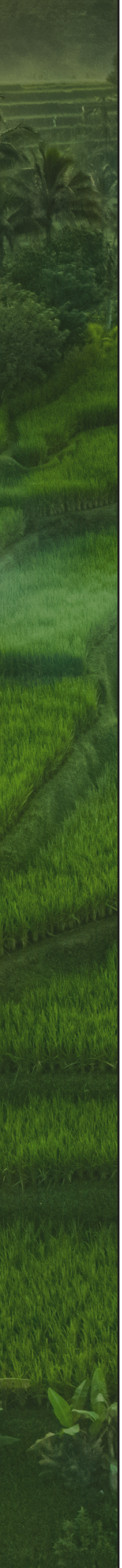
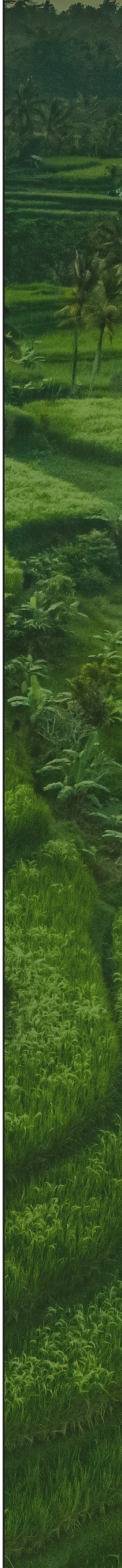


Part I

The Basics of Geothermal



Chapter 1

Geothermal 101: 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 6,400 kilometers from the planet's crust, the core of the Earth is roughly as hot as the surface of the sun—approximately 6,000°C (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 Indonesia, 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

TEMPERATURE OF THE EARTH'S INTERIOR

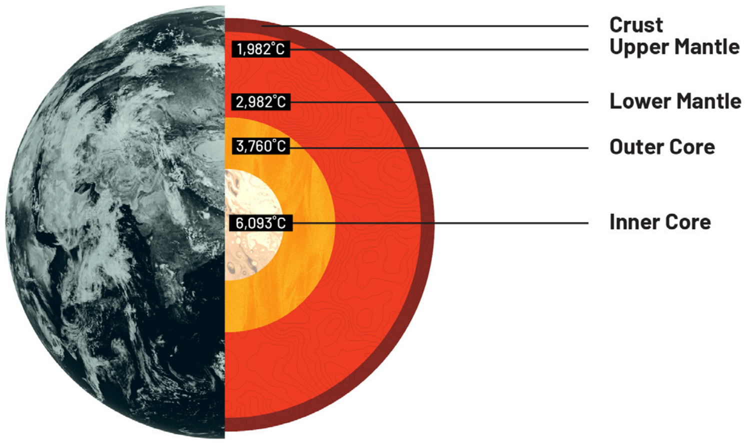


Figure 1.1: The temperature of the core of the Earth exceeds the temperature of the surface of the sun. Because the crust of Earth is an excellent insulator, enough heat is trapped beneath us to power the world thousands of times over. Source: Project InnerSpace.

COMPARING SURFACE FOOTPRINT

Geothermal has the smallest footprint of any renewable energy source

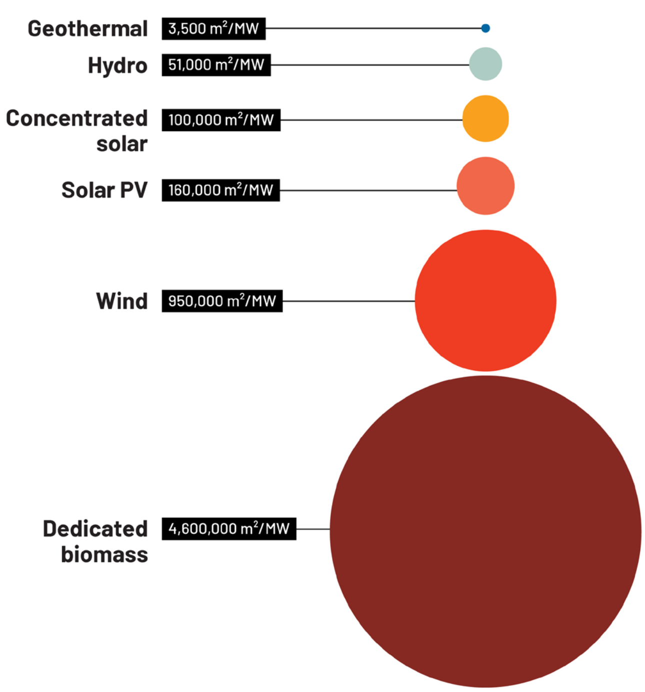


Figure 1.2: The project surface footprint, acre for acre for 1 gigawatt of generating capacity, is smallest for geothermal compared with other renewables and coal. PV = photovoltaic. Source: Lovering, J., Swain, M., Blomqvist, L., & Hernandez, R. R. (2022). [Land-use intensity of electricity production and tomorrow's energy landscape](). *PLOS ONE*, *17*(7), e0270155; National Renewable Energy Laboratory (NREL). (2022). *Land use by system technology*.

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. Add to that, as shown in Figure 1.2, it has the smallest footprint of any power source.

close to the surface. Indonesia is the second-largest producer of utility-scale hydrothermal power in the world, at 2,653 megawatts.[5] Since its first power plant came online in 1983,[6] Indonesia has been a global leader in conventional geothermal electricity production, yet only 5% of the grid is powered by hydrothermal systems, indicating a major opportunity for growth.[7]

But now, adoption of geothermal for various uses can be higher in many other locations as well. How?

Because it is hot everywhere underground, and thanks to technological developments from the oil and gas sector and a new generation of geothermal entrepreneurs, we can now access that heat in regions outside of the sensitive volcanic ecosystems that have previously defined geothermal potential in Indonesia. Geothermal projects that use these technologies are referred to as *next-generation geothermal*. These new approaches—such as advanced geothermal systems and geothermal for cooling—are expanding the future of geothermal energy beyond all of the previous geographical limitations. (See "The Evolution of Geothermal: From Constraints to Possibilities" later in this chapter.)

These newer technologies—directional drilling, deeper drilling, hydraulic fracturing 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—can be very effective for electricity generation. They can enable us to create an artificial heat reservoir.

GEOTHERMAL ELECTRICITY GENERATION

With these new technologies, in general, the hotter the geothermal resource, the more efficient a geothermal power plant will be at producing electricity. The more efficient the production, the lower the cost. As shown in **Figure 1.4**, geothermal electricity generation is possible with fluid temperatures as low as 90°C using "binary" cycle power plants (in other words, two fluid cycles).[8,9] In these binary plants, hot water extracted from the reservoir passes through a heat exchanger to boil a separate low-boiling-point liquid; the vapor from this liquid spins a turbine to make electricity, while the geothermal water never enters the turbine.[10] Both fluids circulate in closed loops—the working fluid is cooled and reused, and the geothermal water is reinjected—keeping emissions to a minimum while enabling power generation from low to moderate temperatures. Flash steam and dry steam electric turbines (see **Figure 1.5**) can be used when the fluid temperature rises above 180°C.[11] 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."[12] That analysis also notes that by 2035, geothermal could be highly competitive with solar photovoltaics and wind when paired with battery storage.

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.[14] 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).

In Indonesia, the cooling and heating of buildings consumes about 60% of all energy use in both residential and commercial sectors.[15] The good news is that

COMPARING CAPACITY FACTOR

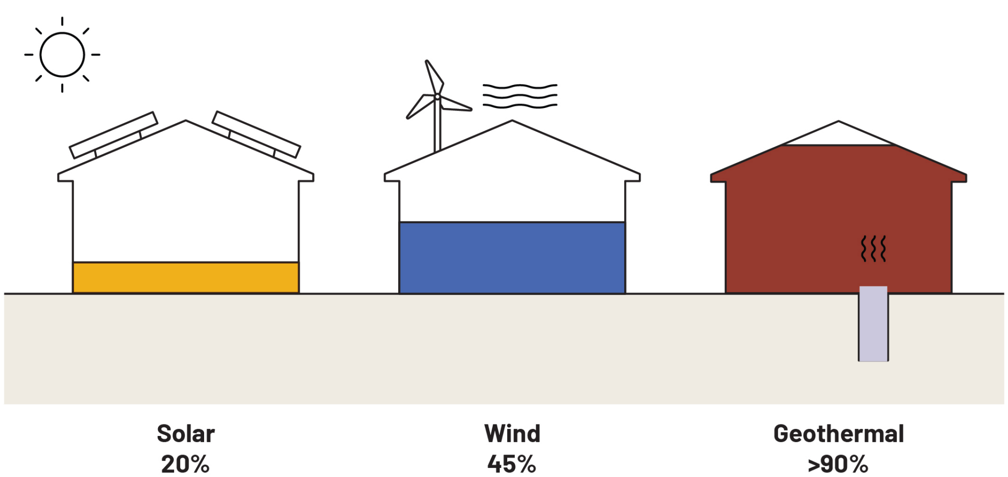


Figure 1.3: Capacity factor is the percentage of time that a power plant is generating electricity in a given day. Source: Adapted from International Energy Agency (IEA). (2024). [The future of geothermal energy](). IEA.

GEOTHERMAL APPLICATIONS AND TEMPERATURE REQUIREMENTS

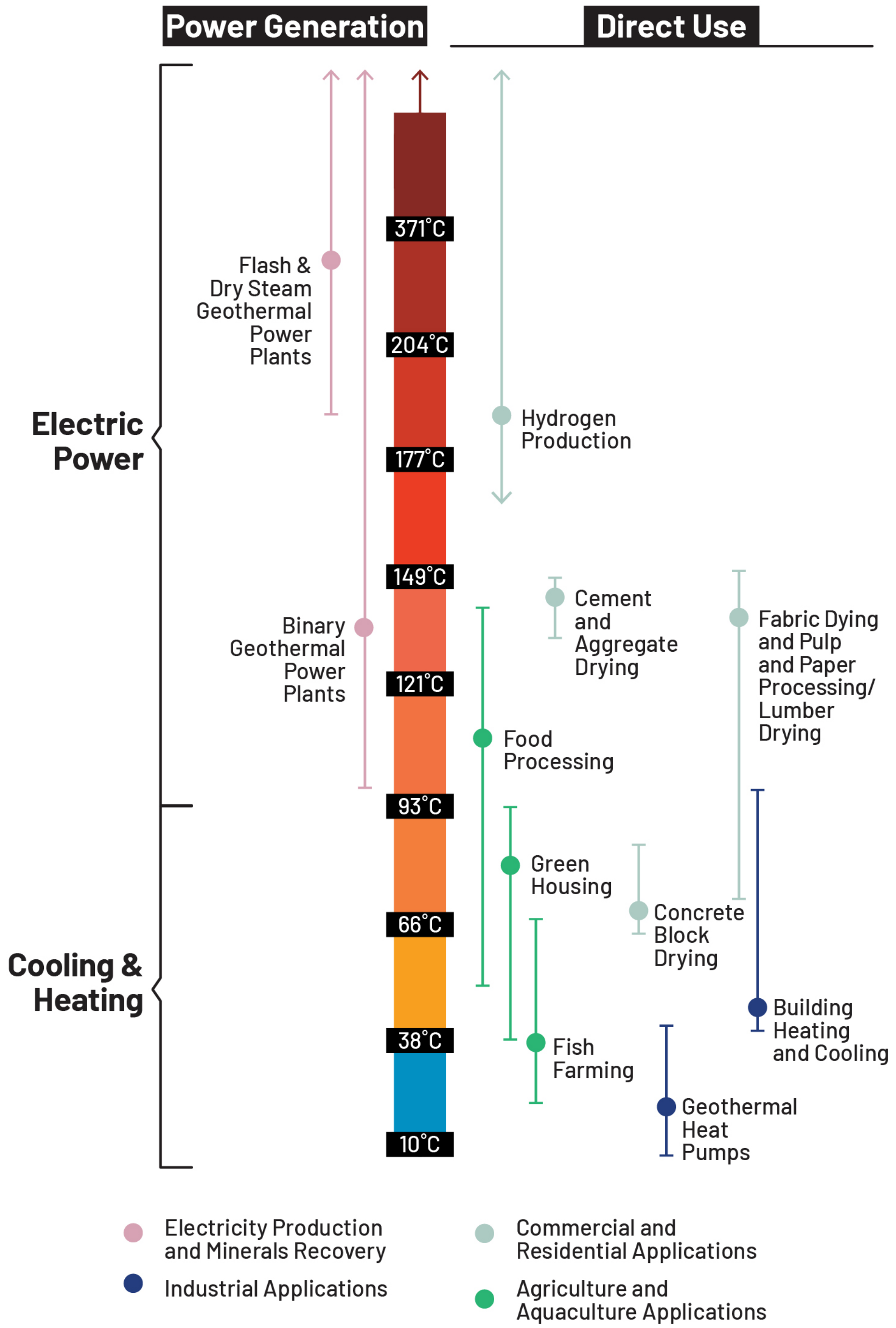


Figure 1.4: Geothermal energy can be used for generating electricity, heating and cooling homes and offices, and manufacturing. There are also new and emerging applications such as geothermal energy storage, where the subsurface serves as an earthen battery, and geothermal critical minerals extraction, for rare elements such as lithium. Source: Adapted from Porse, S. (2021). *Geothermal energy overview and opportunities for collaboration*. Energy Exchange.

TYPES OF GEOTHERMAL ELECTRICITY GENERATION

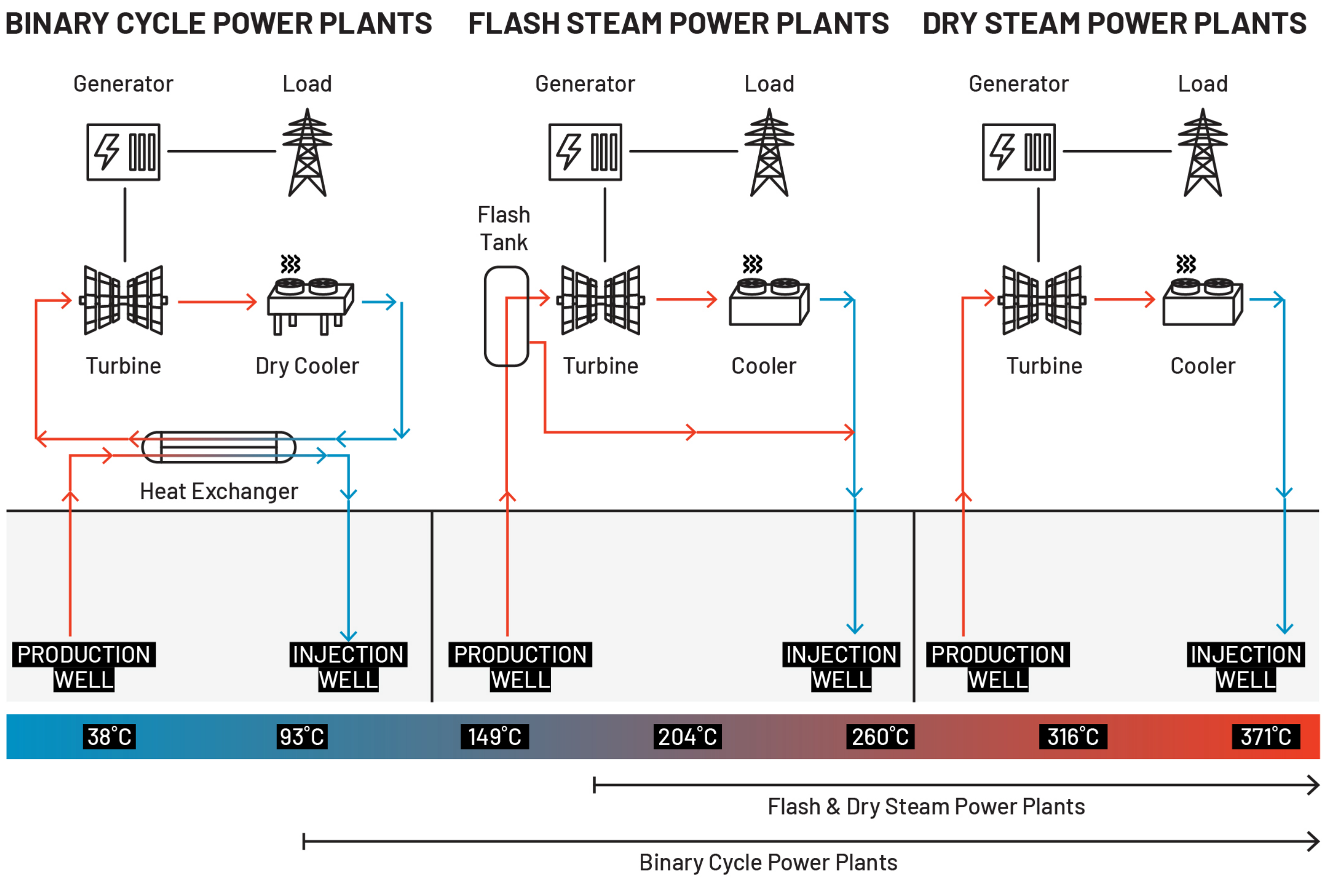


Figure 1.5: There are three primary configurations for generating electricity using geothermal: binary, flash, or dry steam. In general with these new technologies, the hotter the underground geothermal resource—whether conventional hydrothermal or next-generation geothermal—the more efficient the surface equipment will be at producing electricity. Binary geothermal electricity generation is possible with fluid temperatures as low as approximately 95°C. Flash and dry steam geothermal electric turbines can be used when fluid temperature rises above 182°C. 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.

Globally, heat energy makes up about half of all energy consumption and contributes to about 40% of energy-related emissions.[13] 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.

geothermal technologies that can help meet this demand already exist: ground source heat pumps (geothermal heat pumps; see **Figure 1.6**), geothermal district cooling (large-scale connected heat pumps that are also known as *thermal energy networks*, or TENS), and absorption chillers (see the chapter on direct-use geothermal in this report for more information).

Industrial process heat is used to make everything from pens to paper, pasteurized milk to pharmaceuticals. Four of

GEOTHERMAL COOLING AND HEATING NETWORK

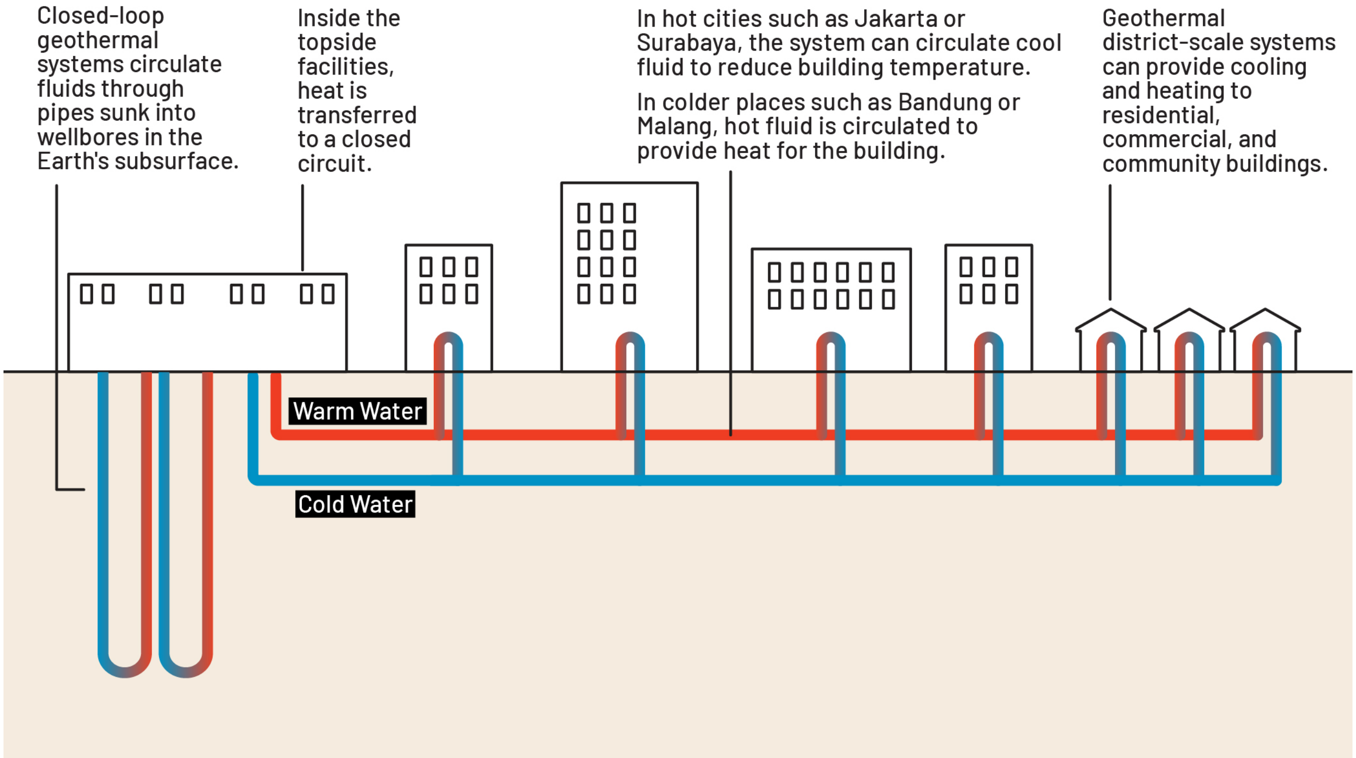


Figure 1.6: District cooling system fluid is typically brought to the surface at a target temperature of around 21°C. That fluid is then passed through a heat pump to provide cold water in the summer for cooling and hot water in the winter for heating. This style of cooling and heating can be more than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

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.[16]

All building cooling and heating (heating, ventilating, and air-conditioning; HVAC) and 30% of heat used for manufacturing processes worldwide use temperatures below 150°C.[17] 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 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.[18] **Figure 1.7** illustrates the range of sectors and processes that could use geothermal heat, with or without heat pumps, depending on whether a facility can reach the necessary heat at a reasonable subsurface depth.

Beyond space conditioning, geothermal energy can be used for refrigeration and commercial cooling operations, via a technology known as an *absorption chiller.* Absorption chillers are cooling systems that mainly use heat instead of electricity to drive refrigeration.

As illustrated in **Figure 1.9**, low-pressure liquid ammonia draws heat out of a cold storage or air-conditioned space, turning the ammonia into low-pressure vapor. This vapor is then absorbed by water, creating an ammonia solution,

INDUSTRIAL PROCESS TEMPERATURES AND HEAT PUMP TECHNOLOGIES

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

Temperature scale: 40, 60, 80, 100, 120, 140, 160, 180, 200

- Conventional heat pump less 80°C, established in industry
- Commercially available high-temperature heat pump 80°C-120°C
- Prototypes and technology demonstration, 120°C+
- Ongoing laboratory research and development, 150°C+

Figure 1.7: Rough technology readiness levels of high-temperature heat pumps as of July 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. Sources: Arpagaus, C., et al. (2023). *Industrial heat pumps: Technology readiness, economic conditions, and sustainable refrigerants*. American Council for an Energy-Efficient Economy (ACEEE).

COOLING AND HEATING WITH GROUND SOURCE HEAT PUMPS

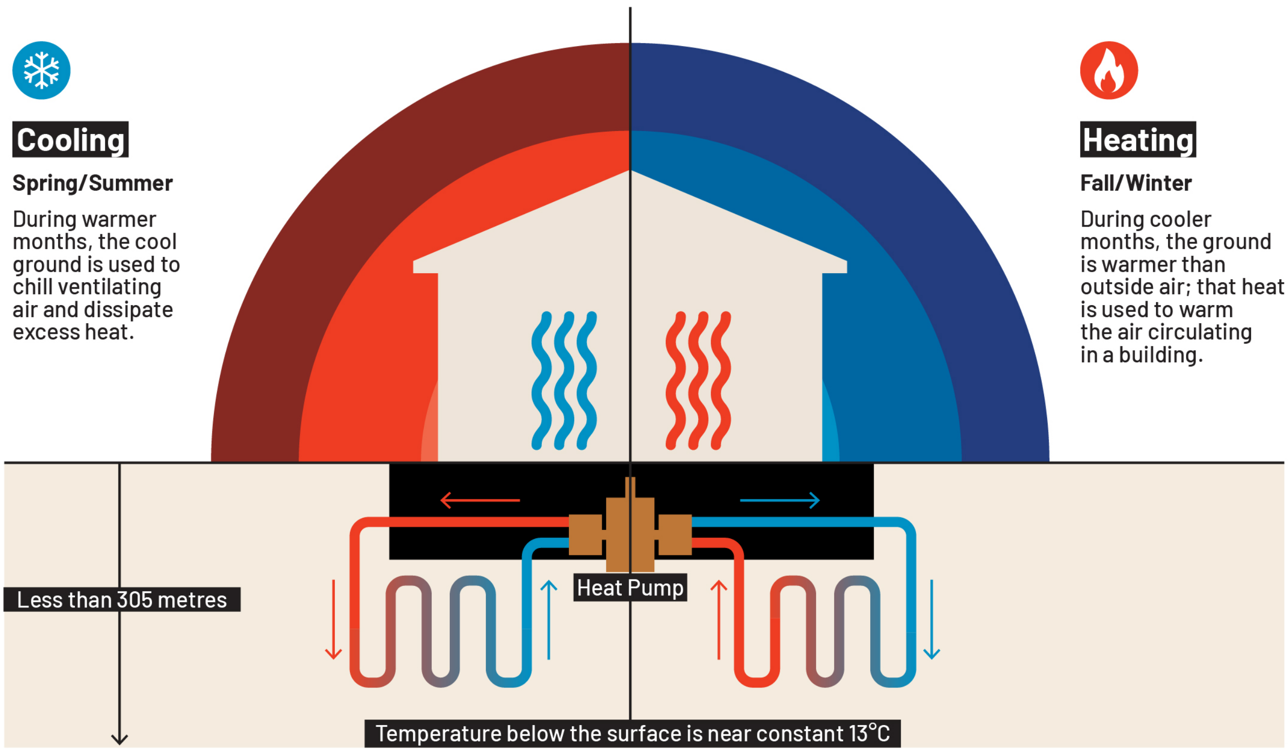


Figure 1.8: The constant temperature of the ground helps improve the efficiency of ground source heat pumps relative to other HVAC methods. Source: Beard, J. C., & Jones, B. A. (Eds.). (2023). *The future of geothermal in Texas: The coming century of growth and prosperity in the Lone Star State*. Energy Institute, University of Texas at Austin.

which is then pumped to a generator. There, geothermal heat can be used to boil the pressurized ammonia solution into high-pressure ammonia vapor, which will reject the heat into a cooling tower and turn it into low-pressure liquid ammonia to repeat the cooling cycle again.

By harnessing the Earth's heat in this way, absorption chillers provide cooling without the need for conventional electric compressors or burning fossil fuels. For Indonesia, where cooling already consumes between 40% and 60% of electricity in major cities,[19] geothermal absorption chillers offer a sustainable solution to meet the country's refrigeration and air-conditioning needs while easing the burden on the power grid and reducing greenhouse gas emissions.

GEOTHERMAL ENERGY STORAGE

The modern electricity grid is a delicate, vital system requiring constant monitoring to balance electricity production against electricity demands. With more 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 needed have highlighted the need for energy storage.[20] Today, hydroelectric storage provides most global energy storage capacity,[21] 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 (e.g., aquifers, boreholes, mines). GES can be primarily mechanical, with hydraulic fracturing techniques storing pressurized fluid in subsurface reservoirs. Or it can be mechanical and thermal, with 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 reduce lithium extraction's environmental impact compared with traditional mining and improve the economics of a geothermal project.

At the Dieng Geothermal Field in Central Java, geothermal brines are moderately to highly saline and contain measurable concentrations of lithium and other dissolved minerals. Traditionally, these minerals were viewed as operational challenges, requiring costly mitigation to prevent scaling and mineral buildup that could obstruct fluid flow and damage infrastructure. Today, however, 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. A pilot project led by PT Geo Dipa Energi is exploring the feasibility of extracting lithium from Dieng's geothermal brine. Early estimates suggest the reservoir could yield up to 2,200 tons of lithium annually.[22]

ABSORPTION CHILLERS

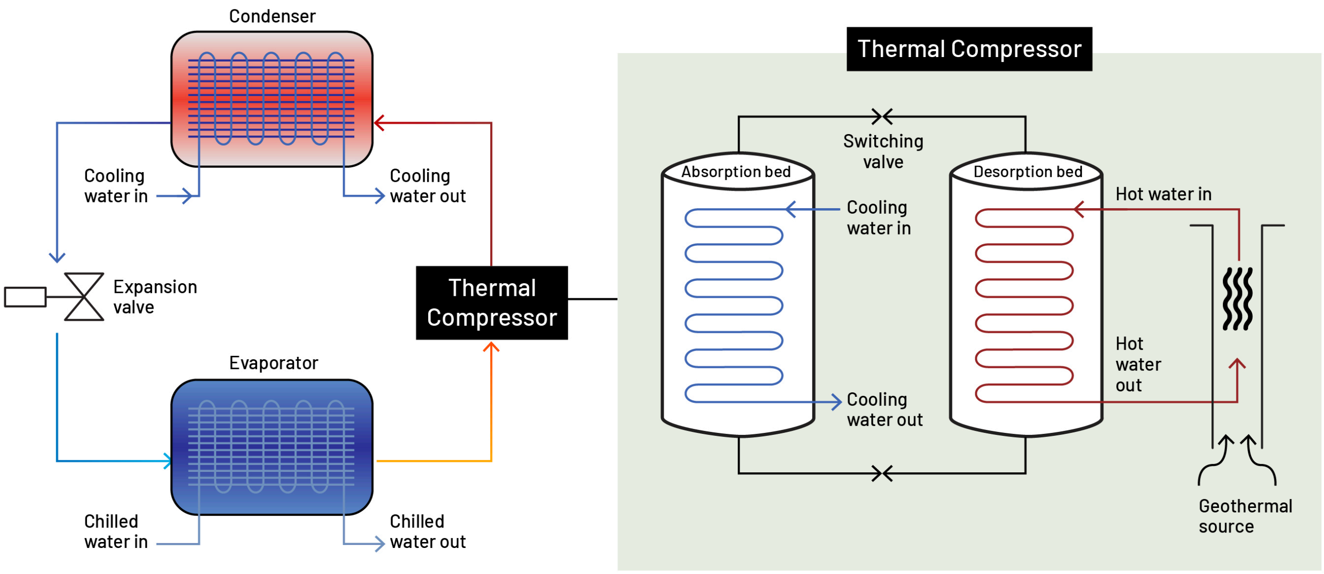


Figure 1.9: Energy flow and balance in the absorption coolers. Source: Modified from Ebrahimi, M., & Keshavarz, A. (2015). [CCHP technology](). In *Combined cooling, heating and power: Decision-making, design and optimization* (pp. 35–91). Elsevier.

TRANSFERABLE SKILL SETS FROM THE OIL AND GAS INDUSTRY

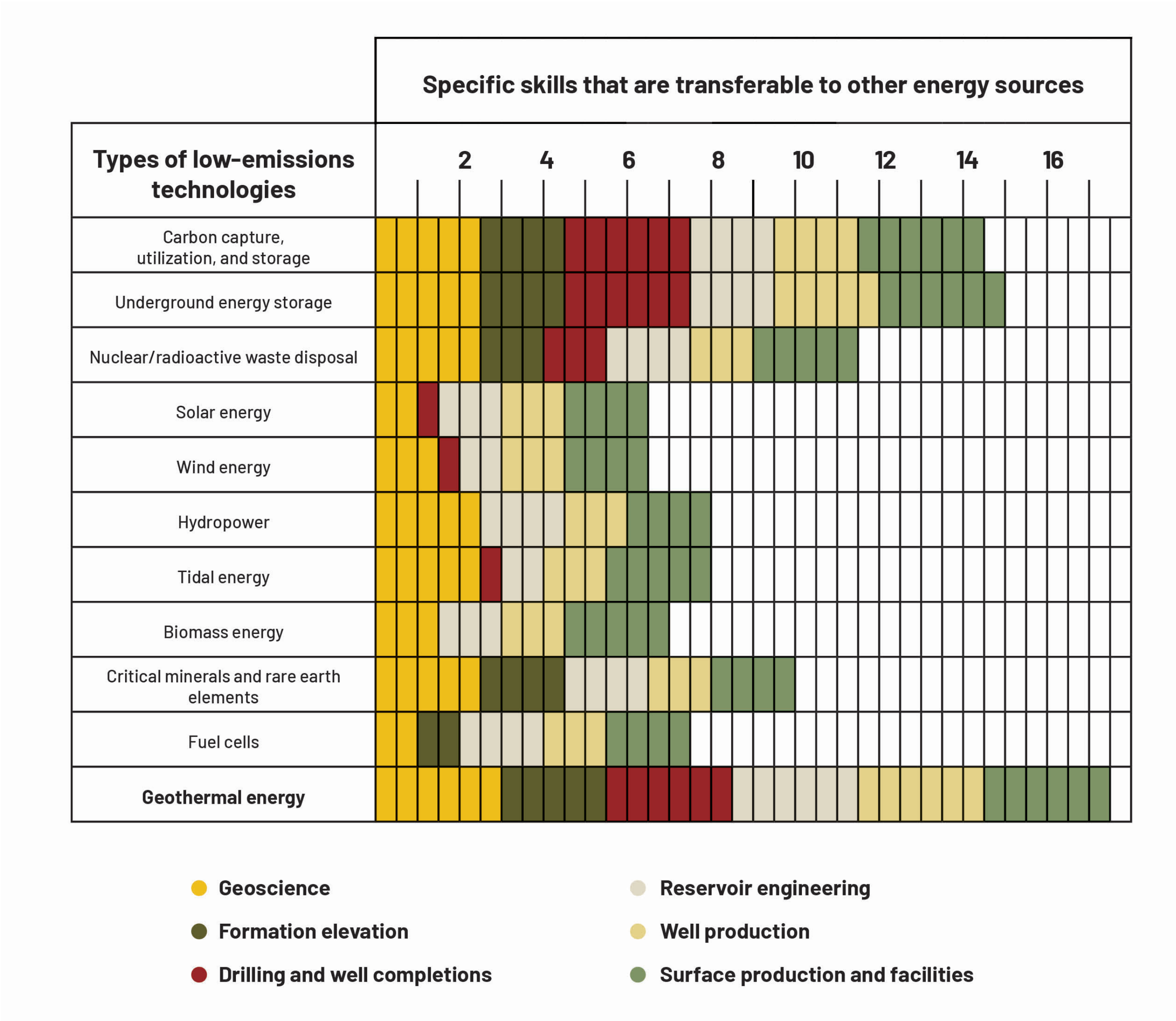


Figure 1.10: As shown, geothermal ranks highest when considering the potential impact of transferring oil and gas skills into other energy transition and low-carbon technologies. Source: Tayyib, D., Ekeoma, P. I., Offor, C. P., Adetula, O., Okoroafor, J., Egbe, T. I., & Okoroafor, E. R. (2023). *Oil and gas skills for low-carbon energy technologies.* *Society of Petroleum Engineers Annual Technical Conference and Exhibition*.

As shown in **Figure 1.11**, the Earth's crust contains more potential thermal energy than is present in all fossil fuels and natural nuclear fissile material combined. The challenge, then, is how to identify the areas and technologies that can tap into that potential energy most efficiently and economically.

Figure 1.12 summarizes the latest geothermal extraction technologies. The following sections describe these technologies in greater detail.

Advanced geothermal system (AGS): Like an engineered geothermal system (EGS), an AGS eliminates the need for permeable subsurface rock. Instead, an 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 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.

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 an EGS, which benefits from the substantial surface area created by hydraulic fracturing, an AGS has only the walls of its wells to conduct heat. As such, an AGS must drill deeper, hotter, or longer well systems than an EGS to conduct similar amounts of heat energy. Because an AGS does not exchange fluids with the subsurface, it can more easily use engineered, nonwater working fluids, such as supercritical CO_2. Along with advances in technology, the AGS is also being scaled for use in industrial-size projects. XGS Energy and Meta recently partnered to construct a first-of-its-kind 150 megawatt AGS power plant in the United States that will target approximately 250°C hot rock to deliver power for data center projects in New Mexico.[23]

An 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.

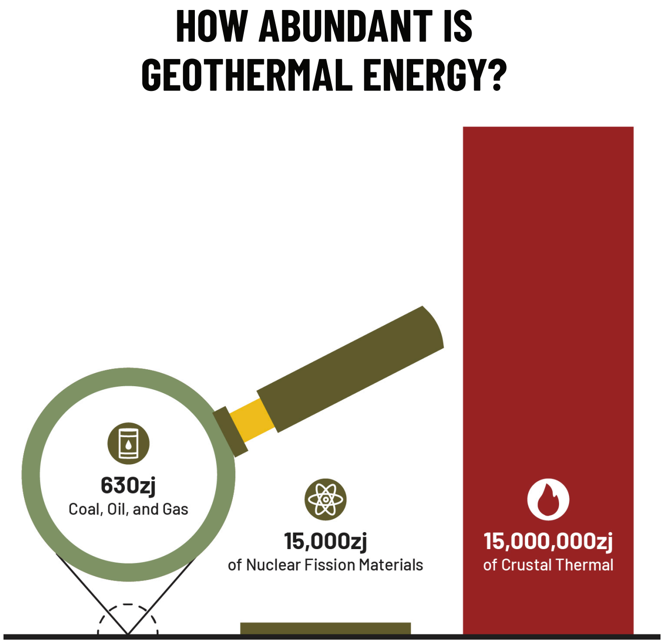


Figure 1.11: Total heat energy in Earth's crust, compared to that contained in fossil fuels and naturally occurring fissile materials. Note that total fossil fuels, when compared with crustal thermal energy, is the equivalent of less than one pixel at the bottom of the graphic, shown magnified to illustrate scale. Measurements in zettajoules (zj). Source: Beard, J. C., & 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. Adapted from Dourado, E. (2021). *The state of next-generation geothermal energy.*

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 the regions with naturally occurring hydrothermal. An 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 there are, the greater the surface area for the flowing fluid to conduct heat from rock.

Although the EGS was conceived as early as the 1970s,[24] 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—an EGS

TYPES OF GEOTHERMAL ENERGY SYSTEMS

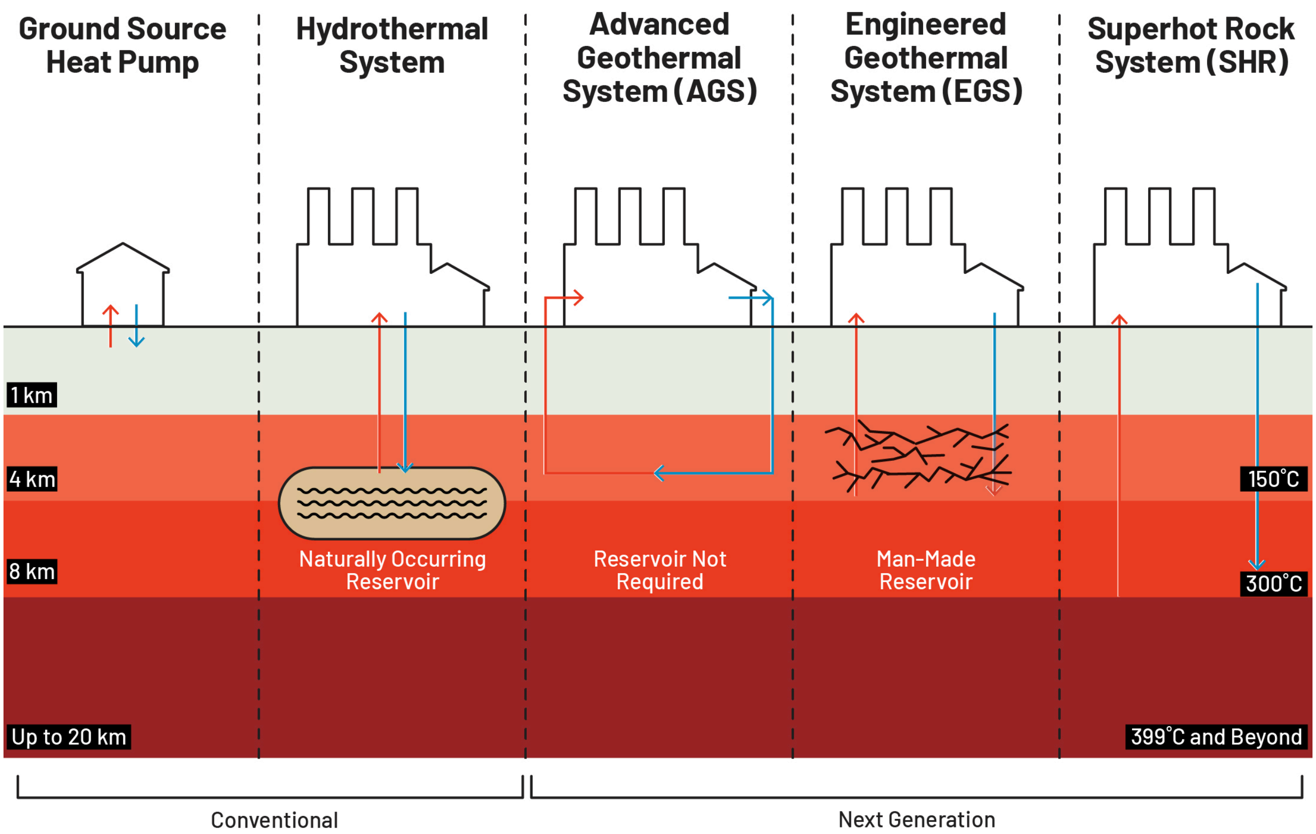


Figure 1.12: Comparison of key geothermal power generation technologies illustrating variations in resource type and heat extraction method for electricity production and industrial direct use. Ground source heat pumps (GSHPs) are also shown, illustrating a building heating scenario. In the GSHP scenario, fluid flow can be reversed to provide cooling. Source: Adapted from D'avack, F., & Omar, M. (2024). *Infographic: Next-generation technologies set the scene for accelerated geothermal growth*. S&P Global.

is designed to reuse fluids, so the same liquid flows continuously through hot rock in a convective loop.

An 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.[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. Because of Indonesia's location along the volcanically active Sunda Arc, it already hosts abundant high-enthalpy hydrothermal resources with natural permeability.[26] In this context, an EGS is less suited for the near term, while scaling hydrothermal and AGS pilots will better match Indonesia's geology and community considerations.

Superhot rock (SHR): SHR is a type of next-generation geothermal that targets extremely deep, high-pressure rocks above approximately 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]

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 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 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, such as 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.

Existing 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	150°C - 350°C	Generally, around 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 between 3 meters and 152 meters 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 1.13: Existing and new geographies, applications, and technologies.

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 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, 50°C -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 (> 100°C) to achieve competitive heat extraction	Utilizes both the shallow natural ground temperature (~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 3 meters and 152 meters, 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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