

10 March 2026

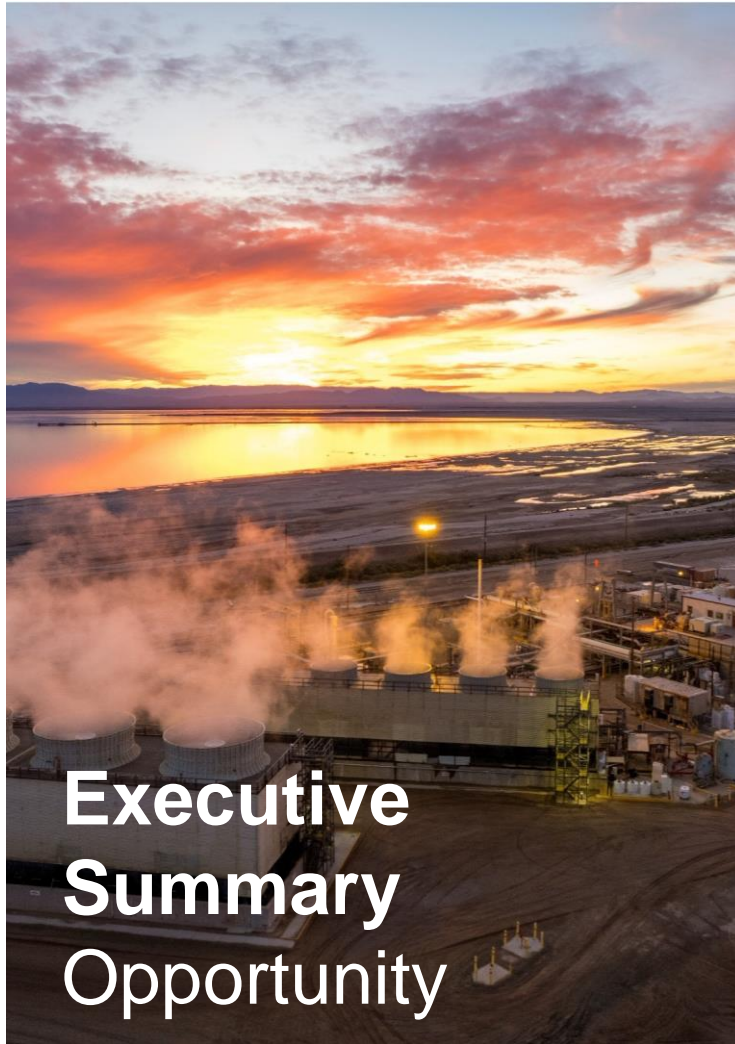
Geothermal Heating and Cooling

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Cooling,” Columbia Business School Climate
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Geothermal Opportunity



Nearly 80% of geothermal energy today is used for heating and cooling (42% heat pumps, 26% district heating systems), not electricity generation. Deployment is **concentrated in 10 countries** accounting for **90% of global use**, with **China alone representing 50%** of all heating and cooling capacity.

Geothermal heating and cooling is a mature, proven technology that is projected to **double by 2050** through residential and district heating expansion, with significant untapped potential for **decarbonizing building thermal loads**.

Geothermal electricity currently supplies **less than 1%** of global power, with conventional installations limited to **~16 GW** in key geographic areas. Yet, **geothermal energy reserves** are multiples larger than all known oil and gas reserves, with the technical potential to meet global electricity demand **140 times over**.

Global energy demand is projected to rise **10 to 20% by 2050**, driven by growth in emerging economies, electrification, and AI data center expansion. This demand is creating urgent need for **firm, reliable, round-the-clock clean power**, a role geothermal is uniquely positioned to fill.

Next-generation technologies including horizontal drilling, enhanced geothermal systems, closed-loop systems, and AI-enabled exploration are expanding geothermal's reach to virtually every region around the globe, overcoming the geographic constraints that limit conventional geothermal today while reducing costs.

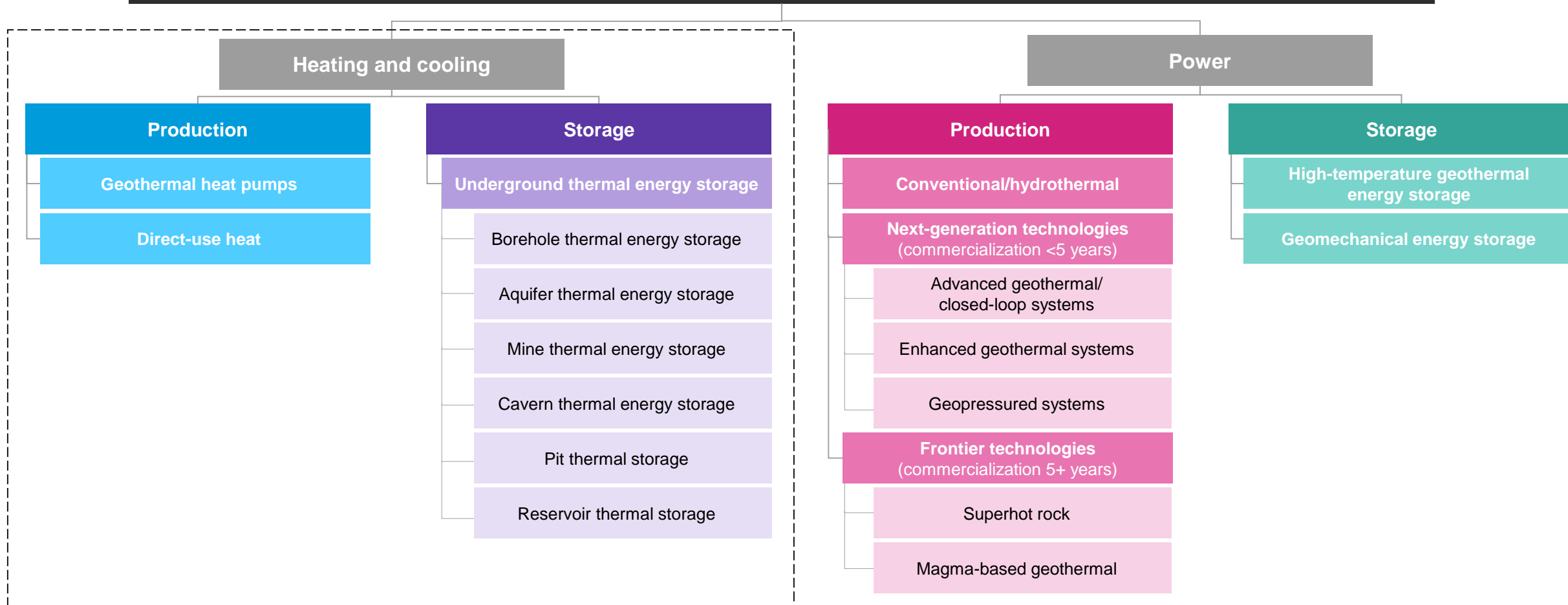
Technological, policy, and financial synergies with the oil and gas industry can dramatically reduce costs and accelerate deployment, particularly by applying advanced subsurface modeling to reduce **exploratory drilling risk**, the highest barrier in project development.

With continued innovation and cost declines, geothermal could become cost competitive with solar and wind plus storage by 2035 and meet **up to 15% of global electricity demand growth by 2050**, representing **800 GW of capacity** and **6,000 TWh annually**.

Geothermal electricity will play an outsized role in select markets, supplying **5 to 45% of power generation** in countries like the U.S., Kenya, the Philippines, and Indonesia.

Geothermal energy technologies span heating & cooling and power generation, with conventional approaches most widely deployed

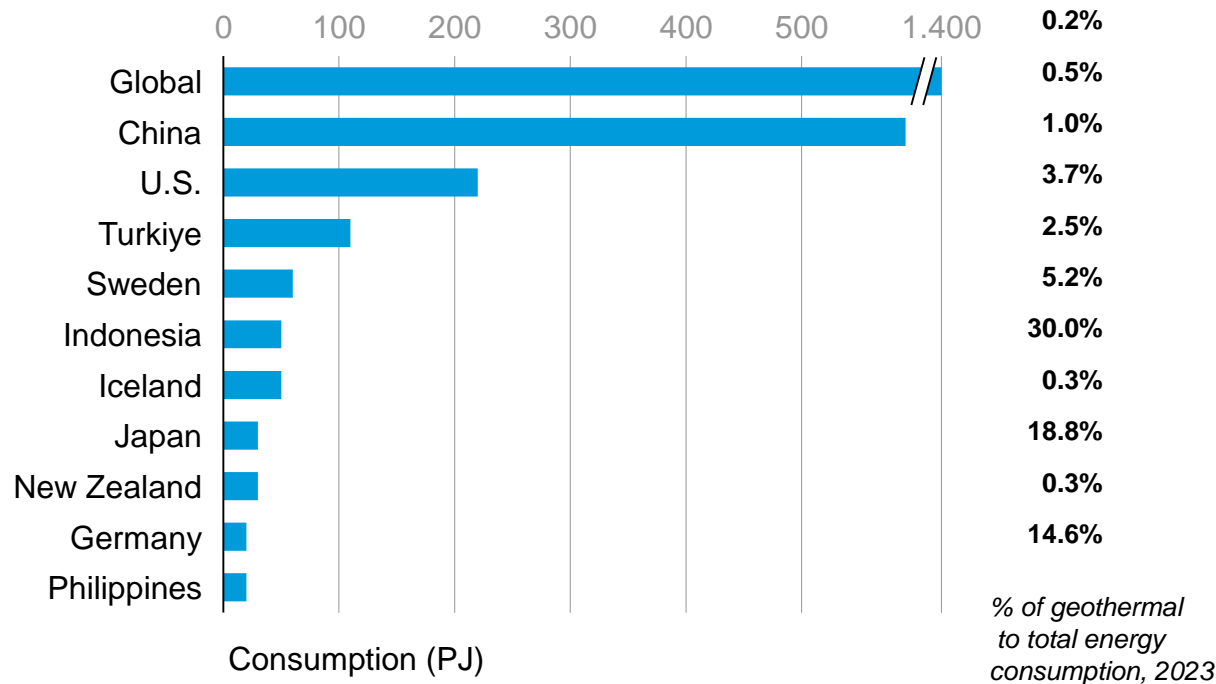
Key pathways for harnessing geothermal energy for heating & cooling and power generation



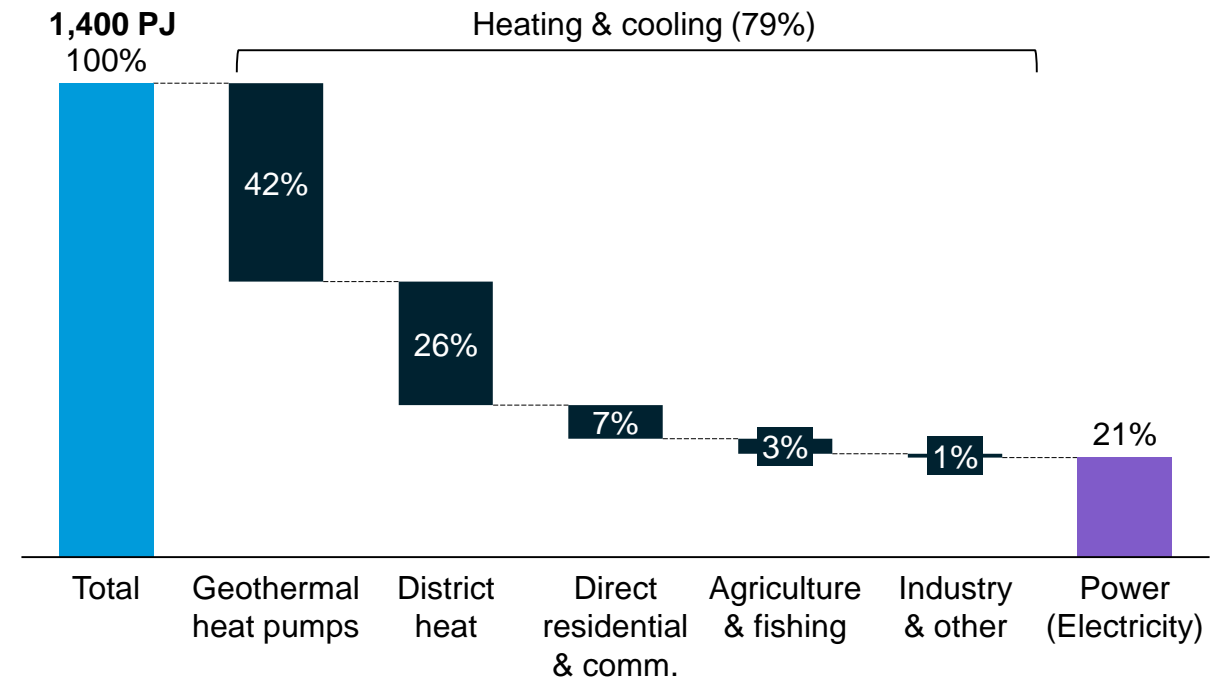
Sources: [Underground Thermal Energy Storage](#) (Nature, 2012); [Pathways to Commercial Liff-off: Geothermal Heating and Cooling](#) (DOE, 2024); [The Future of Geothermal Energy](#) (IEA, 2024).
 Credit: Sevgi Helin Tilkicioglu, Una Oljaca, Pia Doris Morrow, Isabel Hoyos, Hya Ryung Kim, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Today, 10 countries consume 90% of global geothermal energy, with almost 80% of end use for heating and cooling

Total final geothermal energy consumption by consuming countries, 2023



Total final geothermal energy consumption by application, 2023



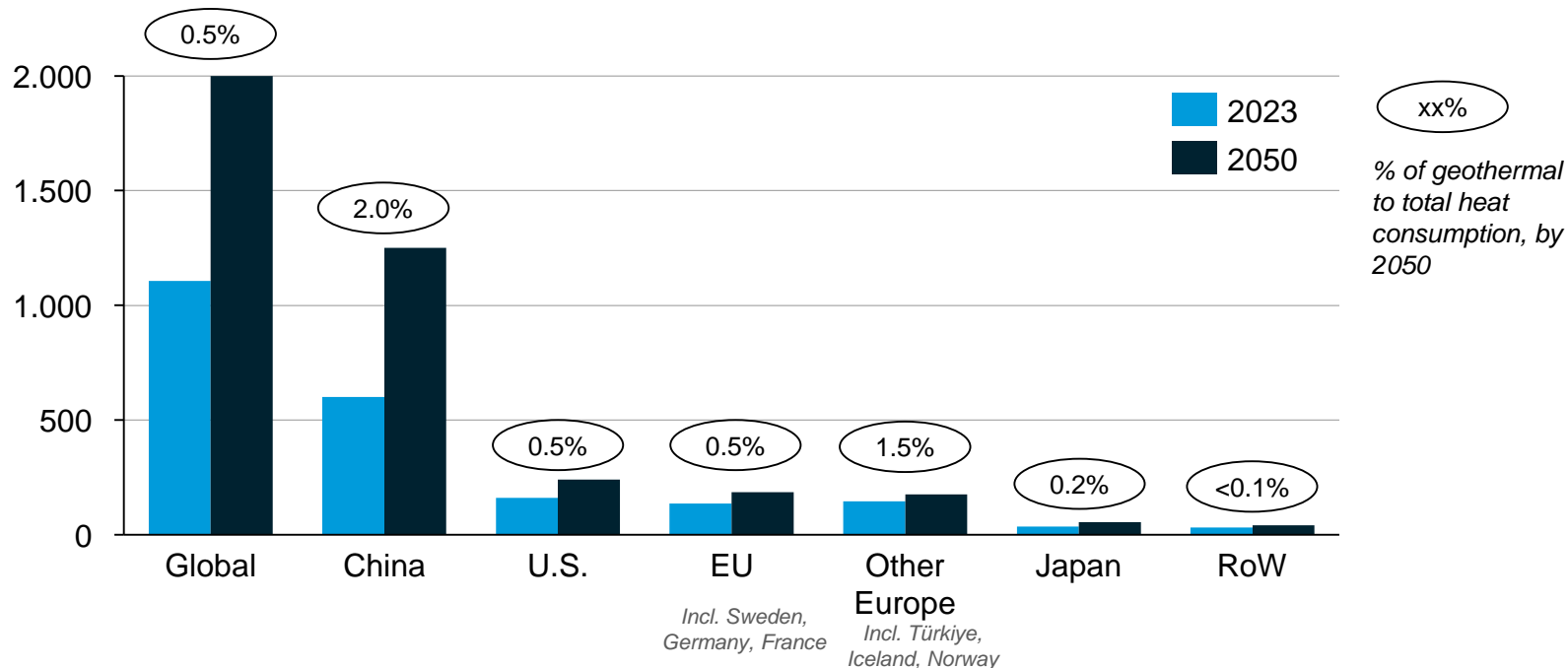
- **Heating:** **China** is the most significant country, accounts for nearly 50% of global geothermal final energy consumption, dedicated entirely to **space heating**.
- **Electricity:** The **U.S., Indonesia, Türkiye, the Philippines, and New Zealand** generate **two-thirds of global geothermal electricity**, with **Iceland, Italy, Kenya, Mexico, and Japan** contributing an additional 25%.

Sources: [The Future of Geothermal Energy](#) (IEA, 2024).

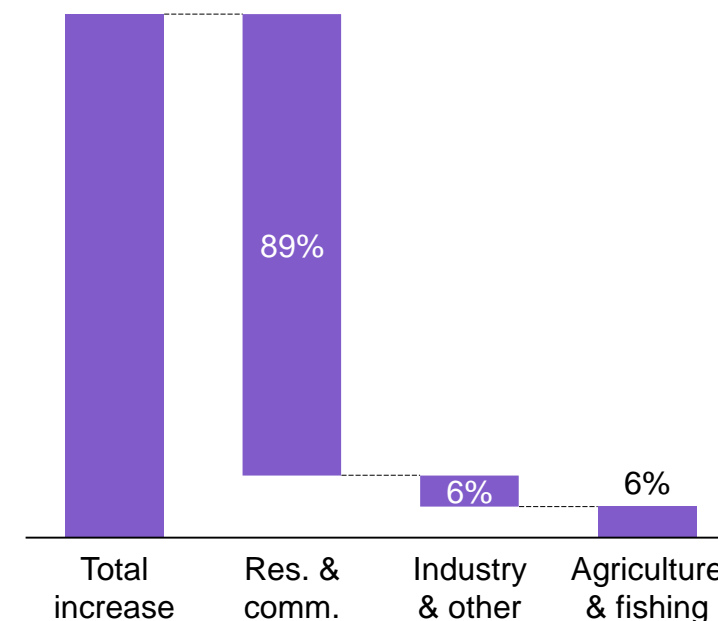
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By 2050, geothermal heating use is projected to almost double, driven largely by China and building and district heating

Geothermal heating consumption (PJ), projection by region 2023-2050



Increase (%) by heating application globally, 2023-2050



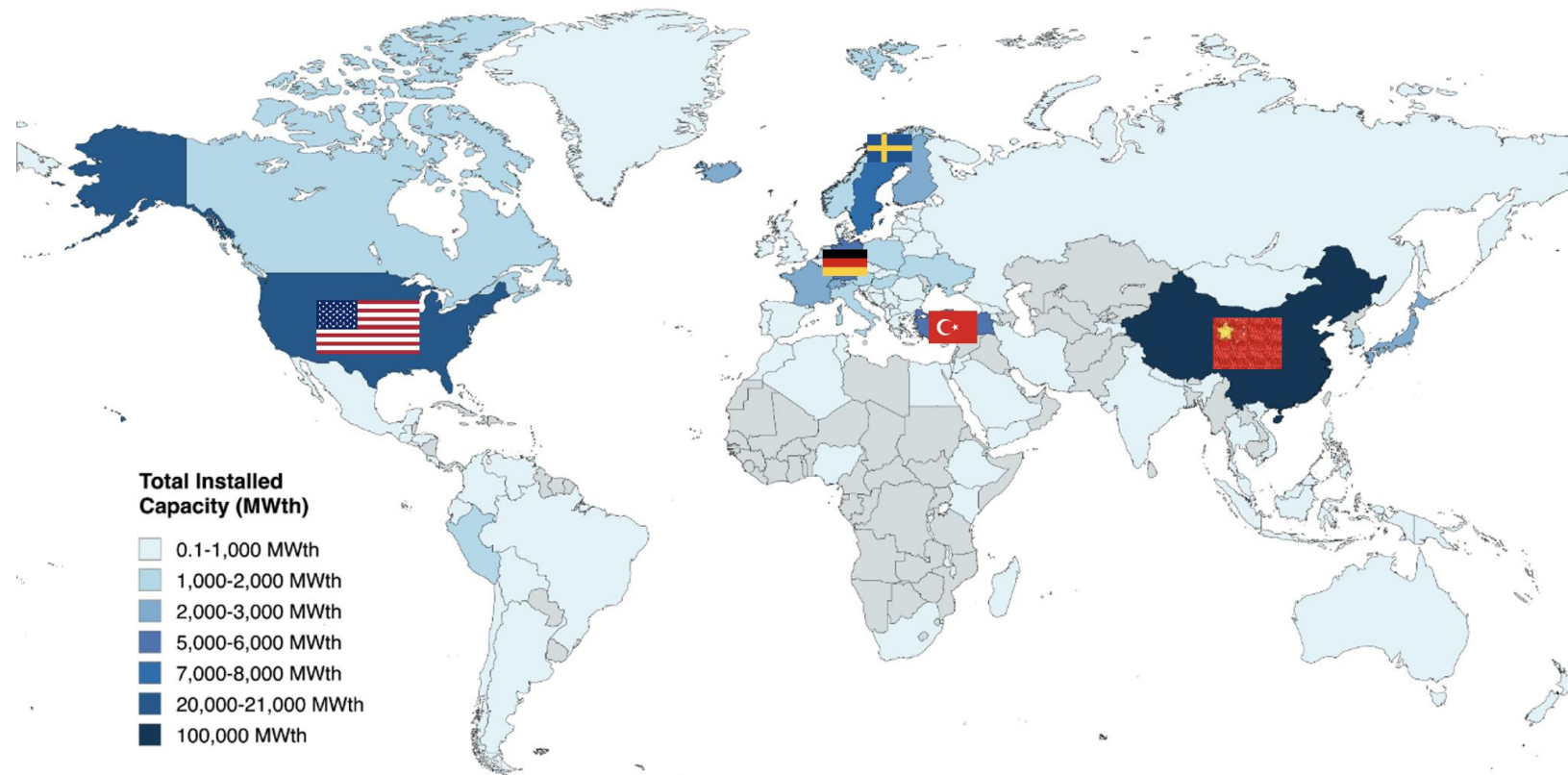
- Geothermal heating use **doubles in 2050** under a realistic government Stated Policies Scenario (STEPS), with China as the biggest source of growth. Yet, it remains **only 0.5% of total heat consumption globally**.
- From the use-case perspective, nearly **90% of geothermal heating consumption comes from residential and commercial buildings**, mainly through district heating networks, including thermal baths in the tourism and wellness sector.

Sources: [The Future of Geothermal Energy](#) (IEA, 2024).

Credit: Faradisa Anintya, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al. "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Global geothermal heating and cooling capacity is ~173,300 MW_{th}, with over 50% of global installed capacity in China

Global geothermal heating & cooling installed capacity, MW_{th}



Largest installed capacity per capita (KW _{th})	
Iceland	7.177
Sweden	0.69
Finland	0.41
Switzerland	0.27
Norway	0.21

Observations

- **China holds over 50%** of installed capacity, and the **10 largest consumers** account for ~90% of the global total.
- **Europe is expected to scale** as a result of the EU Green Deal.
- **Geothermal heat pumps account for 72% of installed capacity**, while 28% is direct use.
- **Global geothermal potential** up to 3 km and >90°C is ~320 TW, while the potential for <90°C increases 10x.

Sources: [Geothermal Energy Database](#) (International Geothermal Association, 2024); [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [World Bank](#) (2023); [Geothermal Energy](#) (European Commission, 2020).
 Credit: Una Oljaca, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

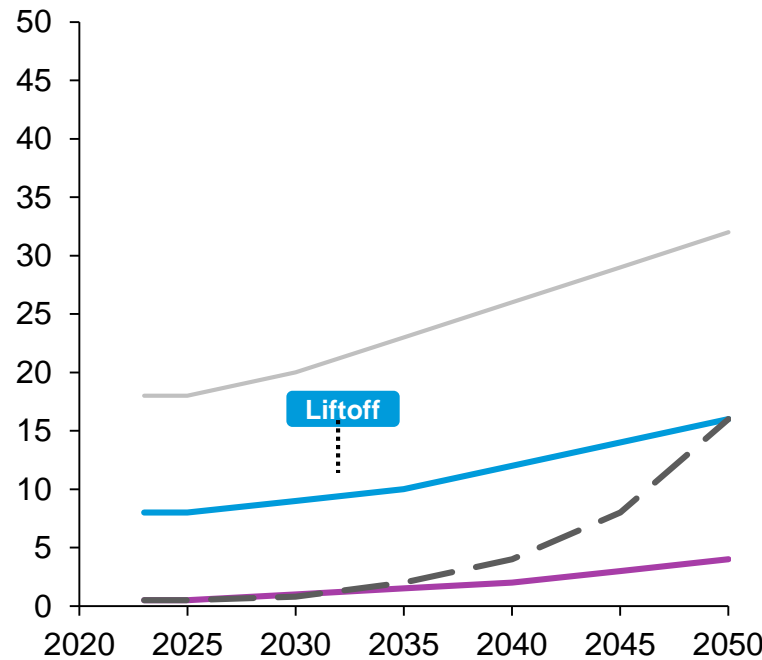
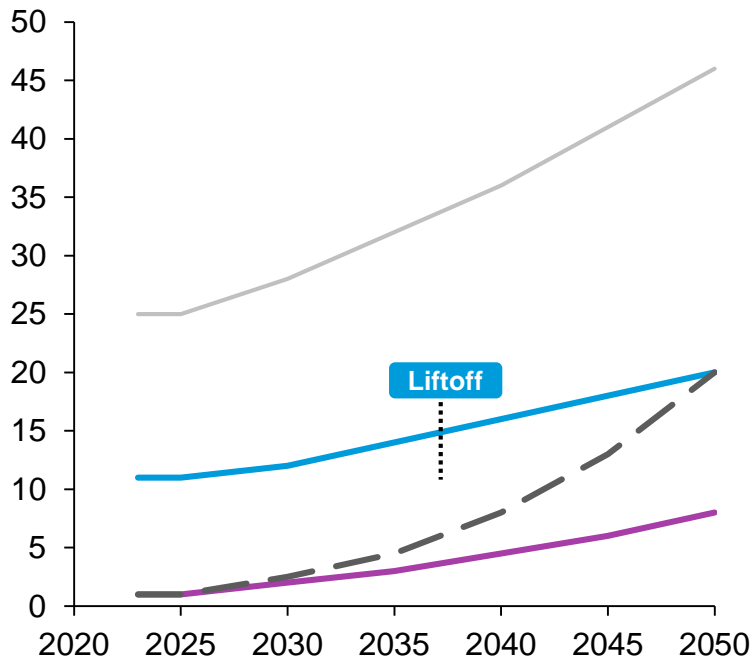
GSHPs could reach millions of U.S. homes by 2050, enabled by tax incentives, business innovation, and workforce development

Total U.S. residential potential (million homes equivalent)

Total U.S. commercial potential (million homes equivalent)

— Economic potential — Market potential — Expected installation — Liftoff trajectory

(baseline)



Observations: Key drivers to successful liftoff

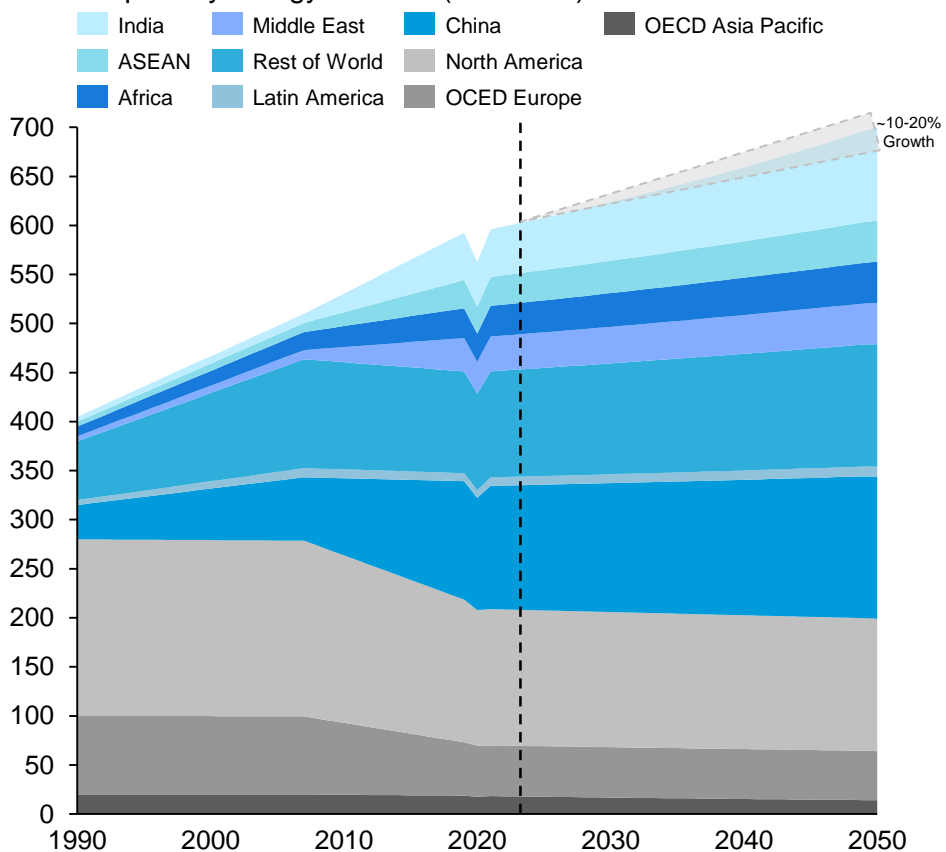
- **Policy and financial support:** Tax incentives are often the single most impactful factor making commercial geothermal projects viable. The OBBA spared ground sourced heat pumps (GSHPs).
- **Workforce readiness:** Availability of trained drillers and installers is a major bottleneck; national and regional training pipelines and certification programs are needed to expand this workforce.
- **Tech and deployment:** Demonstration projects across diverse geographies and use cases (urban, rural, cold and hot climates) help de-risk investment and validate business models. Standardized designs, permitting, and interconnection protocols are needed to streamline and reduce soft costs.
- **Business model innovations:** Utility-driven thermal energy networks (TENs utility-ownership) could provide a scalable and replicable model, especially as an alternative to gas infrastructure.

Sources: [Pathways to Commercial Liftoff: Geothermal Heating and Cooling](#) (DOE, 2024); [The loophole that can give clean heat a boost under Trump](#) (Canary Media, 2025).
 Credit: Faradisa Anintya, Pia Doris Morrow, Zacharia Thurston, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Global energy demand expected to grow ~10-20% by 2050, largely driven by emerging economies, electrification, and data centers

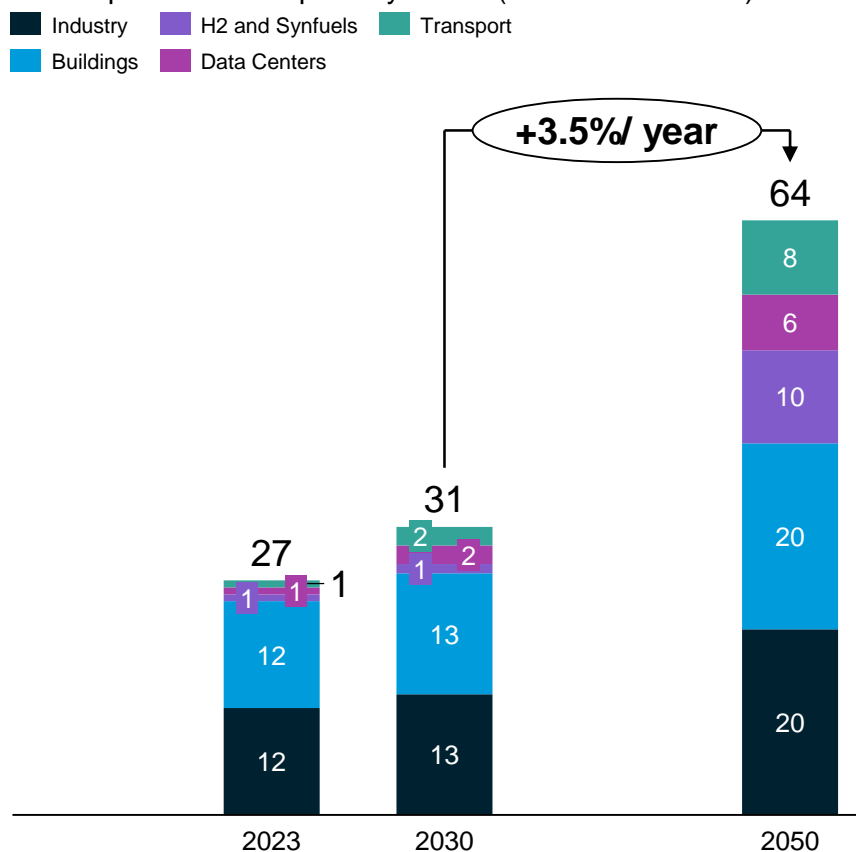
India, ASEAN*, Africa, and the Middle East will be responsible for ~65-95% demand growth

Global primary energy demand (million TJ)



New data centers and electrification of industry and buildings will drive ~5-10% demand growth

Global power consumption by sector (thousands of TWh)



Observations

- By 2050, global energy demand is expected to grow **11 to 8%**, with **66 to 95%** of that growth concentrated in emerging economies such as ASEAN, India, and the Middle East — regions that currently rely heavily on fossil fuels for baseload power.
- New demand will likely stem from the **electrification of industry and buildings**, accounting for over half of demand. **Data centers (2,500 to 4,500 TWh, or 5 to 9% of demand)**, green hydrogen (179 Mtpa, driving ~20% annual power demand growth), and EVs (~10% annual growth, with BEVs dominating car sales) will add to this surge.
- To meet such demand, **economies will need reliable, non-intermittent baseload solutions for their energy grids.**

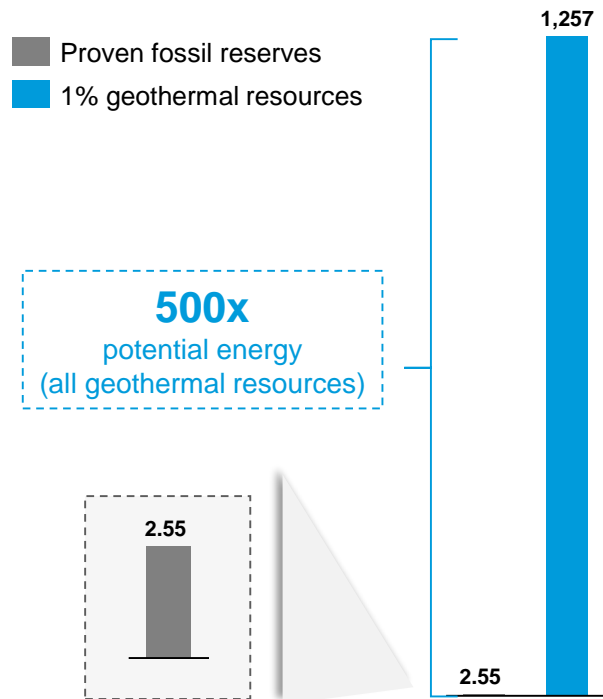
*Association of Southeast Asian Nations

Sources: [Global Energy Perspective](#) (McKinsey, 2024).

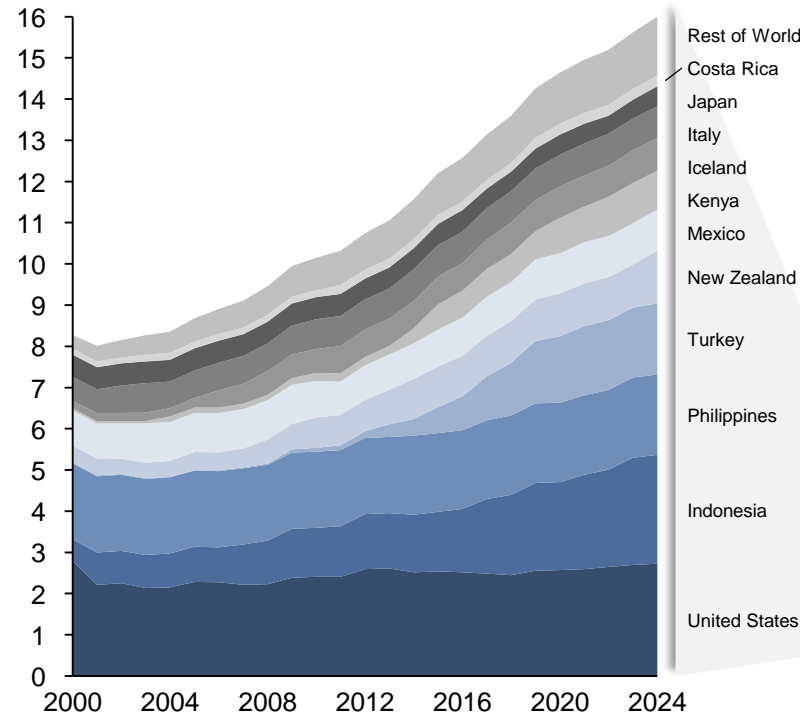
Credit: Zacharia Thurston, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

With vast untapped thermal resources and emerging technological advancements, geothermal power is primed for a breakout decade

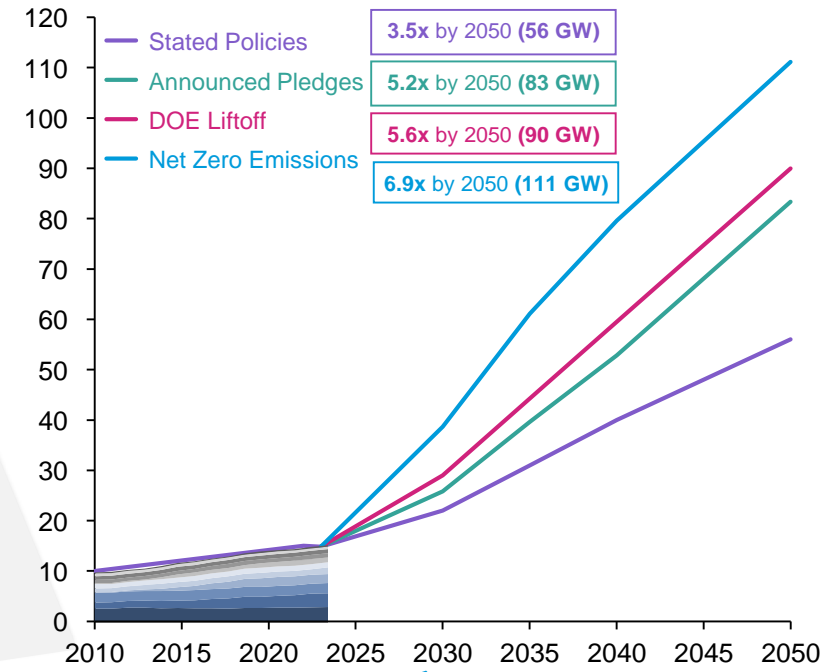
Potential of proven oil & gas reserves vs. 1% geothermal resources*, trillion MWh



Historical installed geothermal capacity by country, GW



Projected global geothermal under different scenarios, GW



In 2025, 32 countries had geothermal power, for a total of ~16 GW global capacity, from 3,700 production wells with an average 3 MWh capacity per well.

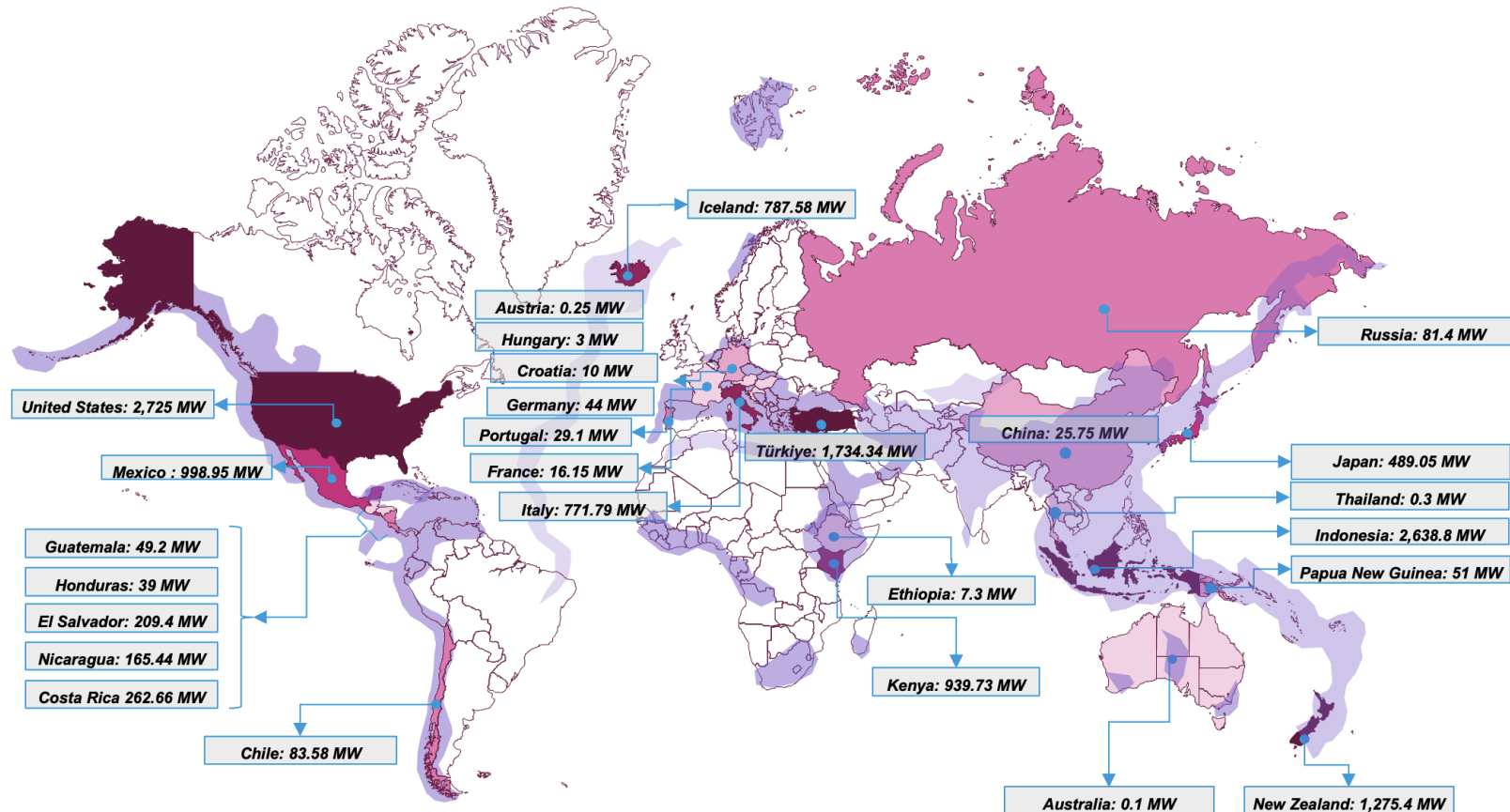
*One barrel of oil/gas is roughly equivalent to 1.7 MWh. There are about 1.5 trillion proven reserves of oil/gas x 1.7 MWh = 2.55 trillion MWh of potential fossil energy remaining (50-year supply remaining).

Sources: [World Energy Outlook 2024](#) (IEA, 2024); [Tapping the Earth's Natural Heat](#) (USGS, 1994); [Oil and Gas Reserves](#) (Penn State University, n.d.); [Total Geothermal Capacity](#) (Our World in Data, 2024); [Evolution of Worldwide Geothermal Power 2020-2023](#) (Geothermal Energy, 2024); [Pathways to Commercial Liftoff: Geothermal Heating and Cooling](#) (DOE, 2024).

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Conventional geothermal power installations have reached ~16 GW but remain constrained to key geographic areas

Geologically active areas show geothermal potential beyond countries with installed capacity



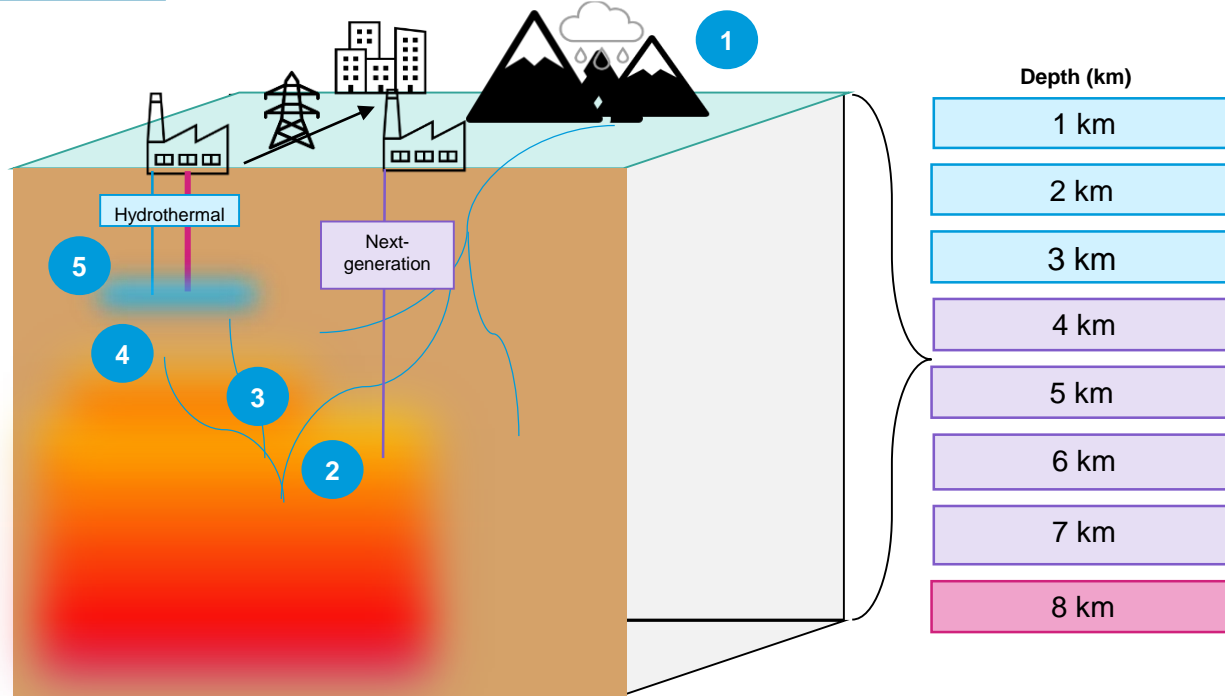
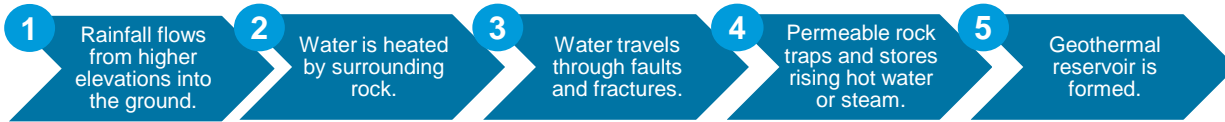
Observations

- The U.S., Indonesia, the Philippines, Mexico, Türkiye, New Zealand, Japan, Kenya, Iceland, and Italy lead in installed geothermal capacity.
- Conventional geothermal relies on rare hydrothermal reservoirs—where heat, water, and permeable rock naturally align near tectonic boundaries like the Pacific Ring of Fire.
- As a result, geothermal generation is concentrated in volcanically active regions. Most other nations face steep costs and technical barriers.
- **Conventional resources are too limited to assist in meeting global energy demand**
- Enhanced and closed-loop geothermal systems aim to overcome geographic limits, unlock deeper heat sources, and deliver 24/7 renewable power worldwide.

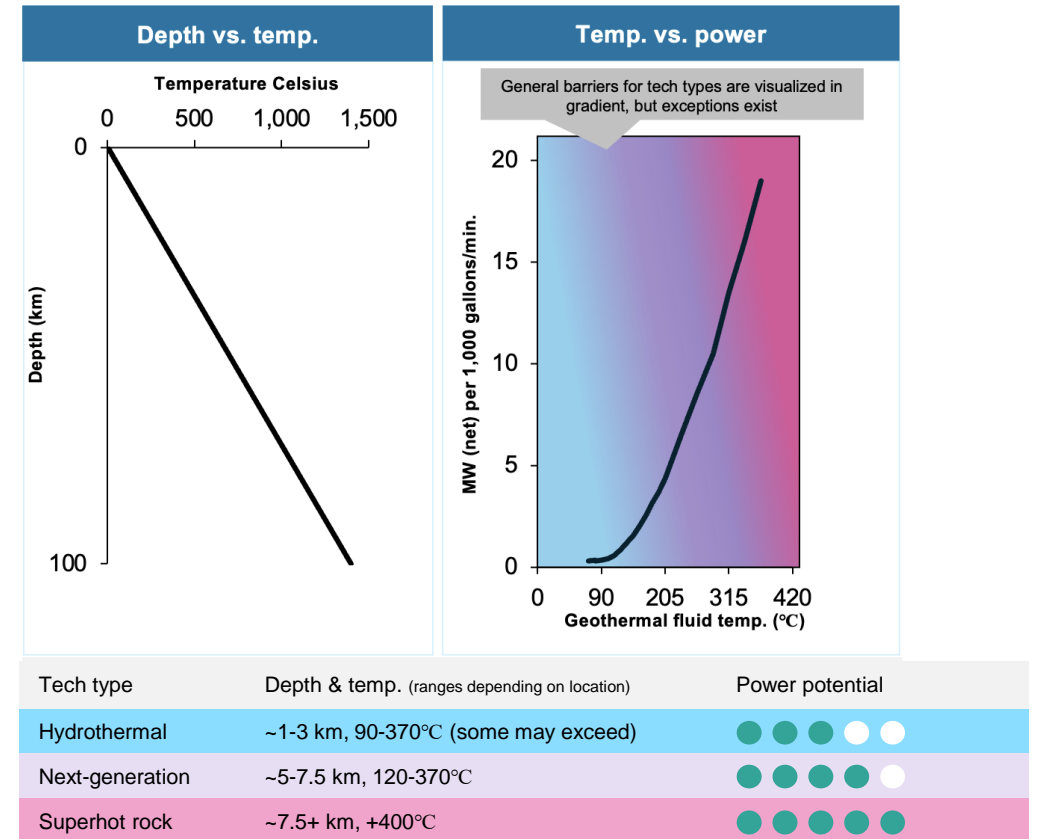
Sources: [Total Geothermal Capacity](#) (Our World in Data, 2024); [Predicting Geographic Suitability of Geothermal Power Plants](#) (Journal of Cleaner Production, 2020).
 Credit: Zacharia Thurston, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al. "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Next-generation technologies enable deeper drilling to unlock greater power potential

Heat reservoir formation process and access



The ability to drill deeper is key to accessing more power*



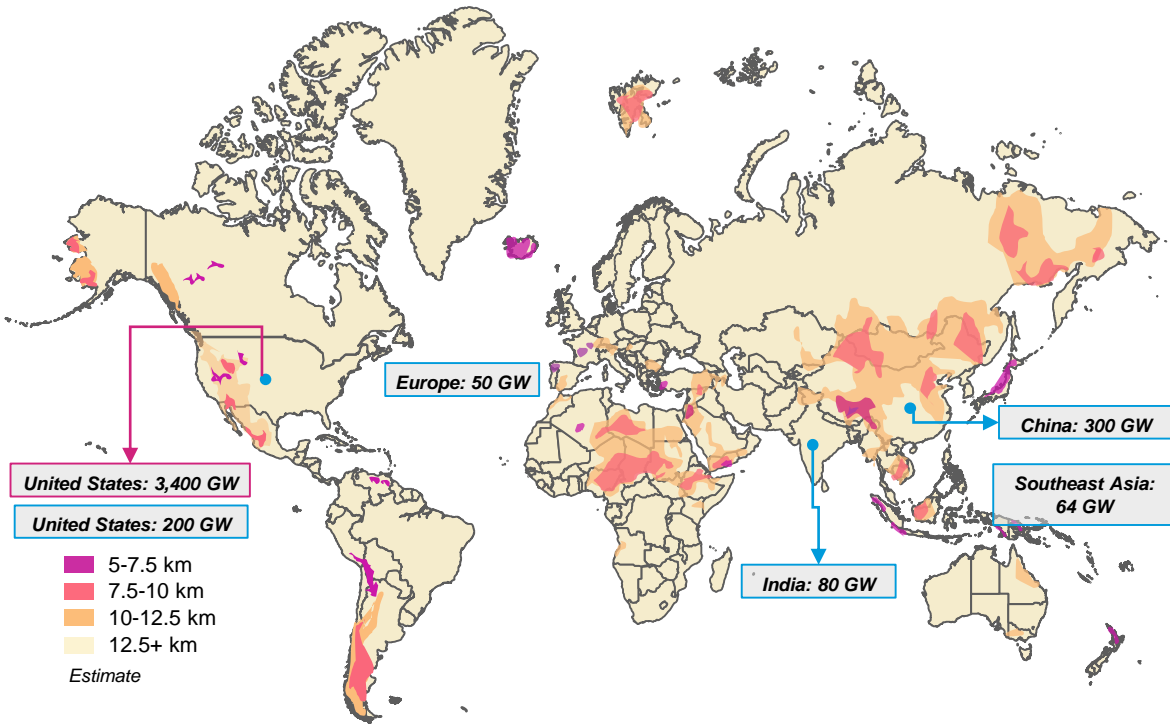
*Graphs indicate general relationship, but reality will vary depending on location, pressure, flow rate, efficiency, and heat distribution.

Sources: [Types of Geothermal power plants](#) (CA.gov, n.d.); [What is a geothermal reservoir?](#) (Geothermal The Next Generation, 2021); [A state of the art review on geothermal](#) (International Journal of Thermofluids, 2023); [Geothermal Technologies](#) (BGS, n.d.); [Power Density in Geothermal Fields](#) (ResearchGate, 2015); [Geothermal Gradient](#) (Energy Education, n.d.); [U.S. utility-scale power plants](#) (EIA, 2020); [The Utah Forge Project](#) (Clean Technica, 2025); [Temperatures are rising](#) (Geoconvention.com, 2021).

Credit: Zacharia Thurston, Pia Doris Morrow, Isabel Hoyos, and Gernot Wagner. [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Next-generation drilling unlocks globalized clean energy access, with notable overlap in emerging economies by 2050

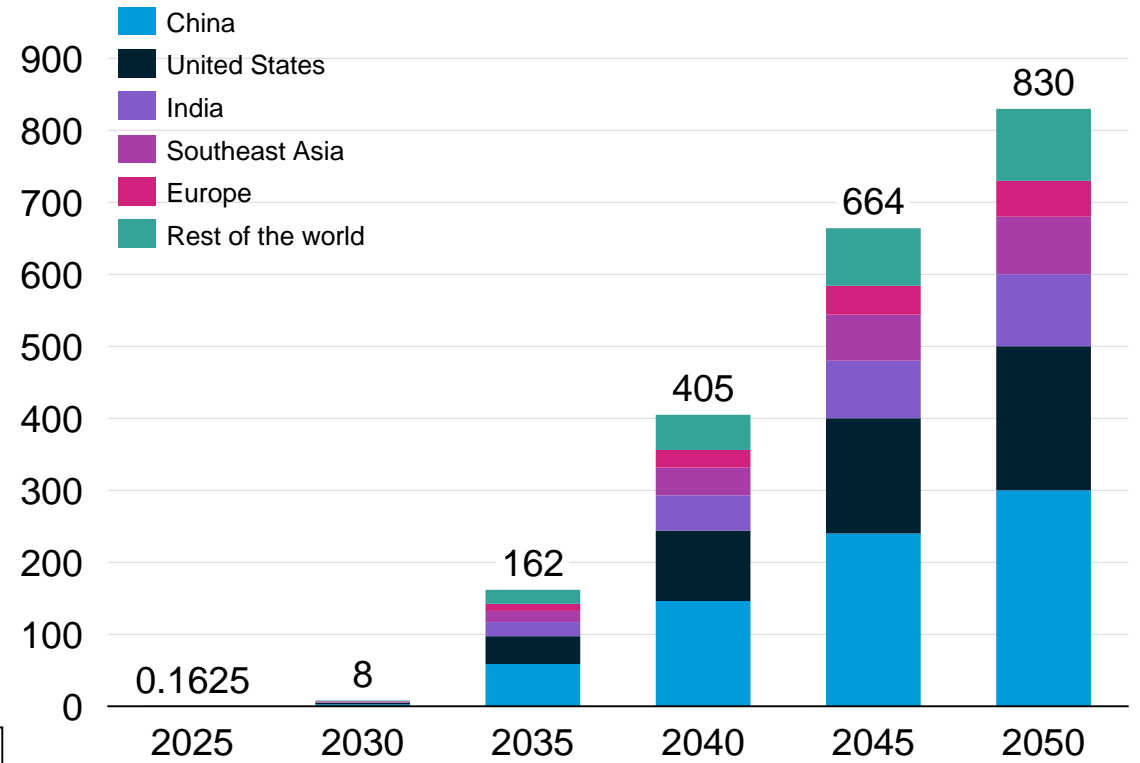
Global EGS hotspots concentrated in emerging economies



Project InnerSpace
IEA

Global next-gen geothermal projections vary. Project InnerSpace's projections likely reflect greater accuracy of global geothermal potential, driven by superior subsurface data collection. IEA estimates are deliberately conservative, focusing on what is deployable under today's policy, cost, and financing conditions.

Potential for next-gen geothermal power capacity by region, GW (IEA projections)



Sources: [Superhot rock and the future of geothermal](#) (Clean Air Taskforce, 2025); [The future of geothermal](#) (IEA, 2025); [East Africa's Geothermal Energy](#) (Africa Oil & Gas Report, 2025); [Project InnerSpace Analysis](#) (Project InnerSpace, 2025).

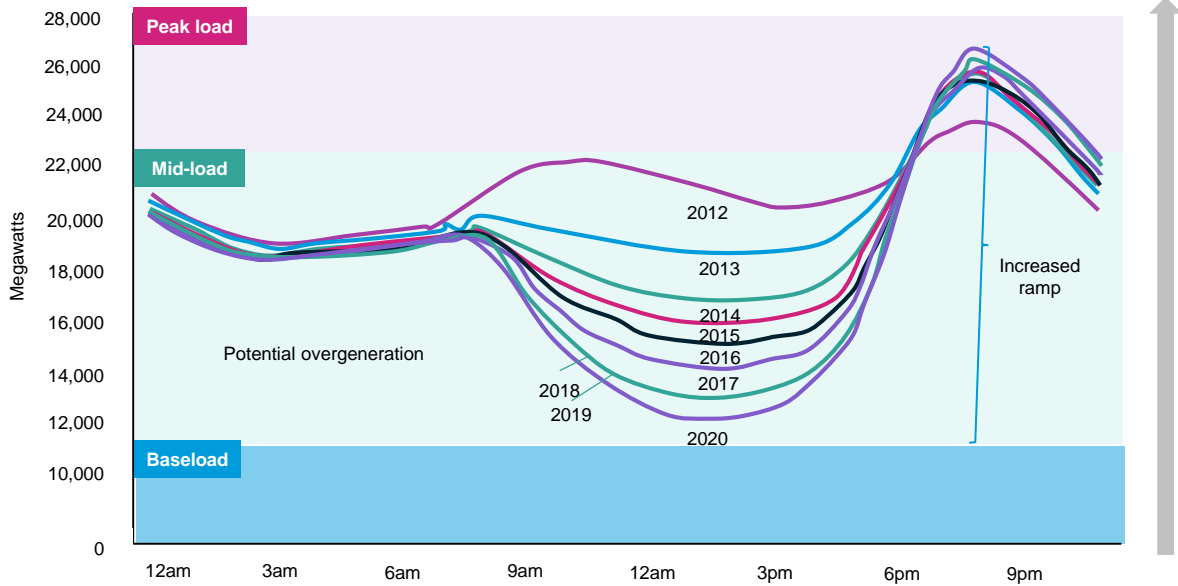
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Geothermal power offers clean baseload capacity to replace retiring coal plants and prevent overreliance on peaker plants

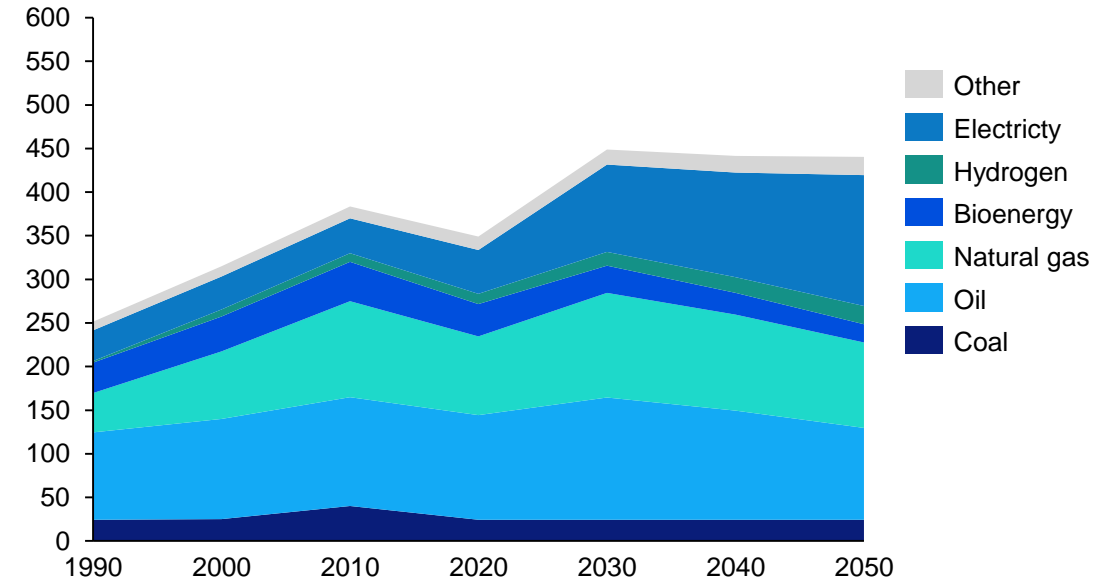
Loss of baseload power leads to overreliance on peaker plants and can drive up costs for consumers

Heavy dependence on intermittent renewables without baseload capacity threatens grid reliability

Hourly net load (year average) in California



Global final energy consumption for Continued Momentum scenario, by fuel, millions of terajoules



What is baseload?

Baseload power is the **minimum amount of electricity** the electrical grid needs at any given time. Runs **continuously** at a **steady output**.



The most common sources of baseload power, chosen for their **low LCOE**. Gas can be used but has higher OpEx.

Fossil energy will plateau despite energy demand increasing.

Grids that are overreliant on wind and solar (intermittent energy) without baseload capacity risk rolling blackouts during periods of low renewable generation.

Sources: [Cumulative Investment for Next-Generation Geothermal 2025-2050](#) (IEA, 2024); [The Duck Pond](#) (Power-Eng.com, 2016); [Baseload Power](#) (Energy Education); [2025 Global Energy Perspective](#) (McKinsey, 2025).
 Credit: Zacharia Thurston, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Key barriers limiting geothermal deployment include exploration risks, drilling technology limits, and heat flow variability

Barriers to geothermal achieving global, dispatchable, and cost-competitive clean power

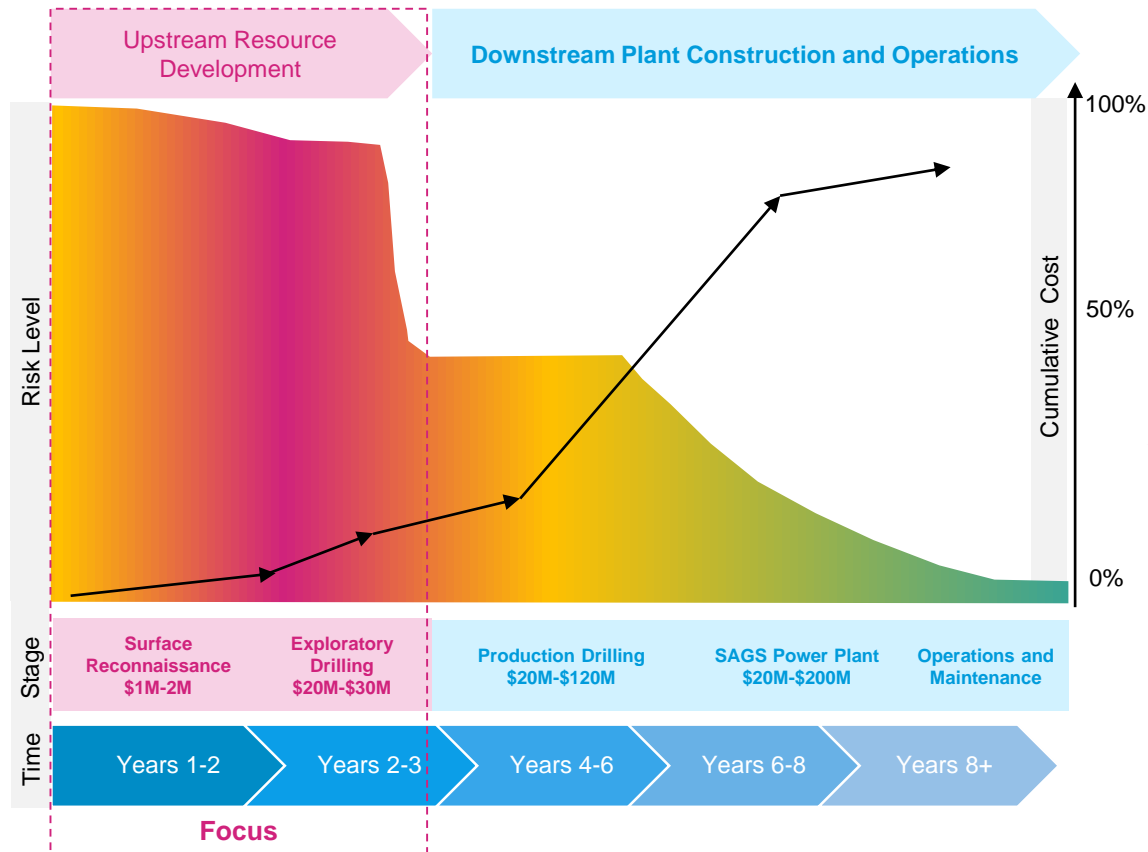
	Barrier	Description	Impact on Deployment	Emerging Solutions
Major Barriers	Exploration Risk & Cost	High upfront cost for resource identification; drilling success uncertain	Major cost bottleneck; limits financing	AI/geophysical modeling, remote sensing, cheaper slim-hole drilling
	Drilling Technology Limits	Conventional rigs struggle with deep/hard rock, high heat, and corrosive fluids	Limits depth/temperature access → limits energy yield	Advanced drilling (plasma, millimeter wave, laser), O&G transfer tech
	Reservoir Stimulation & Permeability	Creating or maintaining fluid pathways in hot dry rock is challenging	Determines long-term productivity; EGS sites often fail after testing	Hydraulic shearing, closed-loop systems, supercritical fluid modeling
	Materials & Corrosion Resistance	Equipment degradation in harsh conditions (heat, pressure, minerals)	Raises O&M costs and reduces lifetime of wells	High-temp alloys, ceramics, coatings
	Power Conversion Efficiency	Efficiency drops at lower temperatures; limited by thermodynamic cycles	Restricts viable sites; reduces energy output	Supercritical CO ₂ cycles, binary cycle optimization
	Monitoring & Reservoir Management	Hard to track subsurface dynamics and avoid induced seismicity	Safety/regulatory constraints; performance loss over time	Fiber-optic sensing, real-time data analytics, seismic monitoring
	Transmission & Integration	Geothermal sites often remote; grid connection costs high	Slows scalability and investment interest	Colocation with industrial heat users, modular systems
	Public & Regulatory Challenges	Concerns about seismicity, permitting delays	Adds time and uncertainty to projects	Streamlined EGS permitting frameworks

Sources: [Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office](#) (NREL, 2023); [What Are the Challenges in Developing Enhanced Geothermal Systems \(EGS\)? Observations from 64 EGS Sites](#) (Worldgeothermal.org, 2021).
 Credit: Zacharia Thurston, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Exploratory drilling carries the highest project development risk, which can be reduced through advanced subsurface modeling

High drilling costs and geological uncertainty make exploration the riskiest phase of geothermal development

Inaccurate subsurface modeling can mischaracterize resources, resulting in failed wells and losses exceeding \$10M per site




Resource Risk
Subsurface temperature, permeability, and fluids can be confirmed only through drilling; surface surveys and models provide limited accuracy, making exploratory wells costly and high risk.

Operational Risk
Inaccurate measurements of reservoir pressure can reduce recoverable power; length of estimated drilling time may ward off willingness for upfront investment in exploratory stages.

Geothermal project finance has initial high risk: Tens of millions of dollars are spent upfront on drilling with no guarantee of a viable resource. This uncertainty makes traditional financing challenging, often requiring government support, insurance, or hybrid financing to secure bankability.

AI-enabled companies are helping de-risk exploration by providing solutions for accurate subsurface reconnaissance and drilling

zanskar  Applied AI geosensing to discover new reservoirs around the underperforming Lightning Dock geothermal facility, which now ranks among the most productive in the U.S.

*Financing structures and regulatory hurdles may also affect project risk profiles during initial development.

Sources: [The Heat Beneath Our Feet](#) (Sightline CTVC, 2022); [Annual Energy Outlook](#) (EIA, 2022); [A New Kind of Energy Company](#) (Zanskar, 2024); [Zanskar raises \\$30M](#) (ThinkGeoEnergy, 2024).
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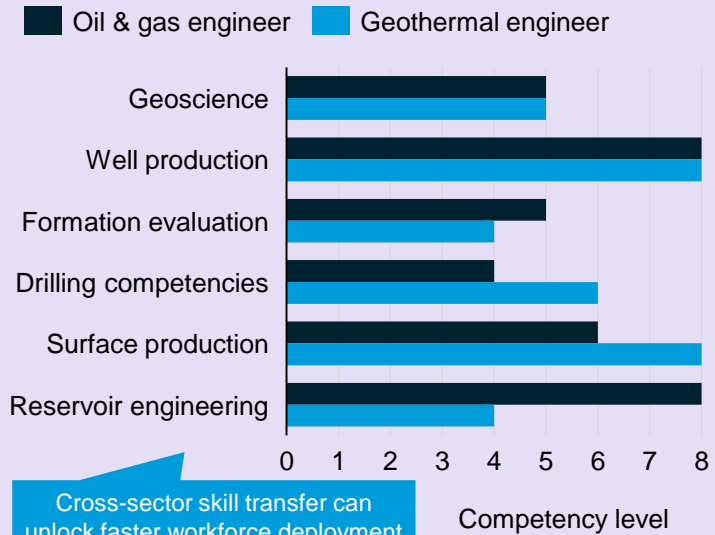
Technological, policy, and financial synergies with the oil & gas industry can drive down geothermal costs and scale deployment

Technological synergies

- 1 Subsurface exploration and drilling**
 Oil and gas data on hydrocarbon reserves and well logs can cut geothermal exploration costs and improve success rates.
- 2 Well completion and management**
 Simulation and zonal isolation techniques from O&G enhance reservoir longevity and reinjection efficiency.
- 3 Data and digital innovation**
 O&G's digital twins and real-time monitoring tools improve geothermal reservoir modeling and predictive maintenance.

Policy priorities

Geothermal and O&G engineering skillset overlap*



Cross-sector skill transfer can unlock faster workforce deployment and lower technical risk.

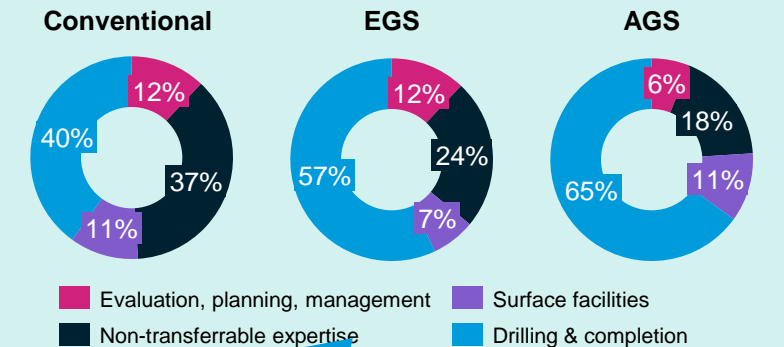
Countries leading the workforce transition

- U.S.: DOE GeoVision + GEODE Consortium
- Iceland: Integrated geothermal-O&G training pipeline
- Türkiye: EGS demonstration from hydrocarbon basins

Cost trends for successful synergy

- ~10%** Reduction in exploration risk and resources mapping
- ~20-30%** Drilling and completion efficiency gains via O&G rigs and methods
- ~30%** R&D and learning-by-doing acceleration

Share of geothermal technology investments that overlap with the O&G industry



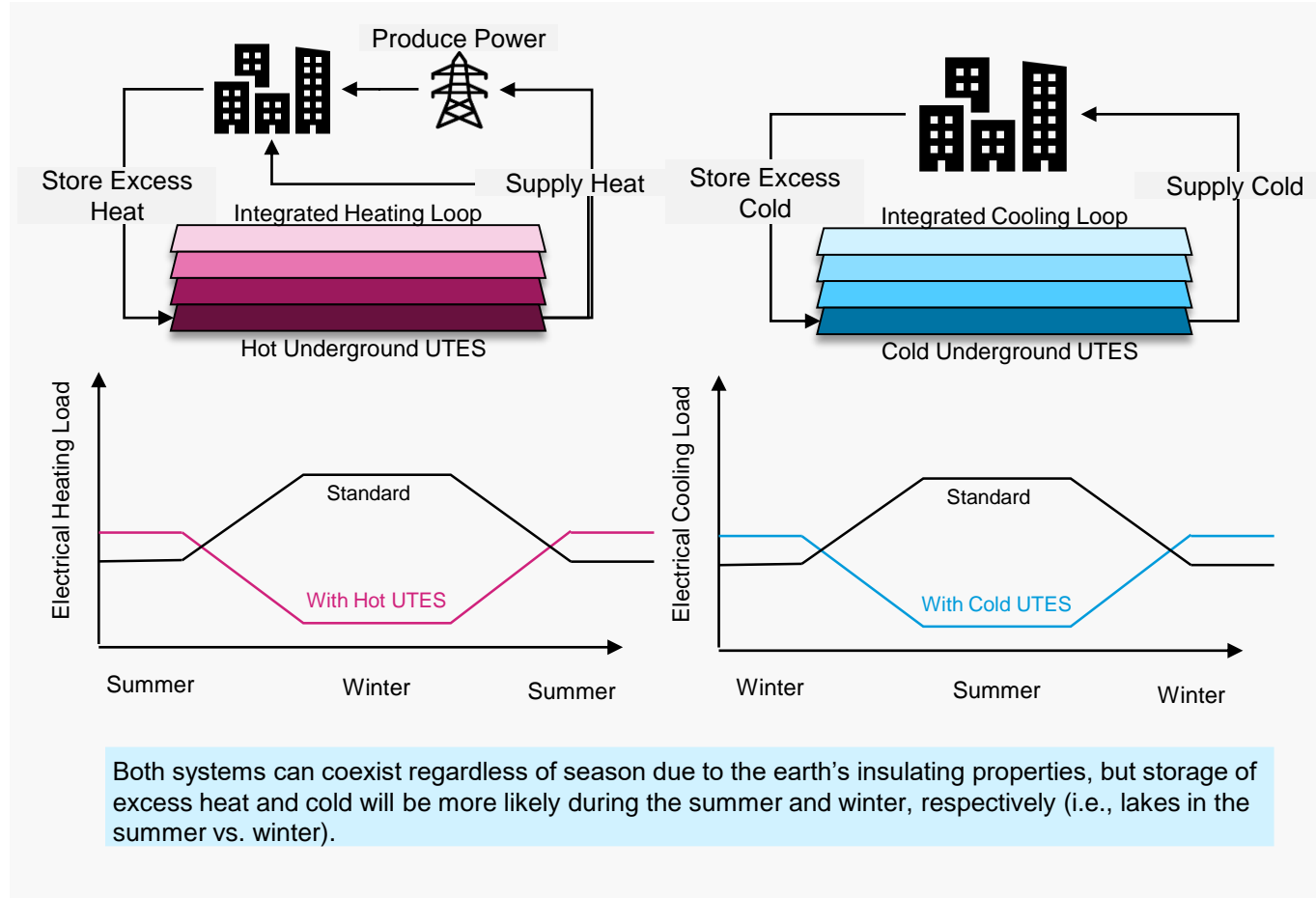
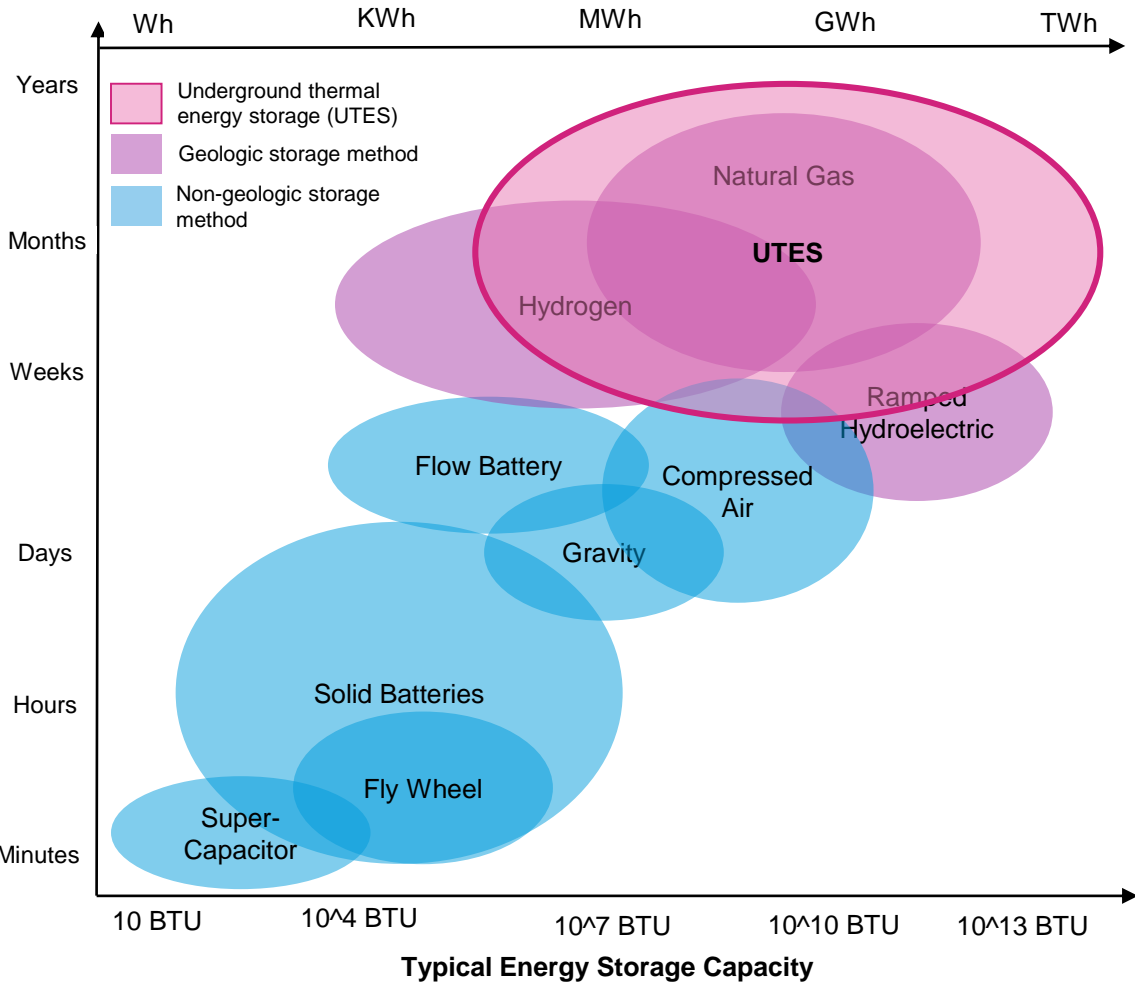
Enhanced geothermal systems (EGS) exhibit the highest transferable expertise (~70%), while advanced geothermal systems (AGS) retains greater reliance on O&G drilling and surface integration.

*Competency levels based on SPE competency matrices.

Sources: [Geothermal Energy: Unveiling the Socioeconomic Benefits](#) (ESMAP, 2024); [The Future of Geothermal Energy](#) (IEA, 2024); [Earth Energy – Human Ingenuity](#) (GEODE, n.d.).

Credit: Una Oljaca, Zacharia Thurston, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

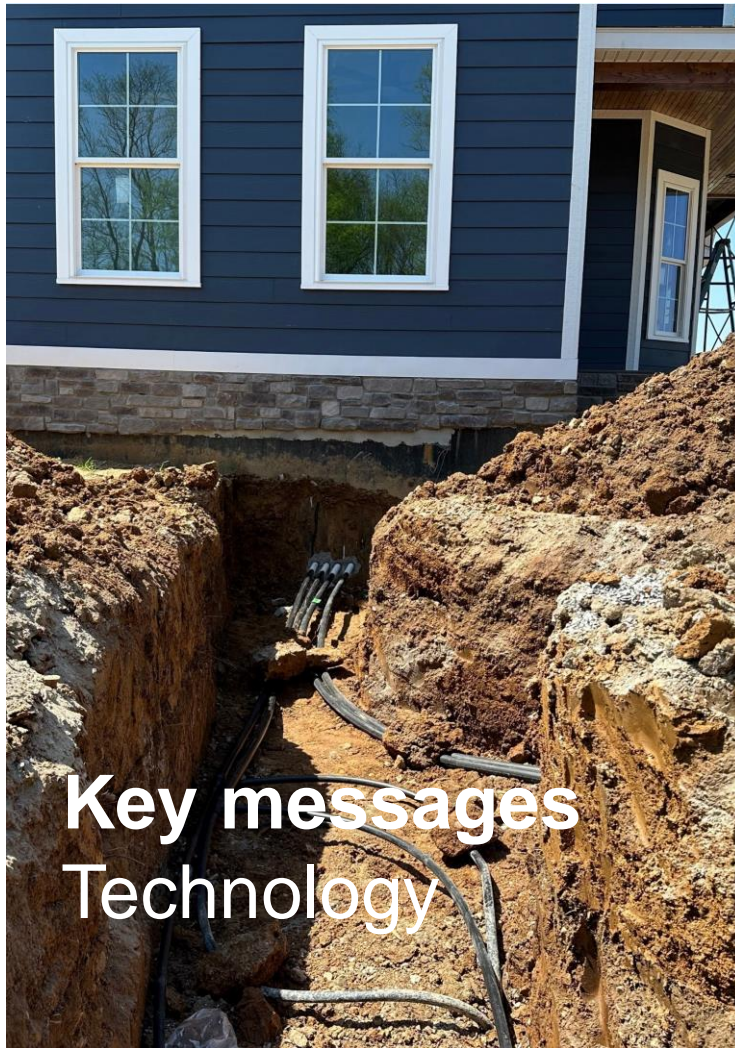
Underground thermal energy storage offers greater capacity potential than battery alternatives and natural gas



Sources: [Reducing Data Center Peak Cooling Demand and Energy Costs With Underground Thermal Energy Storage](#) (Stanford, 2025); [Reducing Data Center Peak Cooling Demand and Energy Costs With Underground Thermal Energy Storage](#) (NREL, 2025).
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Geothermal Heating and Cooling Technology



Geothermal heating and cooling involves the **harnessing of stable underground temperatures via closed- or open-loop circulation.**

- Among conventional geothermal technologies, **geothermal heat pumps (GHPs)** are the most common, accounting for **72% of global installed H&C capacity**. GHPs can harness lower temperatures (4-22°C) at an average COP of 3-5.
- Advancements in **next-generation geothermal technologies** have expanded the use cases, temperature range, and production capacity of geothermal heating and cooling compared with conventional geothermal technologies.

Global geothermal heating and cooling capacity is 173,303 MW_{th}. Over 50% of global installed capacity is in China, while Iceland has the largest per-capita installed capacity (7.18 kW_{th}).

Drilling is the largest and most variable cost driver of both conventional and next-generation geothermal heating and cooling, typically contributing **over 50% of total project cost and/or LCOE.**

- For conventional geothermal technologies, geography and loop design are the primary drivers of drilling costs, due to dependence on hydrothermal reservoirs and the comparative costs of vertical versus horizontal borehole loops.
- For next-generation geothermal technologies, well depth and temperature are the primary drivers of drilling costs.

Synergies with the oil and gas industry can push down geothermal heating and cooling costs and improve efficiency, and growing interest from the O&G industry has led to partnerships and upfront investments, particularly for next-generation geothermal.

- Subsurface data and modeling techniques from the O&G industry can help de-risk geothermal heating projects and lower costs, as demonstrated by the Eavor-Lite™ demonstration project in Alberta, Canada.
- Technical synergies between the geothermal and oil and gas industries highlight strong workforce transferability, which can help streamline geothermal commercialization.

Due to limited deployment of conventional geothermal for industry heating or direct use, **next-generation geothermal may bypass resource-related constraints of conventional technologies and open new avenues for scaling the industry.**

- Next-generation geothermal heating and cooling is most viable for use in direct industrial (process) or district (space) heating.
- Next-generation geothermal costs fell as much as 50% from 2022 to 2024, and the IEA estimates that costs could fall an additional **80%** by 2035 with proper policy and technical support.

Geothermal heating & cooling technologies are proven, deployable solutions for decarbonizing building thermal loads

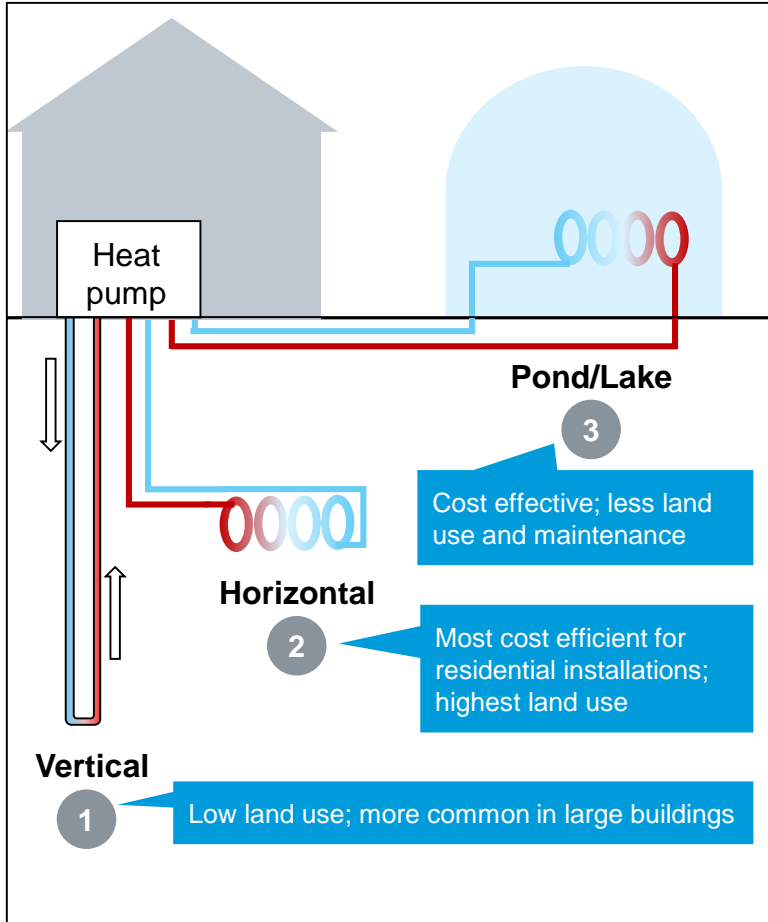
	Geothermal Heat Pumps (GHPs)	Direct-Use Geothermal	Underground Thermal Energy Storage (UTES)
Description	Constant temperatures are harnessed via open- or closed-loop fluid circulation and transferred through heat pumps.	Hot water from naturally occurring underground reservoirs is used directly for heating applications.	Seasonal energy storage in underground formations such as boreholes (BTES) or aquifers (ATES) accommodates later use.
Depth range	50-300 meters	400-2,000 meters	20-1,000 meters
Temperature	4.5-21°C	20-150°C	0-100°C
Alternative to	<ul style="list-style-type: none"> • Air-source heat pumps • Boilers/propane heaters 	<ul style="list-style-type: none"> • Coal, oil, gas boilers used for district heating systems 	<ul style="list-style-type: none"> • Peaking fossil fuel systems • Boilers and furnaces
Advantages	<ul style="list-style-type: none"> • High COP (3-5) • Peak load reduction • Weather resistance 	<ul style="list-style-type: none"> • Suitable for large-scale applications • Can target higher temperature 	<ul style="list-style-type: none"> • Energy savings and grid energy use optimization • Low land use
Barriers	<ul style="list-style-type: none"> • Site specificity • Skilled workforce needs 	<ul style="list-style-type: none"> • Site specificity • Limited use slowing cost reductions 	<ul style="list-style-type: none"> • Site specificity • Heat loss over time • Cost and efficiency uncertainties
Cost	US\$66-\$109/MWh	US\$66-\$109/MWh	N/A

Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [Barriers to Next-Gen Geothermal](#) (IFP, 2023); [Underground Thermal Energy Storage](#) (2012); [Direct Utilization of Geothermal Energy](#) (Geothermics, 2021); [Pathways to Commercial Liftoff: Geothermal Heating and Cooling](#) (DOE, 2024); [A review of borehole thermal energy storage](#) (Renewable and Sustainable Energy Reviews, 2024); [Levelized Cost of Energy](#) (Lazard, 2025); [Annual Technology Baseline](#) (NREL, 2024).

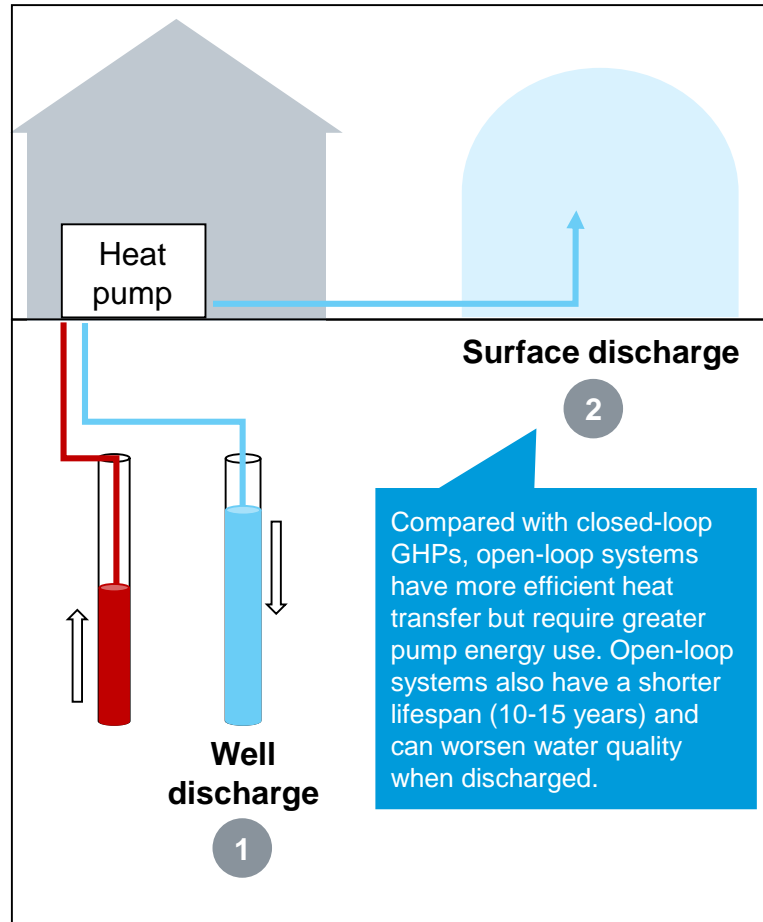
Credit: Una Oljaca, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal heat pumps can be closed loop, open loop, or hybrid, and are most often used in residential or commercial settings

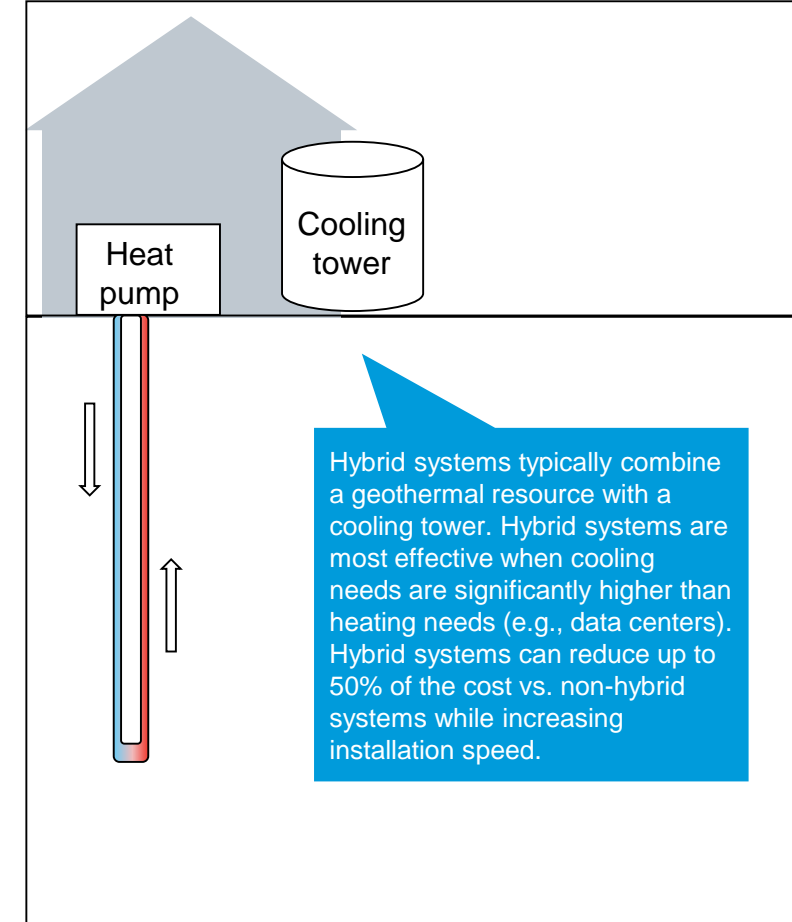
Closed loop



Open loop

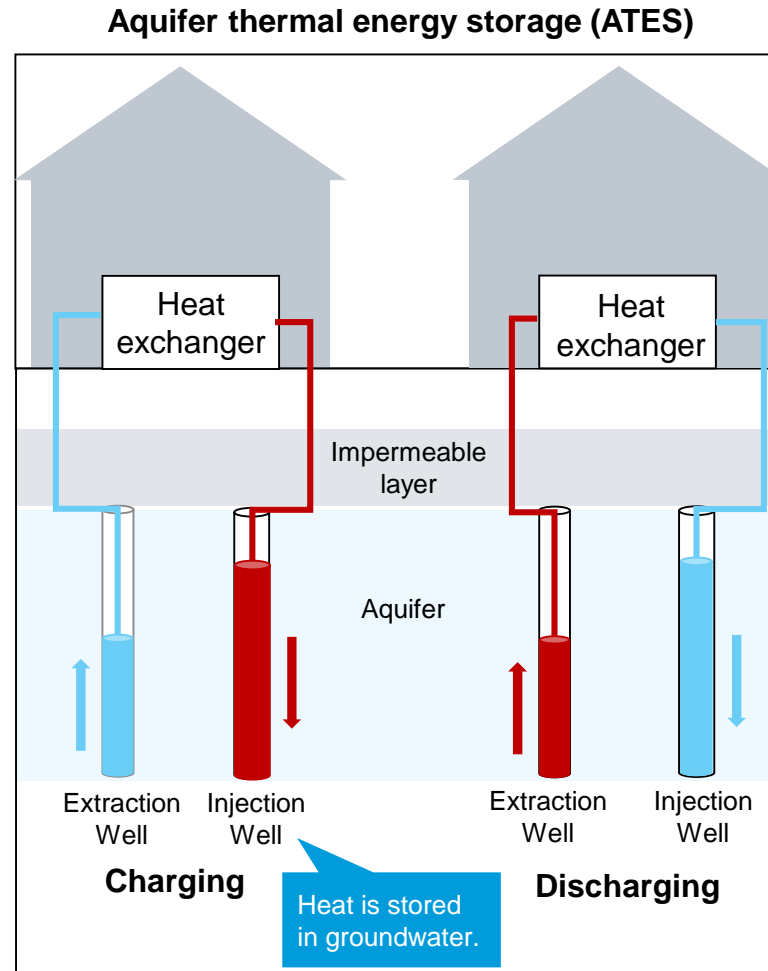
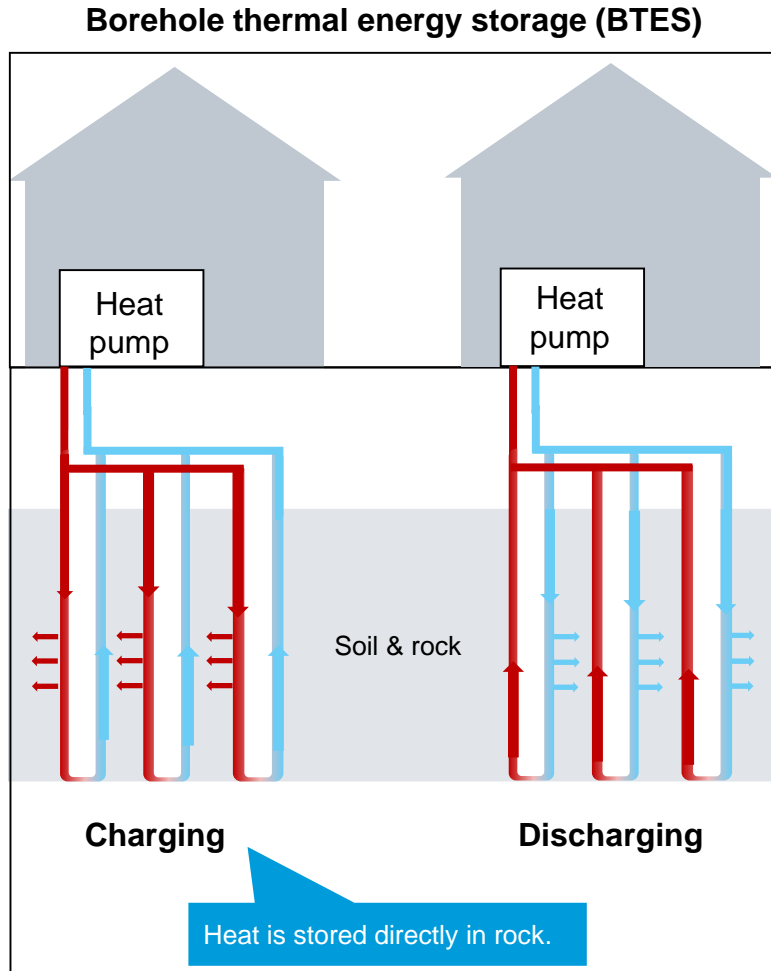


Hybrid



Sources: [Geothermal Heat Pumps, Underground Thermal Energy Storage](#) (DOE, 2012); [Direct utilization of geothermal energy 2020 worldwide review](#) (Geothermics, 2021); [Pathways to Commercial Liftoff: Geothermal Heating and Cooling](#) (DOE, 2024); [Open-Loop vs. Closed-Loop Ground Source Heat Pumps](#) (Energy Vanguard, 2023).
 Credit: Una Oljaca, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling." Columbia Business School Climate Knowledge Initiative (10 March 2026).

Underground thermal energy storage supports renewable energy integration, but adoption is limited by infrastructure needs



BTES and ATES Compared		
	BTES	ATES
Energy Density	15-30 kWh/m ³	30-40 kWh/m ³
Temperature	~80°C	<25°C
Storage Efficiency	Low in first years, increases after 3-4 years; 45-60%	70-100% (cold storage); 50-80% (heat storage)
Storage Volume	3-5 m ³ for 1 m ³ water equivalent	2-3 m ³ for 1 m ³ water equivalent
Use Cases	Wider range of applications	Large-scale applications
Risks	Thermal contamination; subsurface instability	Groundwater contamination
Investment Costs	20-60 US\$/m ³	58-70 US\$/m ³
Lifespan	Can exceed 100 years	25-50 years

Sources: [Sensible thermal energy storage](#) (Future Grid-Scale Energy Storage Solutions, 2023); [Underground Thermal Energy Storage](#) (2012); [Direct Utilization of Geothermal Energy](#) (Geothermics, 2021); [Pathways to Commercial Liftoff: Geothermal Heating and Cooling](#) (DOE, 2024); [A review of borehole thermal energy storage](#) (Renewable and Sustainable Energy Reviews, 2024); [Insights into Aquifer and Borehole Thermal Energy Storage Systems](#) (Energies, 2025).

Credit: Una Oljaca, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Drilling currently drives ~54% of next-gen geothermal LCOE; investments to reduce that share target heat resistance, permeability, and drill-bit life

Emerging technologies aimed at lowering next-generation geothermal drilling costs

Breakdown of projected LCOE components of next-generation geothermal in a low-cost case (US\$/MWh)

Millimeter-Wave Drilling

High-powered millimeter-wave beams from a gyrotron vaporize rock and drill ultradeep boreholes, bypassing the wear and tear of traditional drilling methods.



A full-scale demonstration drilled 10 feet deep using 100 kW of millimeter-wave power; Quaise also plans to deploy a 1 mW gyrotron within two years to reach commercially viable depths.

Repetitive Pulsed Electric Drill (RePED)

High-voltage electric pulses fracture rock, avoiding mechanical contact. Reduces wear on equipment and is designed to work with existing drilling infrastructure.



Tetra Innovation Institute and **NREL** partnered to advance the technology, with potential drilling cost reductions of 75% and applications in industries beyond geothermal.

Directional Steel-Shot Drilling

Steel-shot particles are released under high pressure to erode rock formations and reduce resistance to further rotary drilling.



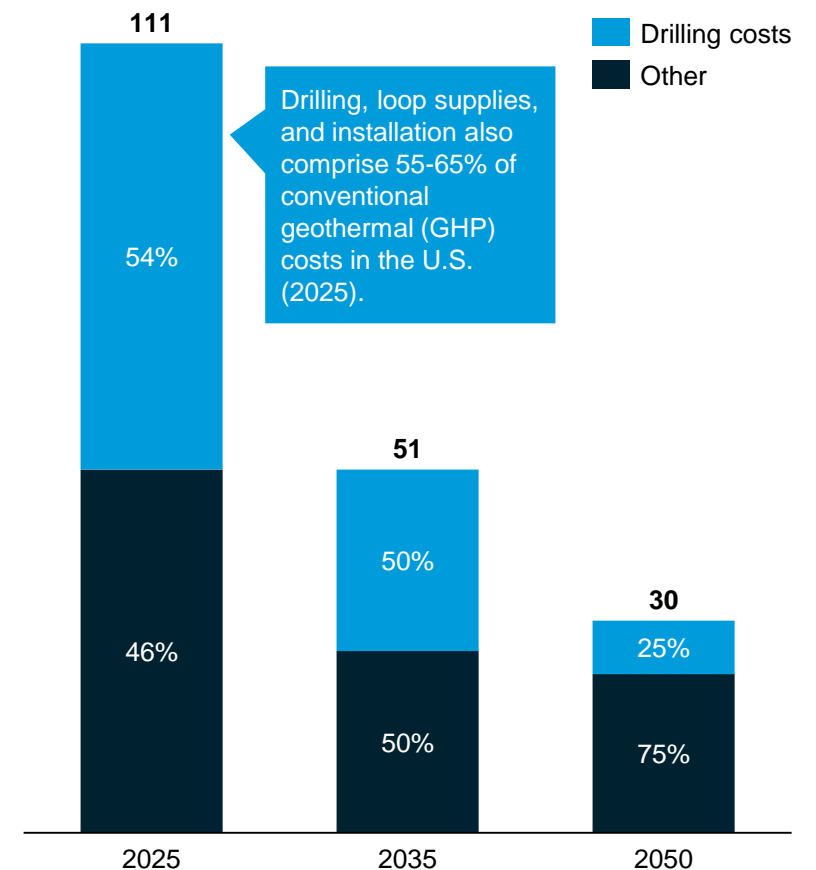
Drilling solutions startup **Canopus** is collaborating with **TNO** and European partners to test the drill system in the Netherlands, funded by a Dutch subsidy scheme.

High-Pressure Water Jet-Assisted Drilling

High-pressure water jets cut rock into shapes that can be broken apart more easily by fluid-powered percussive hammers.



ORCHYD combines high-pressure water jets with fluid-driven percussion drilling, aiming to cut drilling costs by 65%. The project received Horizon 2020 funding from the EU in 2021.



Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [Quaise Energy's Breakthrough in Geothermal Drilling Technology](#) (ACO Cleantech, 2025); [New High-Rate Drilling System Could Revolutionize High-Temperature Power Electronics](#) (NREL, 2020); [DEPLOI](#) (TNO, 2024); [ORCHYD](#) (2021).

Credit: Una Oljaca, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Eavor-Lite™ demonstrates the potential of leveraging oil & gas sector knowledge for next-generation geothermal heating

In 2019, Eavor launched Eavor-Lite™, a full-scale demonstration project in Alberta, Canada, of a closed-loop geothermal system (Eavor-Loop™). Eavor leveraged advances from the shale drilling revolution and growing interest from the oil & gas industry to drive down costs and improve efficiency.



Subsurface Exploration

- **Alberta Energy Regulator’s Core Research Center** has collected:
 - > 1.55 million boxes of well core
 - Daily drilling reports from over 417,000 oil & gas wells
 - > 20 million vials of drill-cutting samples
- This data supported Eavor’s subsurface exploration and reduces the need for experimental drilling in future projects.

Drilling Phase

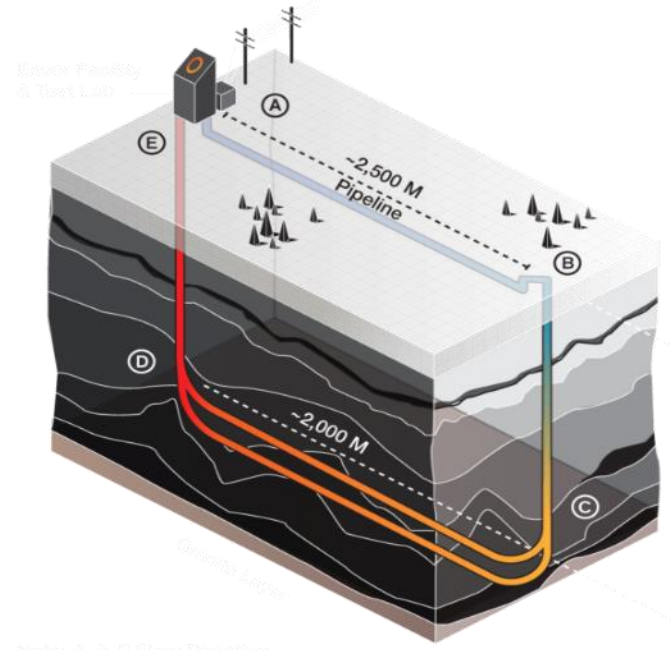
- **Precision Drilling** deployed two rigs to drill 2,400-meter multilateral wells in low-quality sandstone rock.
- **Shell International Exploration and Production** provided technical expertise on drilling, completion, facility construction, and follow-up on commercial implementation.

Investments

- February 2021: **BP and Chevron** were investors in a \$40 million funding round for Eavor.
- June 2023: Eavor received a \$34 million investment from **OMV**, an Austrian oil and gas company, in its Series B equity round.



In May 2020, Eavor announced an Eavor-Loop™ heat and power project in Geretsried, Germany. An additional contract was signed in May 2024 for the development of a district heating network.



20 GW_{th} produced since 2019



~150 people employed during planning and construction

Sources: [Eavor \(2024\)](#); [Eavor Signs a Heat Supply Contract to Further Energy Autonomy in Geretsried](#) (Eavor, 2024); [Eavor commences commercialization through major investment and landmark partnership with OMV](#) (Eavor, 2023); [NS Energy \(2021\)](#); [Eavor-Loop Demonstration Project](#) (Government of Canada, 2024); [Eavor announces Shell collaboration on demonstration of disruptive geothermal technology](#) (Eavor, 2019); [The world’s first truly scalable form of clean baseload power demonstrated by Eavor Technologies Inc.](#) (Eavor, 2020); [Technology](#) (Eavor, 2022).

Credit: Una Oljaca, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* “Geothermal Heating and Cooling,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Eavor-Lite™ demonstrates the potential of leveraging oil & gas sector knowledge for next-generation geothermal heating

Insulated Drill Pipe

Enables **deeper and hotter drilling** by regulating bottom-hole temperatures.

Cools standard drilling equipment for operation in extreme conditions.

Previously used in the oil & gas industry.

Rock-Pipe™

Seals the casing on the Eavor-Loop™ vertical wellbore, improving efficiency.

Decreases well permeability by 10-100x and isolates working fluid within the system.

Is activated using non-hazardous fluids.

Eavor-Lite™ System Performance

3-5x reduction in average permeability due to Rock-Pipe

99.9% system seal rate due to Rock-Pipe technology

99.6% system uptime (excluding trials)

50°C stable outlet temperature after four years

20 m³/hour production rate after four years

Thermosiphon Effect

Differential density between warm and cold working fluids enables the Eavor-Loop™ to operate without a pump.

A pump was used during only **783 hours of >30,000 hours** of total operation during initial startup and testing.

Magnetic Ranging

Magnetic ranging signals are used to drill upper wells directionally toward lower wells.

Signals are interpreted by a **specialized receiver** in the lower wellbore.

Previously used in the **oil & gas industry**.

Sources: [Technology](#) (Eavor, 2022); [Eavor-Lite Update After Four Years Of Operation](#) (Eavor Technologies, 2023).

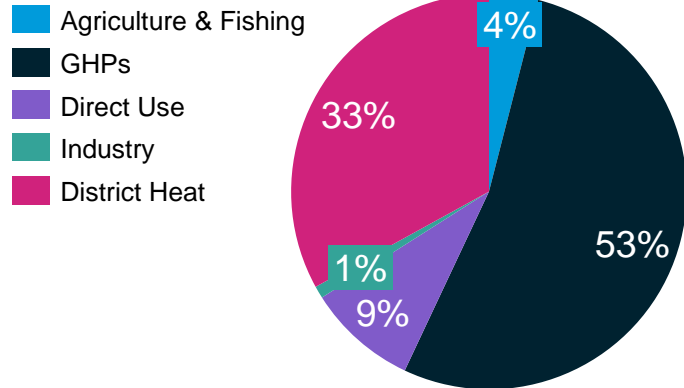
Credit: Una Oljaca, Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Next-generation geothermal may bypass resource-related limitations of conventional geothermal, opening new avenues for scaling the industry

Conventional geothermal is limited by geographical and temperature constraints...

... making next-generation geothermal attractive for reducing emissions in industrial and district heating use

Geothermal heating and cooling consumption by application globally



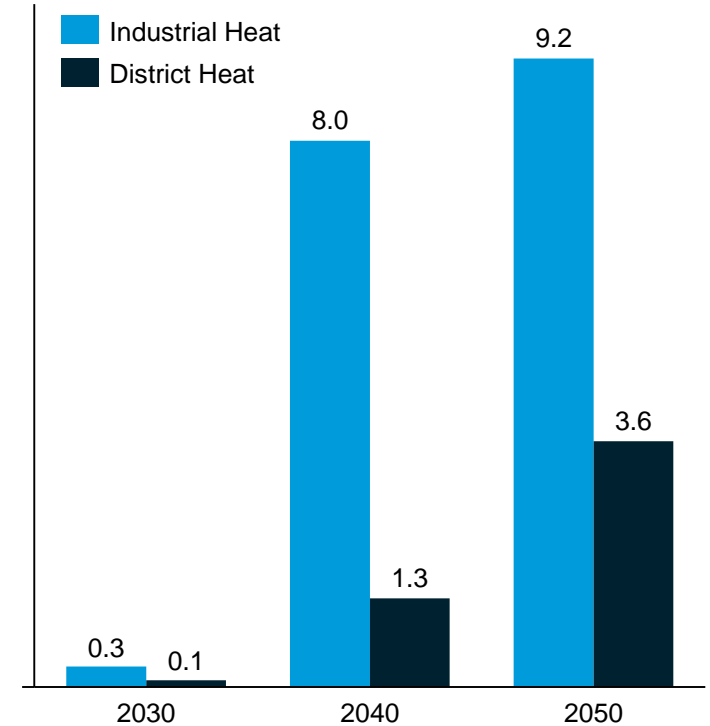
Conventional geothermal heat use in industry remains limited due to **geographical dependence on hydrothermal reservoirs** and **lower relative temperatures**.

Direct use can require **greater temperatures** than those accessed via conventional geothermal.

GHPs remain the most cost-effective application of conventional geothermal resources.

Application	Key Findings
Industrial Heat	<ul style="list-style-type: none"> In a low-cost APS scenario, next-generation geothermal could economically displace ~3 EJ of fossil fuel consumption by 2035 for industrial heat globally (10% of industrial heat <200°C) and almost 10 EJ by 2050 (35% of industrial heat <200°C). Up to 230 Mt of CO₂ emissions could be avoided.
District Heat	<ul style="list-style-type: none"> In a low-cost scenario, next-generation geothermal could capture 20% of district heating growth between 2035 and 2050. Investment costs below US\$4,000/kW would make next-generation geothermal district heating cost competitive. Co-generation (CHP) plants are an economically attractive application due to revenue generation from electricity shares

Share of total supply for next-generation geothermal heating, 2030-2050 (%)



Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023). Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

For industrial applications, geothermal energy is viable for temperature applications <200°C; New Zealand has harnessed this potential since 1957

Temperature requirements and potential geothermal applications for key industrial processes

Temperature (°C)	Industrial applications	Geothermal application
<100°C	<ul style="list-style-type: none"> Food & beverage processing Textile processing Paper processing 	GHPs are most competitive for satisfying low-temperature industrial heat demand.
100-200°C	<ul style="list-style-type: none"> Paper & chemicals production Auxiliary processes in cement production & food processing 	Next-generation geothermal can provide midrange temperatures across a wide geography.
200-400°C	<ul style="list-style-type: none"> Petrochemical cracking Cement & steel pre-processing Aluminum smelting 	Fuel combustion or direct electricity use will most likely remain necessary.

Kawerau Geothermal Field in New Zealand highlights existing direct-use geothermal industrial heating

Geological conditions

- 250-310°C** downhole temperature range
- 35 km²** area covered by the geothermal field
- 350-570 MW** estimated available resources

Key industrial processes

- Paper & pulp mill 
- Wood drying 
- Dairy processing 

Geothermal energy suppliers

- Ngāti Tūwharetoa Geothermal (heating)
- Eastland Generation, Mercury Energy (power)

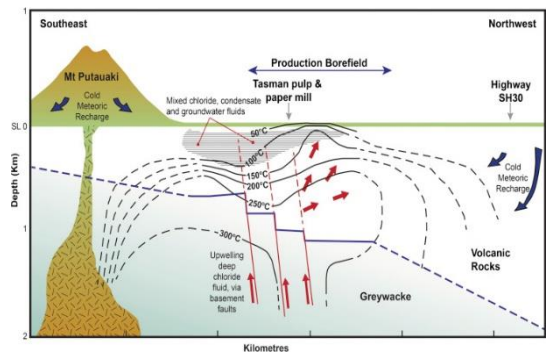
Ngāti Tūwharetoa Geothermal

Supplies various industrial customers in Kawerau

Process steam supplied at pressures of **7-16 bar** and process water at **170°C**

~14.8 PJ geothermal energy produced annually

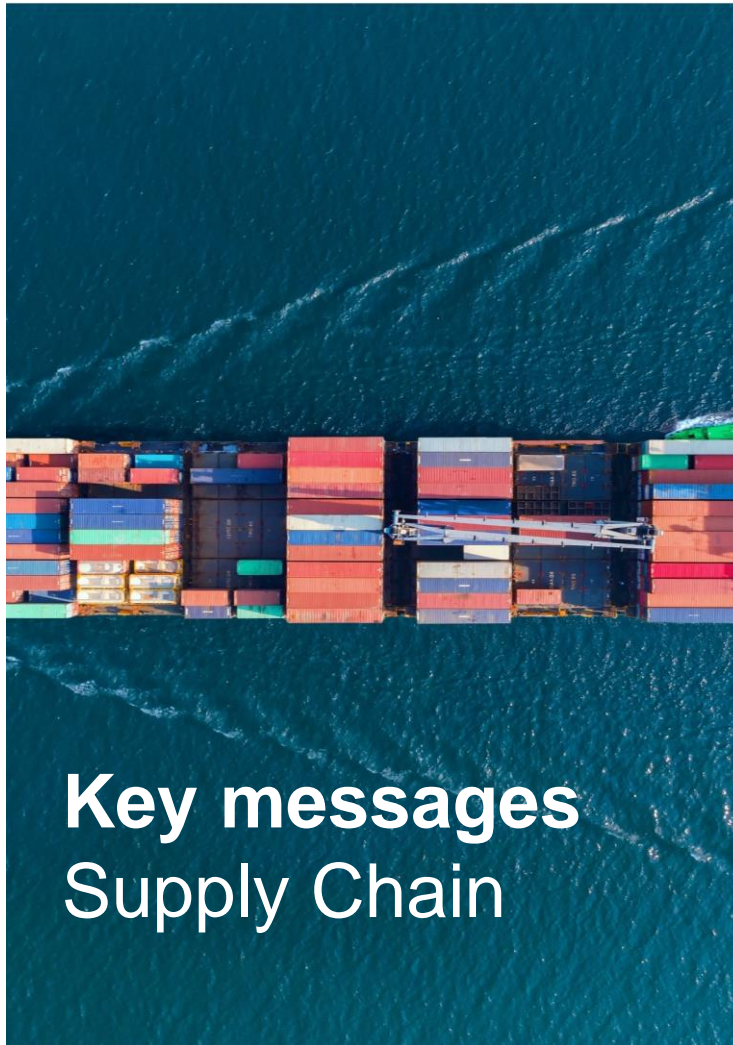
90% less carbon; 0.007 tCO₂e/GJ compared with LNG (0.054 tCO₂e/GJ)



Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [New Zealand Geothermal Association, Kawerau Geothermal Field](#); Tūwharetoa Geothermal, [Geothermal Operations](#).
 Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).



Geothermal Heating and Cooling Supply Chain



Geothermal heat pumps (GHPs) rely on **critical raw materials** like copper, aluminum, steel, and refrigerants, making them **vulnerable to supply chain disruptions**.

Shared supply chain dependencies with other renewable energy sectors create risks for material availability, cost fluctuations, and project feasibility. For instance, copper demand is surging due to its role in solar PV, wind turbines, and EV manufacturing, leading to supply constraints and price volatility.

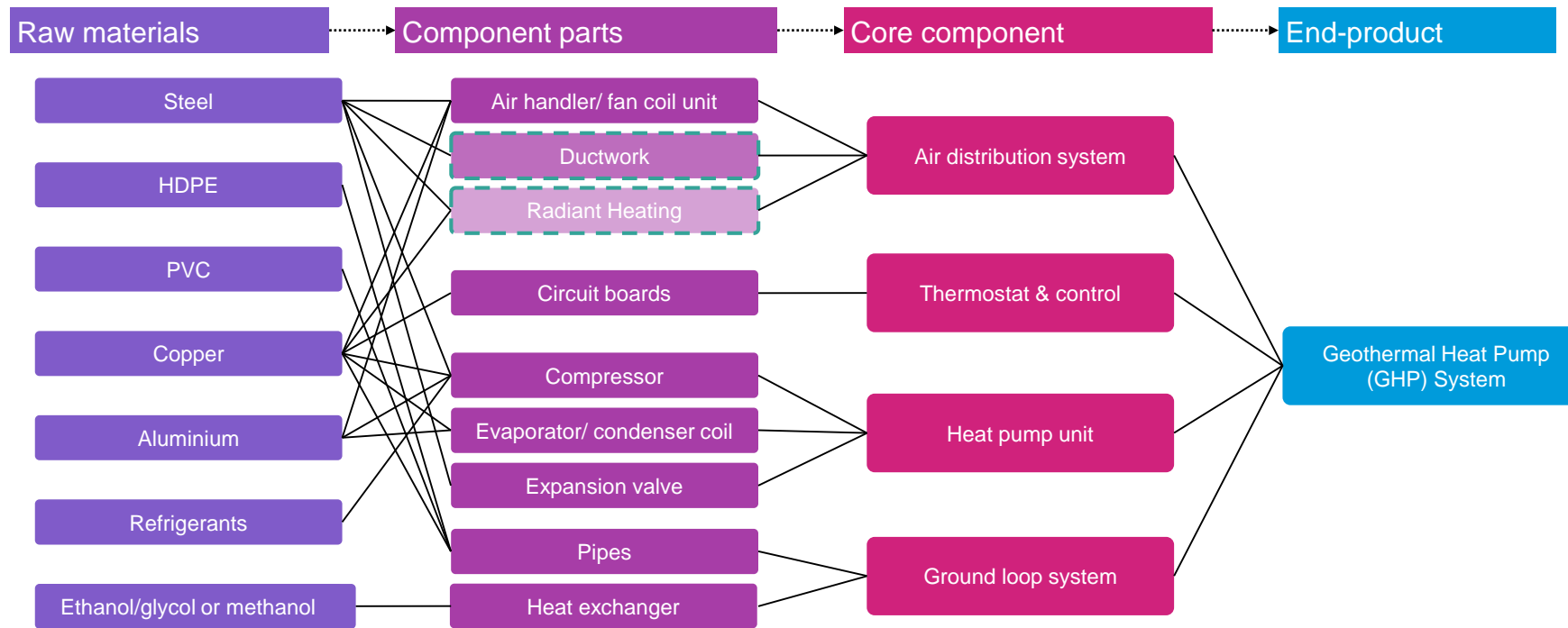
Lack of access to drilling rigs can be a **constraint** for deep geothermal projects, especially for heating and cooling applications in areas without nearby oil and gas activity. In the U.S., geothermal rigs make up only **0.5%** of active rigs, while **81.6%** are used for oil and **17.9%** for gas. In regions where oil and gas operations are active, geothermal developers can often access the same rigs, crews, and supply chain.

Air-source heat pumps (ASHPs) **dominate the market** (93% vs. 1.5% for GHPs) due to **lower costs and easier installation**. Regulatory, labor, and installation challenges make **ASHPs the preferred choice for consumers**, shifting **industry focus and investment away** from GHPs.



The **workforce trained in geothermal drilling, installation, and maintenance** is limited, which is a significant barrier to industry scaling. Countries and corporations must invest in **workforce expansion, licensing reforms, and training programs** to scale geothermal adoption.

Geothermal heat pump systems comprise four core components that consist of a significant share of common raw materials

Simplified materials breakdown of the GHP value chain



Exploration and raw materials → Development → End use

 For forced-air systems  For hydronic systems HDPE: High-density polyethylene PVC: Polyvinyl chloride

Sources: [Life Cycle Analysis of Geothermal Heating and Cooling System: UIC Case Study](#) (Eco Sciences, 2020).

Credit: Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

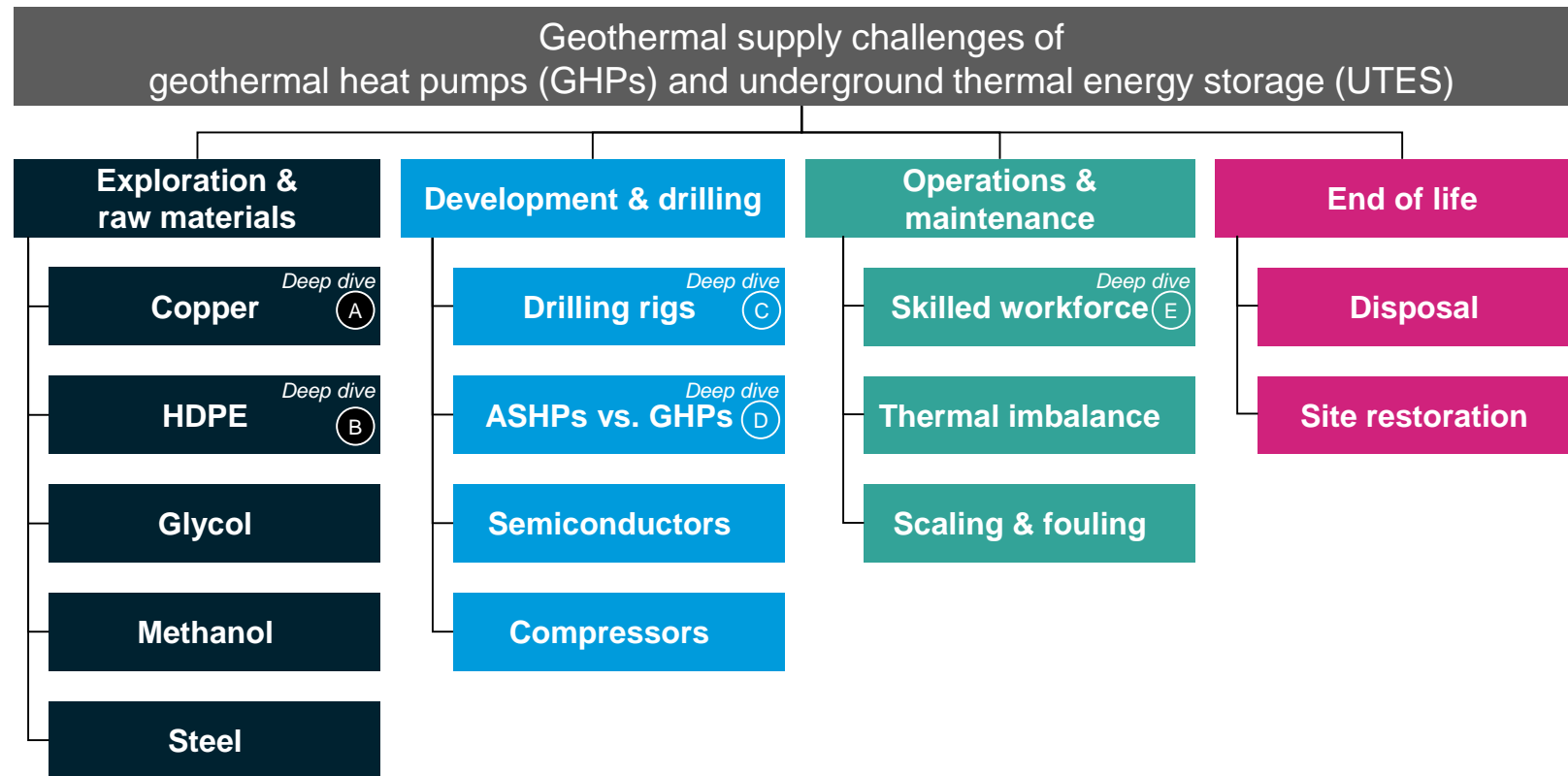
Observations

A geothermal heat pump is generally composed of four elements:

1. Air distribution system
 2. Thermostat and control
 3. Heat pump unit
 4. Ground loop system
- Raw material inputs drive the entire GHP supply chain. Essential materials like steel, HDPE, PVC, copper, aluminum, refrigerants, and ethanol/glycol/methanol (used for antifreeze solutions) are the foundation of component parts manufacturing.
 - The common raw materials demonstrate complex interconnections across the value chain. Multiple raw materials feed into multiple components, highlighting the dependence on supply chain stability, especially for metals such as copper, aluminum, and steel.

Geothermal heating and energy storage face significant challenges across the value chain — specifically for raw materials

Key challenges along the geothermal value chain



Observations

- The demand for **copper** is skyrocketing due to its critical role in renewable energy infrastructure (solar panels, wind turbines) and electric vehicles (EVs).
- Since GHPs require **copper** for their heat exchangers, wiring, and compressors, this puts them in direct competition with solar PV, wind power, and EV manufacturers, leading to supply bottlenecks and price volatility.
- **Drilling rigs** are essential for geothermal systems, but they share similar equipment and expertise with O&G, which drives up costs and limits availability.
- The **skilled workforce** for drilling, maintenance, and system operation is also in high demand for O&G projects, making talent scarce and expensive for the geothermal sector.
- **Disposal** issues stem from hazardous materials used in GHPs, primarily:
 - Refrigerants in compressors
 - Heat transfer fluids (glycol- or methanol-based solutions)
 - Plastics and coatings (HDPE pipes and Teflon seals)
- These materials require **specialized disposal** and recycling infrastructure, adding complexity to the end-of-life phase.

Note: See subsequent slides for deep dives on the challenges highlighted above.

Sources: CKI analysis (2025).

Credit: Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al. "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

A High copper intensity of renewable energies and electric vehicles are propelling copper demand and price surges

Key drivers of copper demand and pricing

Demand driver #1: Renewable energy

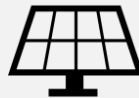
Copper intensity of renewables



Offshore wind
9.6 t/MW



Onshore wind
4.3 t/MW



Solar PV
5 t/MW

Demand driver #2: Electric vehicles

Copper intensity of EVs



Battery electric bus
0.369 t/vehicle

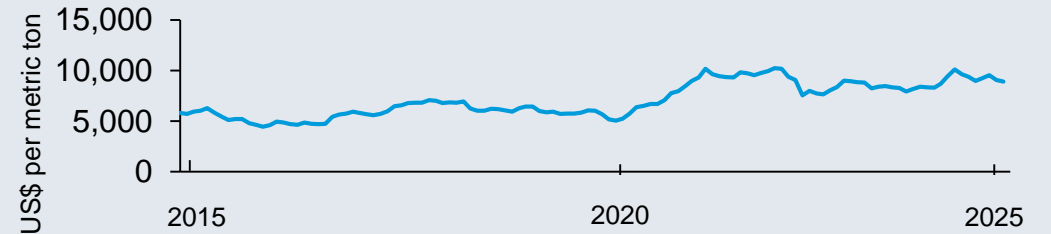


Battery EV
0.083 t/vehicle



Hybrid EV
0.038 t/vehicle

Observations



Copper has the **highest electrical conductivity** of all non-precious metals, making it essential for efficient **power transmission** in renewable energy systems and electric vehicles.

Solar PV systems use **2,450 to 6,985 kg of copper per MW**, while a **660-kW wind turbine contains around 350 kg**, primarily for **wiring, cabling, and heat exchangers**. EVs use **up to four times more copper** than internal combustion engine cars, with fully electric models requiring **up to a mile of copper wiring** in components like motors and inverters.

Copper demand is expected to **nearly double by 2035**, but the limited economically recoverable portion of global copper resources poses risks to the energy transition.

Citi forecasts copper prices will **hit US\$10,000 per metric ton by the end of the year**, climbing to **US\$12,000 by 2026**, driven by strong demand and tight supply.

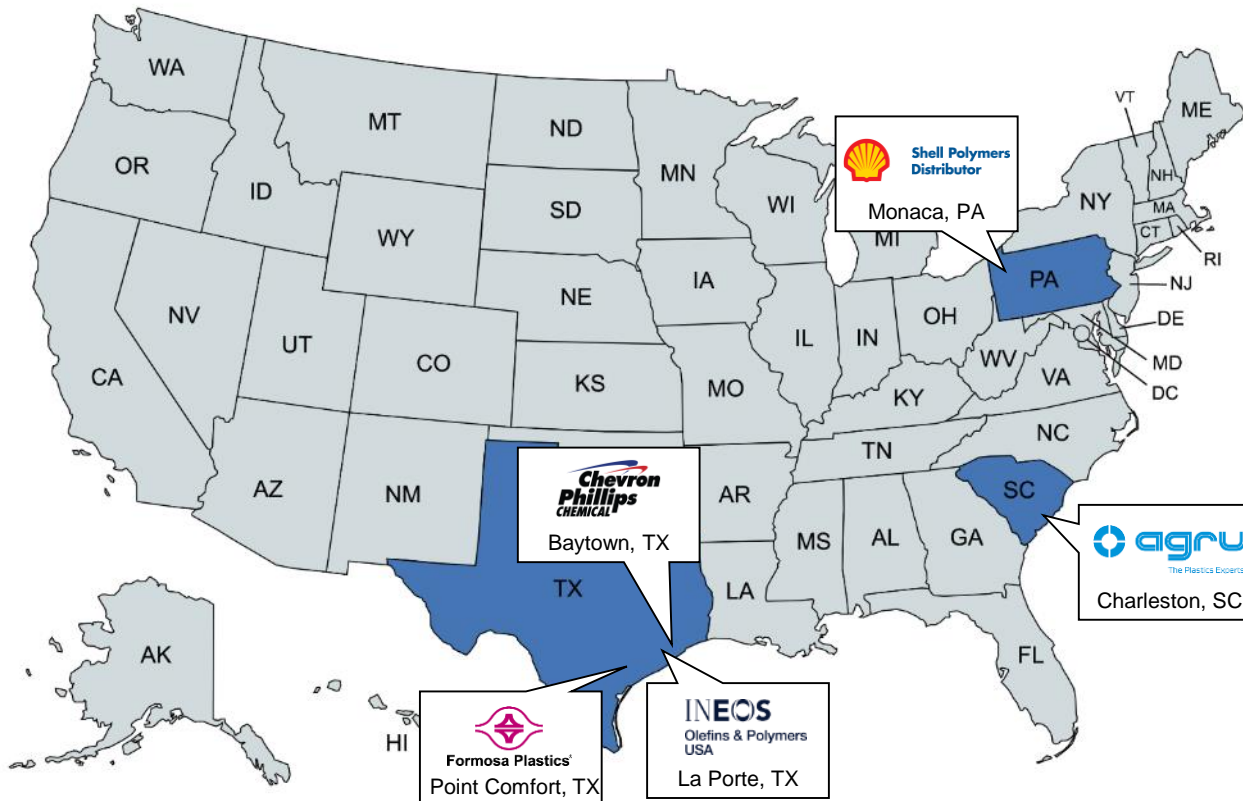
Geothermal systems' low copper intensity offers a cost and supply chain advantage as rising copper demand pushes up prices — making it more resilient than wind or solar.

Sources: [Copper prices climb to 2024 high](#) (CNBC, 2024); [Copper's Price Breakout and Big Role in a Net Zero World](#) (Carbon Credits, 2024).

Credit: Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al. "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

B Clustered along the U.S. Gulf Coast, HDPE resin facilities face natural disaster disruptions, leading to supply shortages

Major HDPE resin facilities in the United States



HDPE scarcity root causes and consequences

High-density polyethylene (HDPE) production relies on petrochemical feedstocks like ethylene monomer and co-monomers, requiring a stable supply chain. However, **recent extreme events** have disrupted these key chemicals, leading to shortages. The **U.S. Gulf Coast**, home to major HDPE resin factories, has faced repeated disruptions, including:

Weather disasters

- Severe weather events, including **Gulf Coast hurricanes** and the **Texas freeze** in February 2021, shut down resin plants unprepared for extreme conditions.
- These disruptions severely **reduced HDPE resin supply** nationwide, leading to shortages.

Pandemic shutdowns










- **COVID-19 outbreaks** caused **temporary plant closures** and **workforce shortages** in chemical and plastics factories.
- **Restarting** complex chemical plants **took time**, delaying production and worsening shortages despite rising demand.

Production and demand Imbalances: Coming out of pandemic lockdowns, demand for plastic materials surged. HDPE pipe manufacturers saw resin prices skyrocket **60 cents per pound from January 2020 to mid-2021** (versus the pre-2020 norm of 1- to 2-cent annual increases). This extreme resin demand and shortage left pipe makers with limited inventories and **backlogs of six to eight months on orders**.






Sources: [Limited Supply and High Demand Keep HDPE Pricing High Through 2021](#) (United Poly Systems, 2021); [Circumvent Polyethylene Supply Disruption with Strategic Suppliers](#) (Shell USA, n.d.); [What's Behind the Shortage of HDPE Products](#) (Polymershapes, n.d.).
 Credit: Pia Doris Morrow, Isabel Hoyos, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

While shallow geothermal heating rigs are readily available, deep drilling rigs remain largely controlled by the oil & gas industry

U.S. land rig market segmentation and key players

	Oil drilling rig	Gas drilling rig	Geothermal drilling rig ¹
Description	Extraction of crude oil from underground reservoirs, often using rotary or directional drilling techniques	Extraction of natural gas from underground formations, including conventional and shale gas reservoirs	Access to underground heat by drilling deep wells into hot rock formations
Market share (2024)	81.6% 	17.9% 	0.5% 
Active rig count (2024)	473	104	3
Avg. rig count (2013-2024)	700	172	2
Key players	 NABORS 	 PATTERSON-UTI DRILLING COMPANY LLC	 Geoprobe  

Recent joint ventures in the geothermal drilling space

-  **OMV and Wien Energie (“Deeep,” 2024):** Deep geothermal energy for up to 20,000 Viennese households from 2028 on; scalable to 200,000 households.
-  **Elemental Energies and Iceland Drilling (2025):** Subsurface-to-drilling service integration.
-  **Arverne Group and Herrenknecht (“DrillDeep,” 2024):** \$4.7M by Herrenknecht backs Arverne’s \$2.6B geothermal-lithium push.
-  **Quaise Energy and Nevada Gold Mines (2024):** Targets 30% GHG cut by 2030; enables 10x more power per well.
-  **Chevron and Baseload Capital (2022):** Scaling from ~1 MW San Ardo pilot to Weepah Hills project, accelerating geothermal retrofits in U.S. oilfields.

1. Used for deep geothermal drilling.
 Sources: [Worldwide Rig Count Report](#) (Baker Hughes, 2025); [Climate-neutral district heating: Wien Energie and OMV establish joint venture for deep geothermal energy](#) (OMV, 2023); [Elemental Energies and Iceland Drilling launch global geothermal joint venture](#) (Elemental Energies, 2025); [Arverne Group Partners With Herrenknecht AG for Its Deep Drilling Operations](#) (Businesswire, 2024); [Quaise Energy and Nevada Gold Mines Partner on Deep Geothermal Pilot Plant to Decarbonize Mining](#) (Quaise Energy, 2024); [Chevron and Baseload Capital create joint venture to explore geothermal development opportunities](#) (Chevron, 2022).

Credit: Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* “Geothermal Heating and Cooling,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Drilling for sustainable heat: OMV and Wien Energie join forces to tap deep geothermal for Vienna

Joint venture “Deeep”



In **November 2023**, **Wien Energie** and **OMV** founded the **joint venture “Deeep”** to develop deep geothermal projects in Greater Vienna.

Project Scope

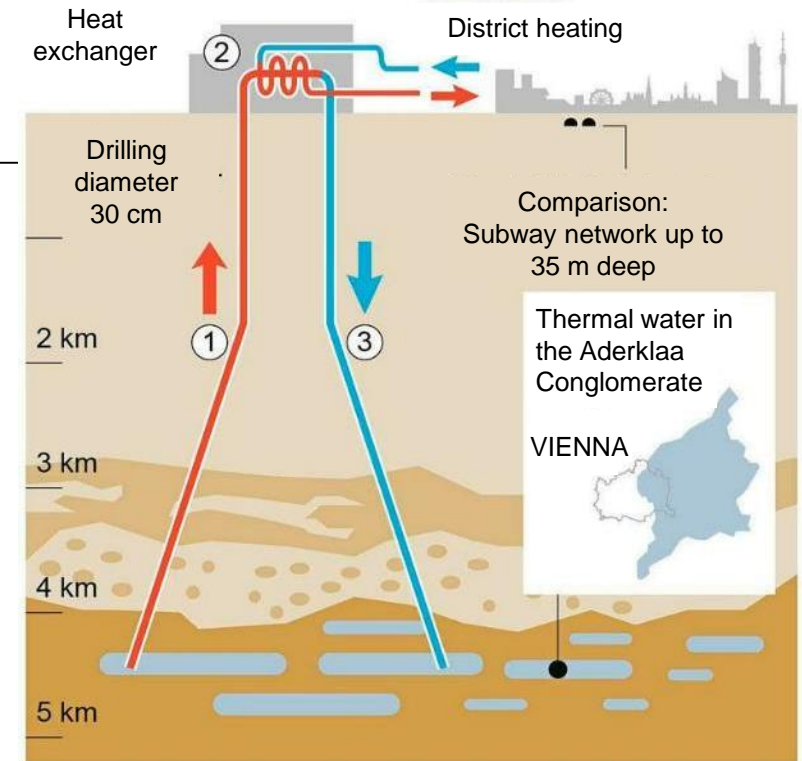
- Up to **200 MW** of geothermal capacity planned
- Aims to supply **200,000 households** with climate-neutral district heating
- Supports Vienna’s **2040** climate-neutral heating target

Initial Project: Aspern, Vienna-Donaustadt

- Located above a geologically **favorable basin** with high water availability and heat flow
- Part of Vienna’s **urban expansion zone** — ideal for integrating infrastructure and clean energy
- Drilling depth:** Up to **3,000 meters** to access deep geothermal heat
- Drilling begins:** December 2024
- Operations start:** 2028

Strategic Partnership

Combines OMV’s expertise in deep drilling with Wien Energie’s district heating network, supporting Vienna’s target of climate-neutral heating by 2040



- ① Thermal water is pumped up.
- ② Heat from deep water is transferred and fed into district heating network.
- ③ Cooled water is returned to the depths.

Graph: APA, Source: Wien Energie









Sources: [Preparations are being made to start drilling for the first deep geothermal plant in Vienna](#) (OMV, 2024); [Climate-neutral district heating: Wien Energie and OMV establish joint venture for deep geothermal energy](#) (OMV, 2023); [OMV and Wien Energie partner for deep geothermal in Vienna, Austria](#) (ThinkGeoEnergy, 2023).

Credit: Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* “Geothermal Heating and Cooling,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

D The increasing adoption of ASHPs is shifting manufacturing and investment priorities away from geothermal heating and cooling

Comparison of ASHPs vs. GHPs

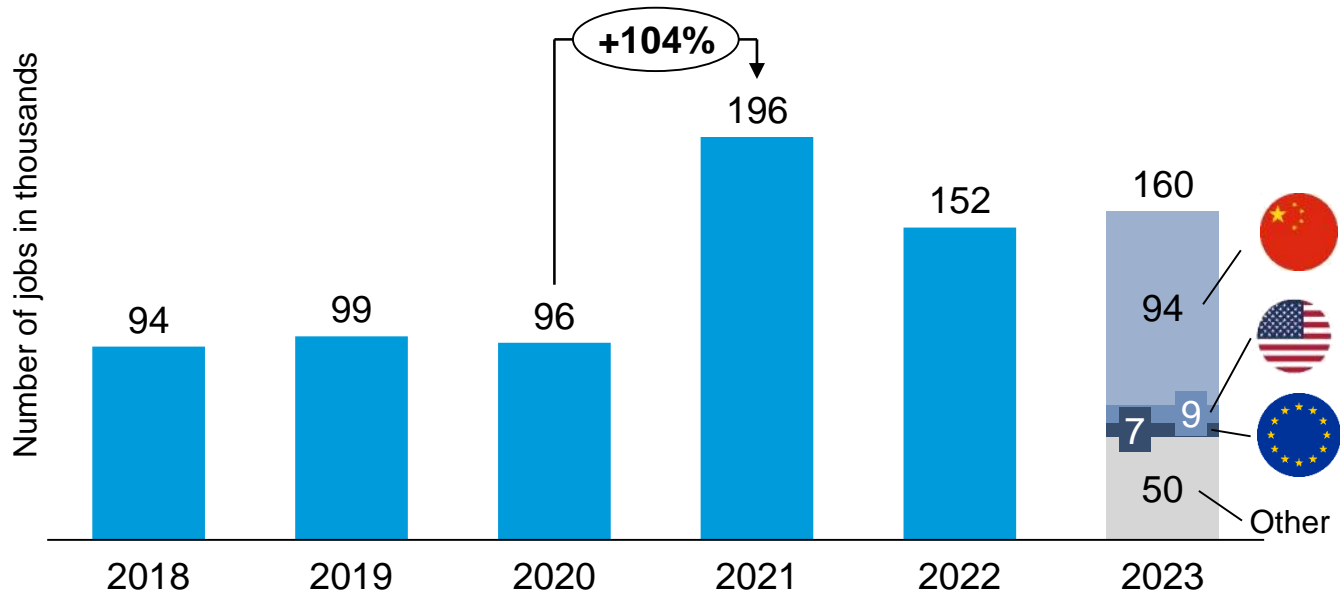
	Air-source heat pump	Geothermal heat pump
Description	<ul style="list-style-type: none"> Transfers heat between the air and a refrigerant to provide heating and cooling 	<ul style="list-style-type: none"> Uses underground loops to extract and dissipate heat for more efficient heating and cooling 
Market share	<ul style="list-style-type: none"> 93% share of U.S. heat pump market (2022), 13% of installed residential heating (15.9 million homes) 	<ul style="list-style-type: none"> 1.5% share of U.S. heat pump market (2022), 1% of installed residential heating (1.3 million homes) 
Investment costs	<ul style="list-style-type: none"> \$3,000 - \$10,000 for residential systems \$214 - \$714 per kW for 4-ton system (14 kW) 	<ul style="list-style-type: none"> \$10,000 - \$30,000+ due to ground loop installation \$714 - \$2,143 per kW for 4-ton system (14 kW)
Installation complexity	<ul style="list-style-type: none"> Easier installation and less regulatory hurdles; can be retrofitted to most buildings 	<ul style="list-style-type: none"> Requires drilling or trenching for ground loops with respective permits, making it more labor-intensive
Key manufacturers		

Sources: [Air source heat pumps vs. geothermal heat pumps](#) (EnergySage, 2024); [US Country Report](#) (Heat Pumping Technologies, n.d.); [Pathways to Commercial Liffoff: Geothermal Heating and Cooling](#) (DOE, 2024).

Credit: Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

E To stay competitive, geothermal must grow its workforce through investments in education, automation, oil & gas talent migration

Global number of geothermal energy jobs (2018-2023)



The geothermal industry experienced a sharp rise in jobs from 96,000 to 196,000 in 2021, but growth has since stagnated. In contrast, the oil and gas sector employed 12.4 million people in 2023 — a 5% increase from the previous year — with further growth expected in the coming year.

China leads in geothermal employment, while the U.S. and EU must take strategic actions to expand their workforce.

Action implications for geothermal workforce expansion

- Transition of oil and gas talent and workforce to geothermal energy
- Investments in education and training
- On-the-job training and apprenticeships
- Technology and automation for complex operations
- Diversity and inclusion of underrepresented groups

Sources: [Number of geothermal energy jobs worldwide in 2023, by region](#) (Statista, 2024); [Number of geothermal energy jobs worldwide from 2018 to 2023](#) (Statista, 2024); [DOE Liftoff Report: Geothermal heating and cooling](#) (DOE, 2025); [World Energy Employment 2024](#) (IEA, 2024).

Credit: Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

E Connecticut leads by example, tackling workforce shortages and supply chain bottlenecks with strategic and targeted solutions

Context

The **Connecticut Geothermal Workforce Development Plan** was created for the District Geothermal Heating + Cooling Deployment project in **Wallingford, Connecticut**.

Funded by the **U.S. Department of Energy**, the initiative aims to develop a **low-temperature geothermal heating and cooling system** for a **low-income community**.

Led by the **Connecticut Department of Energy and Environmental Protection** and a **coalition of partners**, the plan addresses **workforce gaps** through a **needs assessment and workshops**, proposing strategies for **workforce expansion over 30 months**.

Implementation depends on securing **additional funding**, including support from the **New England Heat Pump Accelerator Coalition**.

Needs assessment

The Connecticut Geothermal Workforce Needs Assessment, conducted by NEEP between October 2023 and April 2024, identified **three key barriers to geothermal adoption**:

1. **Lack of awareness and interest** in geothermal careers
2. **Workforce shortages amid rising project demand**, particularly in drilling
3. **High upfront costs, limiting system adoption** and workforce growth

Surveys were conducted with industry stakeholders, including utilities, training centers, and drilling companies, with **19 interviews** and **11 survey responses** collected.

Workshops in May 2024 brought together **45 industry representatives** to discuss licensing, training, drilling, and workforce expansion.

Action steps for identified bottlenecks

Incorporating equity

Set **equity-based recruitment goals**.

Invest in **targeted outreach**.

Provide **financial support**.

Offer **wraparound services** like childcare and transportation stipends.

Track **demographic data**.

Recruiting new entrants

Launch **awareness campaigns**.

Expand **education** in technical high schools and community colleges.

Increase **hands-on learning opportunities**.

Engage **unions and workforce organizations**.

Increasing license accessibility

Clarify **licensing rules**.

Streamline the **licensing process** for workers.

Develop a **heat pump-specific license**.

Provide **guidance and outreach** to help workers understand licensing requirements.

Fostering rig availability

Retrain **existing well water and oil drillers**.

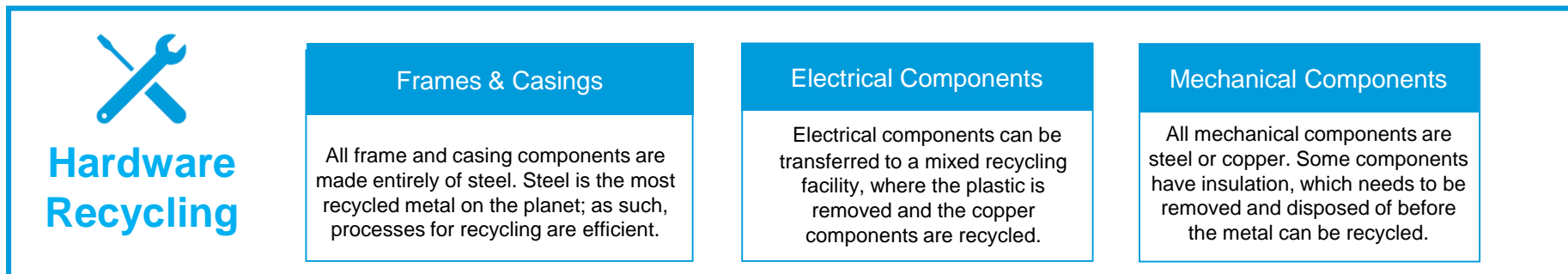
Support **union apprenticeship programs**.

Encourage **public ownership of drilling rigs**.

Establish a **centralized Drilling Center of Excellence**.

F Responsible disposal protects full lifecycle sustainability of geothermal heating and cooling systems

Solution: Companies entering disposal stage services



Observations


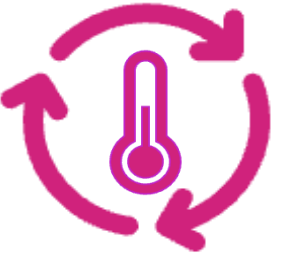
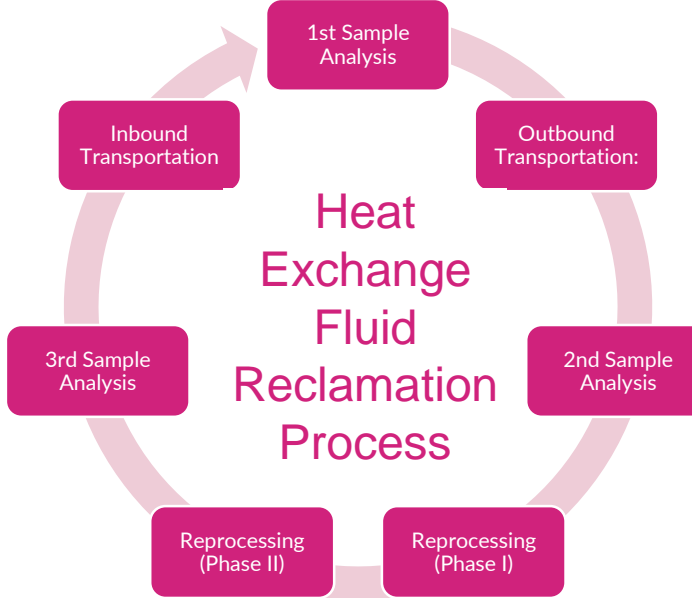
- Proper disposal of geothermal systems involves safely removing refrigerants and fluids to prevent emissions and recycling hardware to preserve climate benefits. HVAC contractors, installers, or specialized firms are typically capable of handling this process.
- Most hardware components are steel or copper, with insulation removed before recycling. Electrical parts go to mixed recycling where plastics are separated and copper is recovered. Frames and casings, made entirely of steel, are easily recycled through established processes.

Sources: [IVT heat pump recycling scheme](#) (Alto Energy, 2025).

Credit: Zacharia Thurston, Pia Doris Morrow, Faradisa Anintya, Hassan Riaz, Una Oljaca, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

F Responsible disposal protects full lifecycle sustainability of geothermal heating and cooling systems

Solution: Companies entering disposal stage services

  <p>Heat Exchange Fluid Reclamation</p>	<h3>Highlights</h3> <p>Offers a sustainable alternative to incineration or landfill disposal. Allows reuse of reclaimed fluids, avoiding full replacement and yielding significant cost savings — especially in large systems. Reclaimed fluids match the performance of virgin fluids and are suitable for continued use. Relatherm has successfully recycled various fluids including Dowtherm A®, Therminol® VP-1, Therminol® 66, Marlotherm SH, and Therminol® 55. Reprocessing yields range from 50 to 95%, depending on degradation severity. Virgin fluid top-off is provided when needed.</p>	 <p>Heat Exchange Fluid Reclamation Process</p>
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Observations

- Proper end-of-life management for geothermal systems requires safely removing refrigerants and heat transfer fluids to prevent emissions and contamination, along with responsibly recycling hardware like piping and pumps to preserve climate benefits. Such work can be done by HVAC contractors, installers, or reclamation firms.
- Relatherm provides a sustainable, cost-effective solution by reclaiming thermal fluids such as Dowtherm A®, Therminol® VP-1, Therminol® 66, Marlotherm SH, and Therminol® 55. The process restores used fluids to near-virgin quality, achieving **50-95% recovery rates**. This reduces waste, cuts disposal costs, and minimizes the need for full fluid replacement.

Sources: [Heat transfer fluid reclamation and recycling](#) (Relatherm.com, 2024).

Credit: Zacharia Thurston, Pia Doris Morrow, Faradisa Anintya, Hassan Riaz, Una Oljaca, and and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Emerging supply chain trends emphasize cost reduction through modular design, predictive maintenance, and circularity

Trend #1

Modular geothermal systems

Modular geothermal systems are gaining traction due to their scalability, reduced installation time, and cost effectiveness.

The systems allow for phased implementation, making geothermal solutions more accessible for various building types.

First movers:



BedrockEnergy

Trend #2

AI for predictive maintenance

Artificial intelligence is impacting HVAC systems by enabling predictive maintenance, which anticipates equipment failures before they occur.

The use of AI enhances system reliability, extends equipment lifespan, and reduces operational costs.

First movers:



kensa

Trend #3

Circular economy for GHPs

The principles of reuse, refurbishment, and recycling of products and materials to minimize waste also apply to geothermal systems.

This includes designing systems for longevity, using recyclable materials, and establishing take-back schemes for end-of-life components.

First movers:

SULZER

Annex 65



Geothermal Heating and Cooling Global Policy



Four key policy priorities can help scale geothermal heating and cooling (H&C) deployment and lower costs.

- **Global collaboration** on geothermal energy largely favors power generation over H&C.
- As a human capital-intensive industry, **transitioning the oil and gas workforce**, which has extensive overlapping competencies with the geothermal sector, is a high policy priority.
- **Strong funding for R&D** is key in scaling geothermal H&C across diverse geographies and in driving down next-generation geothermal costs.
- Geothermal projects carry high early-stage risks, necessitating strong **risk mitigation policies** to incentivize adoption.

Current policy on geothermal H&C remains an afterthought in the global policy landscape.

- Only **~30 countries** have active geothermal H&C policies compared with **>100** for solar PV and wind.
- Strong H&C policy is concentrated in Europe, while China leads in deployment on the domestic level.
- While the **U.S. has the second-highest installed H&C capacity**, fragmented federal policy has prevented economies of scale in the industry.
- Geothermal H&C leads in deployment, yet there are more active policies in place for power generation.

Country-level geothermal H&C policy, primarily in Europe and China, has **enabled conventional geothermal to scale and next-generation technologies to take root.**

- China's robust R&D policy support **enabled Sinopec to double its installed H&C capacity in four years.**
- While Iceland punches above its weight in the sector through workforce development, France's risk mitigation schemes have supported **81% of conventional geothermal adoption since 1970.**
- Through streamlined permitting policy, the number of exploration permits for deep geothermal plants in Germany **doubled from 82 in 2023 to 155 in 2025**; these permitting improvements may serve as a model for the Netherlands, which aims to similarly scale geothermal H&C adoption.

Four key policy priorities can help scale geothermal heating & cooling deployment and drive down costs



Global Collaboration

Global collaboration on geothermal energy – particularly heating and cooling – lags behind other renewables, slowing innovation and increasing risk. Stronger, more large-scale collaboration is a priority.



Workforce Development

Geothermal expansion will require a skilled workforce in engineering, geology, and drilling sectors. Transitioning the oil and gas workforce will streamline geothermal workforce development.



Research & Development

Poor funding infrastructure for geothermal exploration and drilling drives up investment costs and slows technological progress. Strong funding mechanisms will be necessary to speed geothermal deployment.









Risk Mitigation

Geothermal projects have higher predevelopment risks compared with other renewable energy technologies due to complex geological and subsurface conditions. Mitigating risk is critical in lowering project costs.

Observations

- Stronger implementation of policy goals could **boost new geothermal heat developments 50% by 2030** in the APS compared with the Stated Policies scenario.
- Strong policy can also help drive **next-generation geothermal cost reductions of up to 80%** by 2035.
- In the APS, expanding policy support and cost reductions would **scale GHP consumption to almost 3,000 PJ — 50% higher than in the Stated Policy scenario** (China, U.S., and Europe together account for 80% of this growth).
- Almost **two-thirds of geothermal power capacity additions between 2024 and 2030** are expected to be policy-driven – primarily tax credits, fixed tariffs, and premiums.

Global collaboration favors geothermal power production, leaving room for growth in heating and cooling expansion

Scale	Heating & Cooling	Power Generation
Global	 <p>Although World Bank does not have a dedicated global program for geothermal heating, it has provided one-off investments in district heating in countries including Türkiye and El Salvador.</p>	 <p>The Global Geothermal Development Plan (GGDP), launched by ESMAP in 2013 to scale geothermal power, has supported 13 countries and brought three projects online.</p>
Regional	 <p>Geothermica's €32.5 million Joint Call 2021 aims to accelerate geothermal heating and cooling projects by 2030 through large-scale, commercially viable projects.</p>	 <p>The GRMF finances geothermal power projects in East Africa, expanding to include heating in 2022; 26 power and 5 direct-use projects have received funding.</p>
Bilateral	 <p>The German Agency for International Cooperation and the Central American Integration System have cooperated on geothermal heating and cooling in El Salvador, including a pilot geothermal-powered coffee dryer.</p>	 <p>Japan's International Cooperation Agency invests in building geothermal power capacity in Latin America and Africa, including over 400 MW of geothermal power plants in Kenya.</p>

Drivers of variable global collaboration on geothermal power versus heat

- Heating projects tend to be more localized, limiting returns compared to large-scale power projects.
- There is a differential global emphasis on electricity access compared to heating access.
- The development of EGS has spurred greater collaboration on geothermal power generation.
- Scalability of power projects attracts greater private investment.




Opportunities for collaboration on H&C

- Integrate geothermal heating into decarbonization strategies.
- Develop standardized financing mechanisms.
- Invest in combined heat and power projects to maximize returns.

Sources: [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [GRMF](#) (2025); [Promoting Development in Kenya: Six Years of Partnerships](#) (JICA, 2025); [Third series of funded projects](#) (Geothermica, 2021); [Global Geothermal Development Plan](#) (ESMAP, GGDP, n.d.); [The Global Geothermal Development Plan: Mitigating Upstream Cost and Risk](#) (World Bank Group, 2020). Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Leveraging oil & gas capabilities can lower geothermal power costs and accelerate deployment

○○○○○ Level of shared competencies ●●●●●

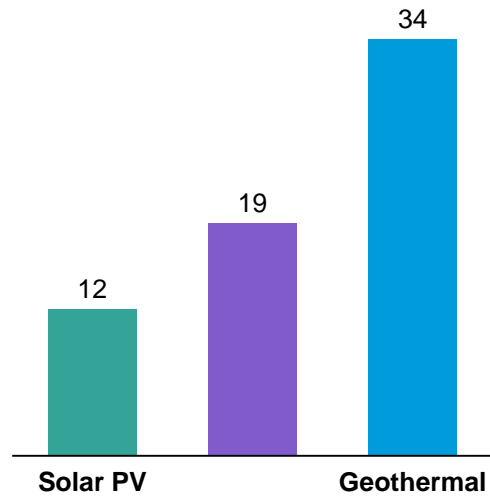
Problem	Current Challenge	Oil & Gas Synergy	Limitations	Case Example
Resource Identification  ●●●●○	Accurate geothermal resource identification and modeling require multi-parameter surface data (seismic, geology, heat flow, permeability).	Oil and gas surface imaging and drilling data reduce exploration risk and improve reservoir targeting .	Legacy oil and gas datasets often lack thermal gradient resolution or long-term heat recharge data .	Hungary and the Netherlands: Open oil and gas subsurface databases reduce geothermal exploration costs and uncertainty.
Skilled Workforce Needs  ●●●●○	Skilled workforce shortages in reservoir engineering and well completion delay project scaling.	Oil and gas professionals have skills that can apply to geothermal exploration, development, and operation .	Current policy frameworks provide limited financial incentives for geothermal workforce transfer.	DOE Geothermal from O&G Initiative: Demonstrates feasibility of cross-sector workforce and skill transfer.
Drilling Costs  ●●●○○	Subsurface drilling represents 60 to 80% of total next-generation geothermal CapEx.	Hydrocarbon well technology (e.g., horizontal drilling, multistage stimulation) can be directly transferred to EGS .	Geothermal wells require sustained reinjection and higher temperatures tolerance than O&G operations.	Fervo Energy's Project Red: Achieved record flow rates by adapting shale fracking and fiber-optic monitoring.
Co-production and Well Repurposing ●●○○○	High initial exploration, drilling, and completion costs can be a limiting factor in geothermal projects.	Co-production or heat extraction from abandoned wells can de-risk geothermal projects.	Wells require a large heat gradient and flow rate, flexible permitting, and proximity to demand.	Zanskar Project (U.S.): AI-driven reservoir modeling revitalized legacy wells, cutting exploration risk by >50%.

Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [Barriers to Next-Gen Geothermal](#) (IFP, 2023); [Can Zanskar use AI to de-risk conventional geothermal?](#) (Latitude Media, 2025).

Credit: Pia Doris Morrow, Faradisa Anintya, Una Oljaca, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

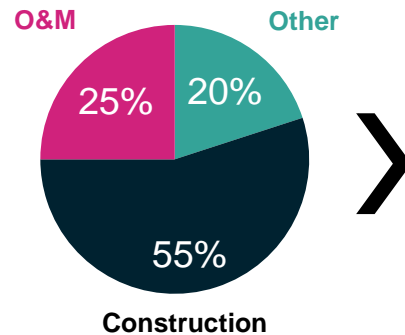
High workforce needs in the geothermal industry create room for skill development and workforce transition from fossil fuel sectors

Job creation per MW installed*

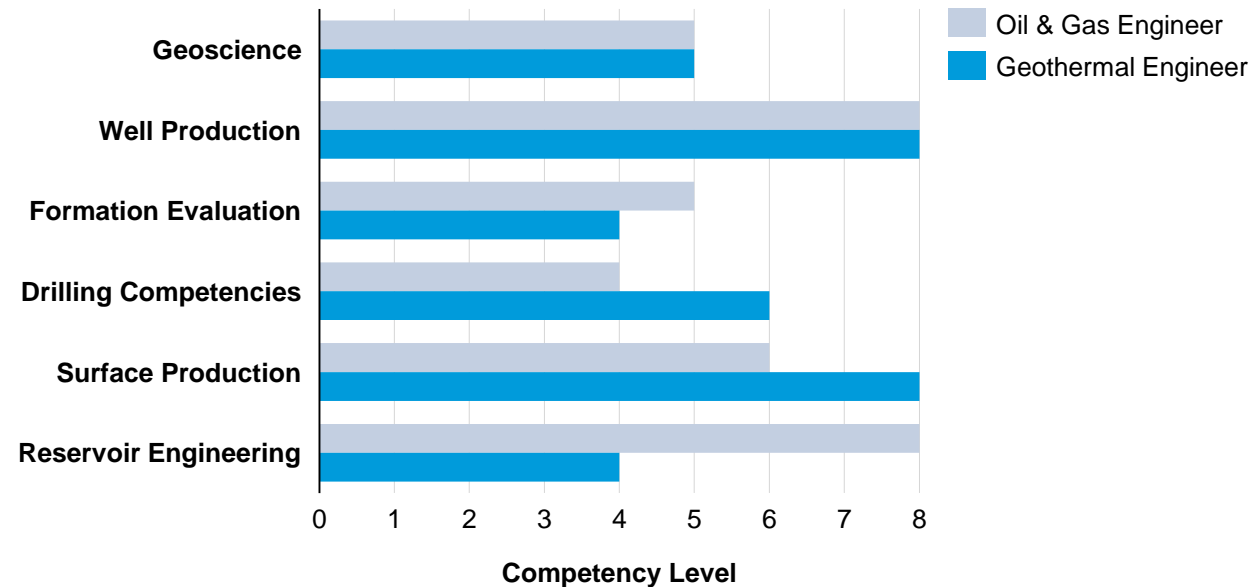


*Both power and H&C

By project phase



Geothermal and oil & gas engineering skillset overlap*



Drivers of job creation in the geothermal industry

- Extensive site exploration, drilling, and subsurface analysis requires skilled labor in the development phase.
- Continuous plant operation, subsurface resource management, and system upkeep contribute to long-term O&M needs.

Transitioning oil and gas workers presents a strong opportunity to meet the skilled workforce needs of the geothermal industry.

*Competency levels based on SPE competency matrices.

Sources: [Geothermal Energy: Unveiling the Socioeconomic Benefits](#) (ESMAP, 2024); [Mission](#) (GRO Geothermal Training Program, n.d.); [The Future of Geothermal Energy](#) (IEA, 2024).

Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Field testing, cross-sector collaboration, and specialized research facilities are key to strengthening R&D

R&D priorities for scaling geothermal H&C

Pilot Projects

Scaling pilot projects is key in field testing and improving new technologies.

Public-Private Partnerships

PPPs enhance data sharing, de-risk innovation, and optimize policy frameworks.

Current Limitation

Only three of 326 projects funded by the EU Innovation Fund were for geothermal R&D.

High upfront costs deter private investment without strong risk-sharing mechanisms.

Highlight

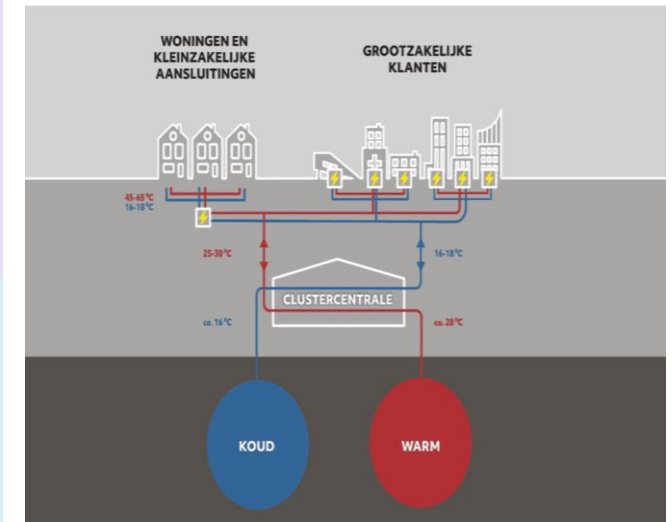
Kirchweidach Deep Geothermal Heating Project: Received funding support from KfW to construct a district heating network in Bavaria.

The DOE's **Community Geothermal H&C Initiative** funded a district-scale geothermal project in Framingham, Massachusetts, in partnership with Eversource.

Case Study: Heerlen Minewater Project | Heerlen, Netherlands

	Timeline	Highlights
Phase 1: Pilot	<p>2003: Pilot project launched for heat extraction from abandoned coal mines</p>	<ul style="list-style-type: none"> Funded by the European Interreg IIB NWE Program Provided H&C to 2 buildings, (>40,000m²)
Phase 2: System Upgrades	<p>2013: System upgraded to a demand-driven, automated thermal smart grid to increase efficiency</p>	<ul style="list-style-type: none"> Supplied heat for 200,000m² of building equivalents 4 MW installed capacity Excess heat provided further input to the grid
Phase 3: Optimization	<p>2020-present: Optimization via a self-learning and adaptive intelligent control framework</p>	<ul style="list-style-type: none"> Funded by the EU's Horizon 2020 65% reduction in regional H&C CO₂ emissions

- ✓ > **€25 million** in EU funding advanced the project in its exploration stage.
- ✓ Restructuring the initiative into a **district-owned enterprise** helped secure private investment and strengthen technical knowledge and capacity.



Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Innovation Fund projects](#) (European Commission, 2025); [Bedretto Lab](#) (2024); [MetroWest Daily News](#) (2024); [Community Geothermal Heating and Cooling Initiative](#) (DOE, 2024); [The use of mine water in district heating systems](#) (EU Publications Office, 2024); [Mijnwater](#) (2025).

Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Successful geothermal risk mitigation policies target early-stage resource and exploration risks; grant schemes lead in nascent geothermal markets

Early-stage geothermal risks and relevant risk mitigation schemes



Limited geological data increases uncertainty.



Lengthy permitting processes can slow project timelines.



High upfront drilling costs can stunt private investment.



Wells may have low temperature or flowrates.

Policy Priorities

Increase data quality and accuracy
Create open-source data repositories

Simplify and consolidate permitting processes
Expand geothermal-specific permitting regimes

Invest in drill efficiency technologies
Expand financial incentives for private-sector investment

Strengthen R&D on subsurface modeling
Account for well failure in subsidies and grants

Relevant Risk Mitigation Scheme(s)

Resource assessment
State-led development

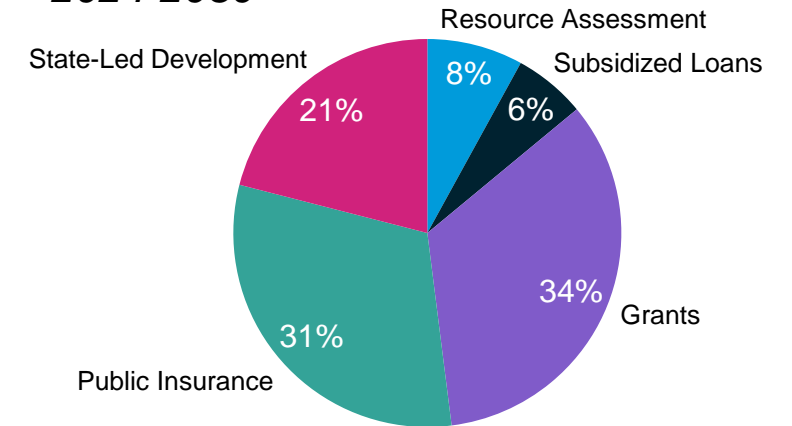
Public insurance
State-led development

Grants
Subsidized loans

Grants
Public insurance

Conventional geothermal capacity additions by risk mitigation scheme

2024-2030



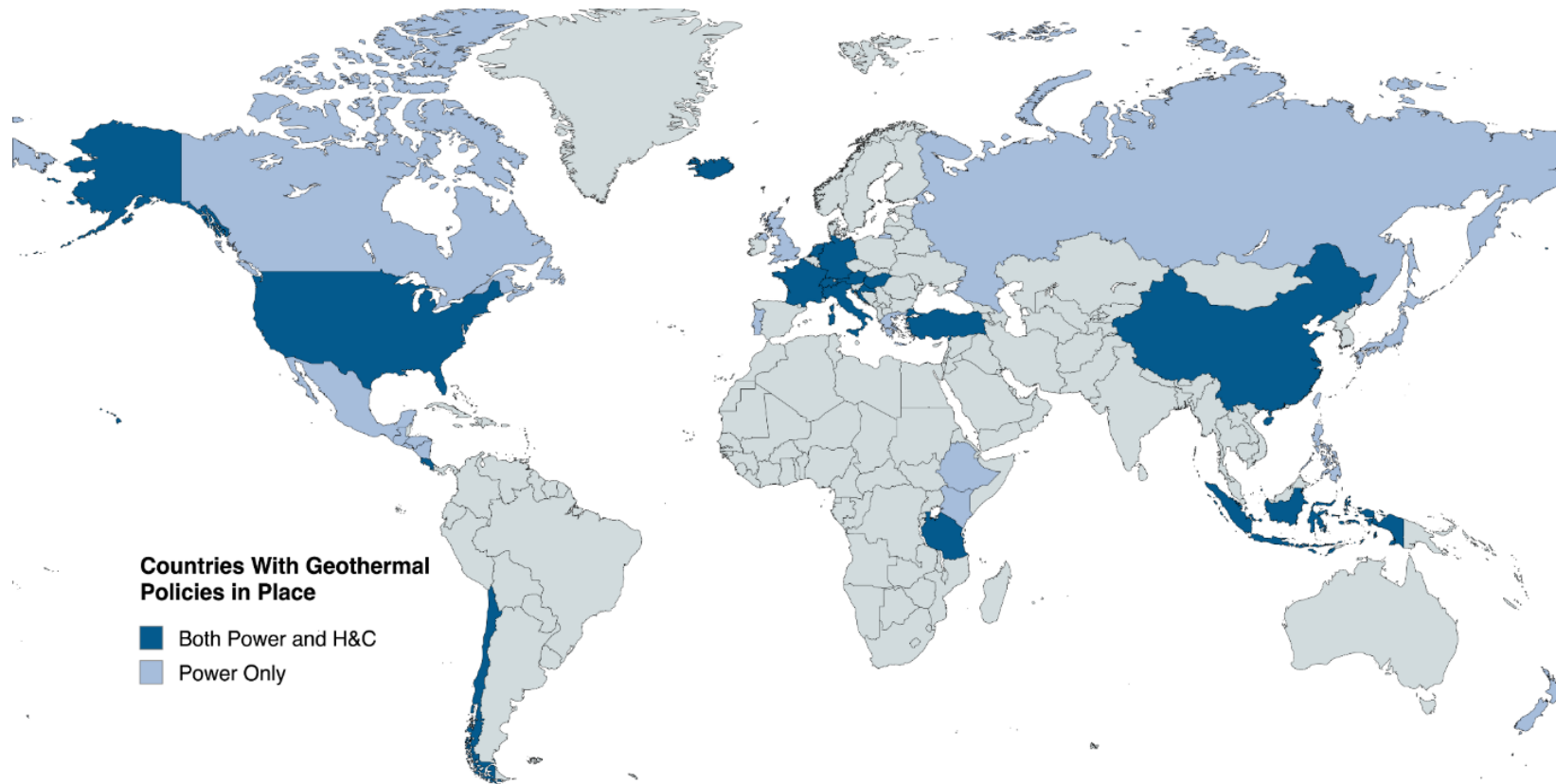
Observations

- Grants are useful and most common in nascent geothermal markets.
- Some schemes target exploration only, while others also support drilling and operations; strong policy supports both.

Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [The successful geothermal risk mitigation system in France from 1980 to 2015](#) (European Federation of Geologists, 2016); [France launches \\$54m geothermal risk mitigation fund](#) (ThinkGeoEnergy, 2015); [EUR 195M guarantee fund approved for deep geothermal projects in France](#) (ThinkGeoEnergy, 2023).
Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Europe leads in geothermal heating & cooling regional policy adoption and collaboration; rest of the world lags behind

Countries with geothermal policies in place, 2024 (risk mitigation and/or remuneration)



Observations

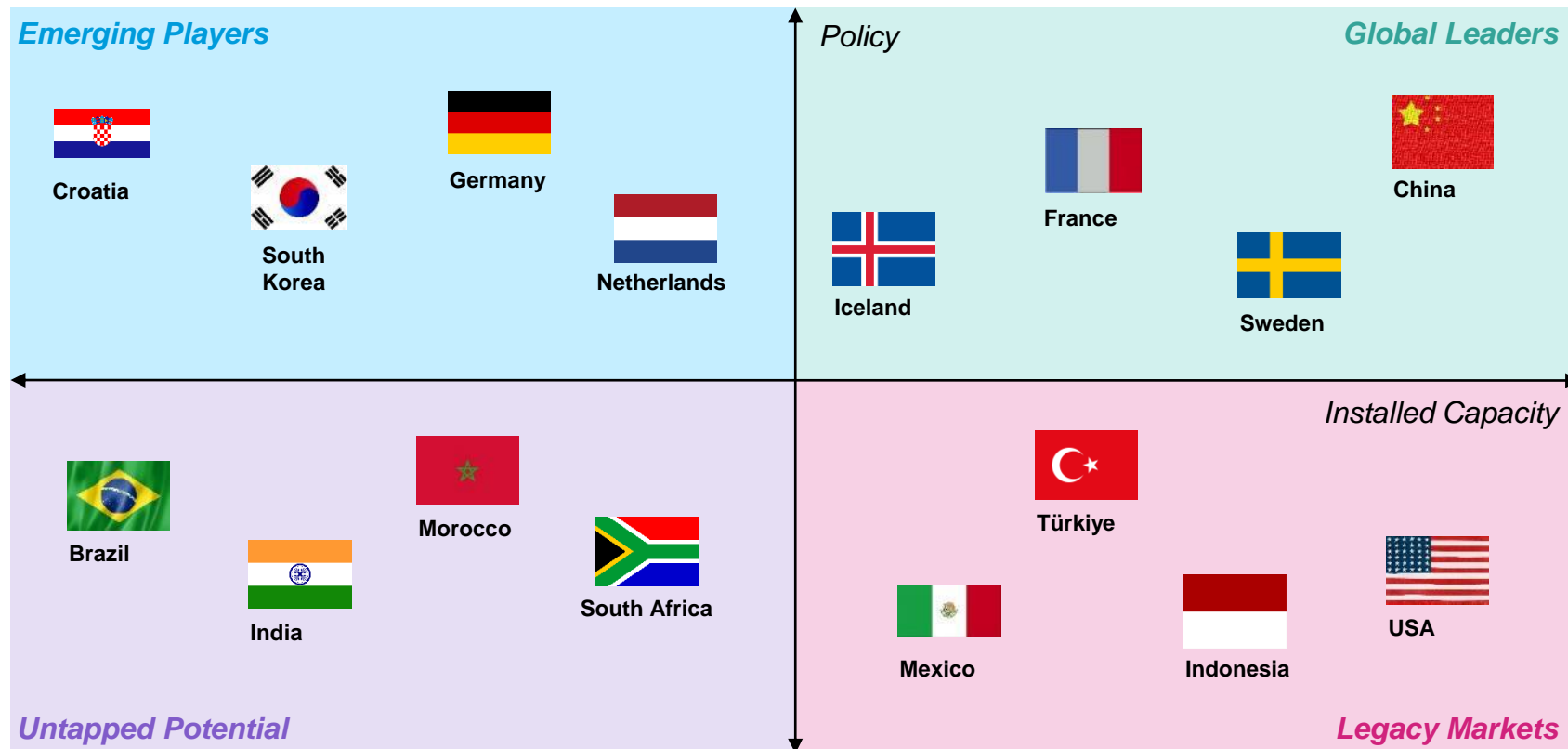
- Over half of all countries with geothermal policies in place (16 of 31) focus **exclusively on power generation**.
- Regional policy schemes in **Latin America** and **East Africa** are not included in this map.
- Only **eight countries** (all in Europe) have adopted geothermal roadmaps for their heating & cooling sectors.
- **>100 countries** have policies in place for solar PV and onshore wind — over 3x as many as for geothermal energy.
- **Europe** is a regional hub for geothermal heating & cooling policies, while **China** leads on the country level.
- Geothermal energy is a priority mitigation option in only **9% of NDCs'** submitted data.
- While the risk mitigation-to-remuneration policy ratio is ~1:2 for solar and wind energy, the ratio for geothermal energy is ~1:1 due to high early-stage risk.

Sources: [Geothermal Energy Database](#) (IGA, 2024); [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023).

Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

While strong policy support is concentrated in China and Europe, installed capacity grows even in subpar policy landscapes

Global policy and installed capacity matrix for geothermal heating & cooling







Observations

- China has one of the strongest policy frameworks, but its geothermal heating policies may not be easily transferrable.
- **In Europe, both domestic and regional interest in geothermal heating & cooling has grown** in the context of energy security concerns.
- Untapped potential is concentrated in Africa and Latin America, where **geothermal power is prioritized over H&C** due to warmer climates and regional needs.
- Legacy markets such as the U.S. have high installed capacity, but **fragmented policy has inhibited economies of scale**.
- While global leaders have strong policy on conventional geothermal, **emerging players are increasingly investing in next-generation technologies**.

Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [Geothermal Energy Database](#) (International Geothermal Association, 2024).
Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

China leads in domestic policy and capacity addition; Europe has scaled domestic and regional policy support





○○○○○ Policy Strength ●●●●●

	China <i>Deep dive A</i>	Iceland <i>Deep dive B</i>	France <i>Deep dive C</i>	Sweden
Share of Global Installed Capacity	 58% (100,219 MWt)	 1.6% (2,823 MWt)	 1.7% (2,868 MWt)	 4.2% (7,280 MWt)
Global Collaboration	●●●○○ Global involvement primarily in bilateral partnerships	●●●●○ Extensive global leadership in workforce development and policy	●●●○○ Growing interest in the French geothermal export market	●●○○○ Primarily regional collaboration; minimal bilateral activity
Workforce Development	●●●●○ Home to ~40% of the global geothermal workforce	●●●●● Global leader in training programs and specialized studies	●●●●○ Professionals and associations are united through the AFPG	●●●●○ Strong domestic workforce with dedicated training programs
Research & Development	●●●●● Accounted for 70% of all geothermal investments in 2023, with R&D focused on digitalization	●●●●○ Renewed interest in geothermal R&D, with over €3 million awarded to 8 exploration projects	●●●●○ ADEME financed 71 feasibility studies and 31 investment projects with €7.9 million in aid in 2024	●●●●○ Early adoption of carbon pricing spurred investment in GHP R&D; strong EU research collaboration
Risk Mitigation	●●●●○ National and regional subsidies; international grants and loans	●●●○○ While abundant geothermal resources reduce risk, Iceland has maintained a strong grant program	●●●●○ Four risk mitigation funds currently active, yet risks remain high for next-generation projects	●●●○○ Lacks strong subsidies for next-generation technologies, despite being a global leader in GHPs

Note: See subsequent slides for deep dives on the challenges highlighted above.

Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Geothermal Energy Database](#) (IGA, 2024); [Iceland opens applications for grants under ISK 1 billion geothermal initiative](#) (ThinkGeoEnergy, 2025); [Iceland approves funding for eight geothermal exploration projects](#) (ThinkGeoEnergy, 2023); [France](#) (Global Geothermal Alliance, n.d.); [Regional action plan signed](#) (ThinkGeoEnergy, 2025).
Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Emerging players across Europe and Asia have scaled geothermal H&C policies to advance energy security and clean energy targets

	<i>Deep dive D</i> Germany	<i>Deep dive E</i> Netherlands	South Korea	Croatia
Installed Capacity	 3.1% (5,381 MWt)	 1.1% (1,830 MWt)	 0.93% (1,622 MWt)	 0.04% (74 MWt)
National Target	Scale deep geothermal from 1.8 TWh to 10 TWh per year by 2030	25-30% of heat demand supplied by geothermal energy by 2050	1 GW geothermal heating & cooling capacity by 2030 in Seoul	> 36.6% renewable energy in final energy consumption by 2030
Status and Pipeline of Geothermal Projects	<ul style="list-style-type: none"> • 42 deep geothermal projects in operation • >150 projects in planning phase 	<ul style="list-style-type: none"> • 28 operating projects with >70 projects in the pipeline 	<ul style="list-style-type: none"> • Five geothermal landmarks in major areas in Seoul are being planned 	<ul style="list-style-type: none"> • 12 active production areas and 24 active exploration areas
Policy Highlights	Current number of exploration permits has almost doubled, from 82 in 2023 to 155 in 2025	NL RNES Geothermal Guarantee Scheme provides grants and insurance up to 85% of testing and drilling costs	R&D funding in 2023 supported a hybrid energy supply system including GSHPs	€30 million approved for geothermal R&D in 2023, with the first major geothermal conference held in March 2025
Current Limitations	Changes in leadership at the federal level have left investors uncertain of the risk associated with new geothermal projects	Permitting delays increase the risk of losing subsidies given a strict realization term of four years	A 5.5 magnitude earthquake in 2017 linked to an EGS project led to increased public opposition and a reorientation toward GHPs	The government has not yet developed a streamlined permitting process, prolonging project timelines

Note: See subsequent slides for deep dives on the challenges highlighted above.

Sources: [Geothermal Energy Database](#) (IGA, 2024); [Geothermal industry in the Netherlands has promising potential for strong growth](#) (ThinkGeoEnergy, 2022); [Geothermal Potential Development Plan of the Republic of Croatia through 2030](#) (2022); [Croatia approves EUR 30 million grant for geothermal research](#) (ThinkGeoEnergy, 2023); [Updated map shows over 150 geothermal projects in Germany in planning phase](#) (ThinkGeoEnergy, 2025); [Up to 1 GW of geothermal energy by 2030 as a world-class geothermal energy city](#) (Seoul Metropolitan Government, 2023).

Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

A Through research and development policy integration, Sinopec doubled its geothermal H&C installed capacity in four years

Case study: Sinopec Green Energy's Arctic Green Center of Innovation

- Sinopec Green Energy (SGE) is a joint venture between Sinopec (51%) and Iceland's Arctic Green (49%)
- SGE is the world's largest and most technically advanced geothermal heating & cooling company
- Government policy incentivized investment and scale, including **research funding, land access for pilot projects, and grid integration mandate**

SGE's Timeline

- 2009** • Began construction on **Xiong'an**, China's first smog-free city.
- 2011** • Expanded into Hebei, doubling heating capacity.
- 2016** • Established Sino-Icelandic geothermal technology R&D center (Arctic Green Center of Innovation) as a global hub for geothermal expertise, research, and capacity-building, with state support accelerating R&D.
- 2021** • Expanded into Beijing and Tianjin, increasing total heating capacity by 26%.
- 2023** • Announced global expansion, focusing on the high-growth markets of Central Europe, the Middle East, and Indonesia.



SGE's Operational Coverage

- SGE has invested over **half a billion dollars** in geothermal since 2009.
- Over **920 wells** have been drilled in over **70 cities** and municipalities.
- SGE **doubled its geothermal district heating coverage** from approximately 60 million m² in 2020 to 120 million m² by year-end 2024. Total installed geothermal direct utilization capacity is **over 4 GW**.
- Holds over **130 patents** related to geothermal resource development.
- Xiong'an was **recognized by IRENA** as a global showcase for city energy transition.

Sources: [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [Geothermal Energy Database](#) (International Geothermal Association, 2024).

Credit: Leo Gordon, Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

A Despite common geothermal barriers, China has scaled low- to medium-temperature resources for clean urban heating

Barriers

Resource availability

•Only **viable to specific areas** with **high geothermal activity** and easily accessible underground hydrothermal reservoirs

Regulatory and environmental barriers



4- to 8-year permitting timeline

Opposition could arise due to **potential environmental impacts**, including increased **seismicity risks**, gas leak risks, and high water consumption for cooling.

High risk and upfront costs



Commercial risk

Exploration

Drilling

Construction



40-60%↑ LCOE vs. solar & wind

Technology limitations



Low scalability

•EGS immature, expansion = more drilling, difficult + expensive

Solutions

Large and diverse range of geothermal resources



Strong government support and policy initiatives

Geothermal is a **significant part of clean-heating policies by local governments, especially in northern China**, since the early 2000s, as part of efforts to replace coal-based heating systems. There is also a specific implementation of a regional plan, e.g., Hebei Province Geothermal Resources Exploration and Development Five-Year Plan.

At the country level, the Chinese government has **integrated geothermal into its broader energy transition** and carbon-neutrality goals since 2017, through policies including its Five-Year Plans for Renewable Energy.

Financial incentives and instruments creations for Sinopec Chinese oil & gas company



SINOPEC

Energy system \$ invested by 2020 Expansion

Geotherma +\$500M 14 provinces

Policies and subsidies for district heating projects have **incentivized investment**.

Creation of green financing instruments: green loans, green bonds, and green equity funds

Actively investing in geothermal R&D



SINOPEC

130 geothermal technology patents

Sources: [Development of GHP in China](#) (NREL, 2013); [Assessment of Economic Impact of Permitting Timelines](#) (Idaho National Laboratory, 2022); [Strategic Analysis of China's Geothermal Industry](#) (HEP Journal, 2021); [Scaling Geothermal Heating](#) (CleanTechnica, 2025).

Credit: Faradisa Anintya, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

A Xiongxian Field shows how geothermal success can drive national momentum through local innovation and private-public partnership



Capacity

Largest single project of its kind (largest district heating capacity in the world from a single geothermal field)
Currently supplying heat for **4.5 million sqm of homes**; supports the entire city of Xiongxian (**390,000 residents**), meeting **100%** of home heating needs from geothermal energy

Ownership & Operator

Operated by **Sinopec Green Energy** Geothermal Development Co. (SGE), a joint venture established in November 2006 between:
Sinopec Star Co. (a subsidiary of Sinopec Corp., a **state-owned oil company**)
Arctic Green Energy Corp. (an **Icelandic company**)

Government Support

Local governments began promoting the large-scale utilization of geothermal resources for heating around 2000.

In 2009, Xiongxian County reached an agreement with SGE to develop geothermal resources sustainably.

The establishment of the Xiong'an New Area in 2017, which includes Xiongxian, has **put a spotlight on geothermal resources nationally**.

In 2017, the National Development and Reform Commission included guidelines for geothermal energy in the National Five-Year Plan for the first time, potentially leading to state subsidies and tripling the volume of geothermal heating systems.

While **initial development lacked significant government support**, the success of the **Xiongxian geothermal field has led to increased attention and backing from both local and national authorities**, positioning it as a key component in China's clean energy strategy.

Sources: [Xiongxian Project](#) (ThinkGeoEnergy, 2017); [Strategic Analysis of China's Geothermal Industry](#) (HEP Journal, 2021).

Credit: Faradisa Antitya, Pia Doris Morrow, and [Gernot Wagner](#). Share with attribution: Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Europe is the third-largest growth market for geothermal H&C with policy leadership fueled by security concerns and transition goals

European countries with geothermal H&C roadmaps, 2024



Technical Potential

Geothermal energy could provide **~8 TW** of heat at **90°C** — 30 times the energy currently supplied by district heating systems — to supply over **70 million people** in the region.

Long-Term Geothermal Target

The **EU Implementation Plan's vision for 2050** has geothermal supplying >25% of Europe's space heating & cooling demand, >25% in the agricultural sector, and 5% in industrial sectors.

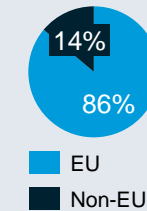
R&D Funding

The EU's **\$80 billion Horizon 2020 Program** funded large research projects that deployed EGS, promoted national risk mitigation schemes, and advanced resource mapping and assessment.

Data Transparency

The **European Geological Data Infrastructure** standardizes data for public access; Germany, Italy, the Netherlands, and France have also developed public-access geothermal repositories.

District Heating Leadership



>**86%** of district heating systems are in EU member states, and the European continent hosts **6 GWh** of district heating capacity.

Regulatory Support

The **Net-Zero Industry Act** supports strategic net-zero technologies to simplify permitting processes and increase access to funding.

Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Global Geothermal Market and Technology Assessment](#) (IRENA, 2023); [Implementation Plan](#) (Geothermal Implementation Working Group, 2023); [The Geothermal District Heating Market: Challenges and Opportunities in Europe](#) (Toth et al., 2025); [Net-Zero Industry Act](#) (European Commission, 2025). Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). Share with attribution: Wagner et al. "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

B Through its global leadership on workforce development, Iceland punches above its weight in the geothermal H&C sector

Through the GRÓ Geothermal Training Program, Iceland has strengthened workforce development, engaging over 60 countries

Six-Month Trainee Program

- Draws trainees from developing and transitional countries with high geothermal potential.
- **816 fellows** from **67 countries** have graduated from the program.

MSc and PhD Scholarships

- Trainees can extend their studies to an MSc or PhD.
- **89 fellows** have graduated with an MSc.
- **6 fellows** have graduated with a PhD.

Key Topics

Geophysical exploration and reservoir engineering

Drilling technologies

Project management and financing

Chemistry of thermal fluids

Iceland has also contributed to two centers of excellence to advance regional workforce development in resource-rich areas



El Salvador Centre of Excellence

- Provides coursework for professionals in Latin America and the Caribbean.
- Formed via a collaboration with El Salvador's state geothermal company.
- Over **700 professionals** have participated.
- **World Bank** announced a **\$150 million investment** over the next six years, in part funding El Salvador's Centre of Excellence.



Kenya Centre of Excellence

- Aims to develop skilled labor in the geothermal industry in Africa.
- Formed via a collaboration between UNEP, Iceland's International Development Agency, and geothermal developers in Kenya.
- **22 students have been trained.**
- **World Bank** awarded the center **\$10.8 million** for upgrades, training, and infrastructure development.

Sources: [The Future of Geothermal Energy](#) (IEA, 2024); [Mission](#) (GRÓ GTP, n.d.); [Regional and international training centres](#) (Global Geothermal Alliance, n.d.); [World Bank announces \\$150 million investment for geothermal in El Salvador](#) (Think Geoenergy, 2025); [Centre of Excellence](#) (KenGen, n.d.).

Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

France's risk mitigation schemes have helped scale conventional geothermal capacity in recent decades

Risk insurance overseen by ADEME fueled 81% of conventional geothermal development in France between 1970 and 2015

Since 2009, the Heat Fund has supported additional district heating and GHP installation

	Short-Term Fund (1981-1999)	Long-Term Fund (1982-2015)
Insurance Structure	<ul style="list-style-type: none"> • 20% of drilling cost in case of failure • Additional compensation up to 90% 	<ul style="list-style-type: none"> • 20% of the cost of drilling • Insurance over 15 years of operations
Investment Amount	<ul style="list-style-type: none"> • €3.4 million in high-priority R&D and repair initiatives • €200 million guaranteed for drilling 	<ul style="list-style-type: none"> • €260 million guaranteed for drilling works and geothermal loops, insuring long-term operations in addition to early-stage risk
Highlights	<ul style="list-style-type: none"> + 500 MW_{th} installed, saving 3 MTOE of fossil fuels over 35 years + 102 wells drilled between 1970 and 2015 benefitted from the funds + For every €1 invested by the state, €33 of investments were covered for 25 years 	
Challenges	<ul style="list-style-type: none"> — Operating income, indexed to the cost of fossil fuels, fell with oil prices after 1987, leading to debt renegotiations. — Risk mitigation for next-generation technologies has proved more difficult. 	

Eligible technologies: Biomass, solar thermal, geothermal, and heat recovery

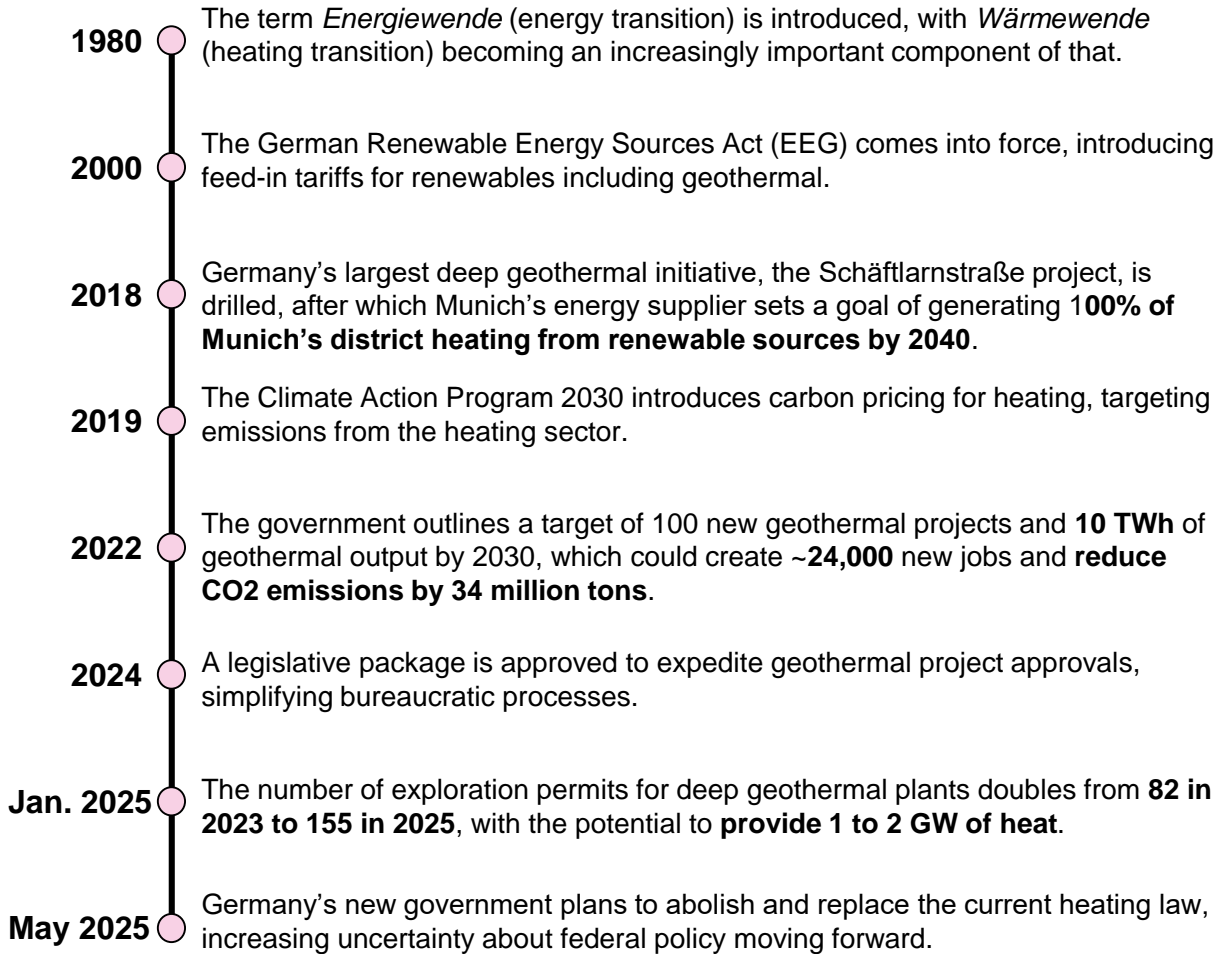
Heat Fund grants finance up to:

- 60% of feasibility studies
- 45% of investment in renewable energy
- 30% of investments for waste heat recovery
- 40% of investment in district H&C networks
- Bonus of 10-20% for SMEs

Grant outcomes:

- ✓ €106 million invested in geothermal projects
- ✓ 678 geothermal installations subsidized

D Germany's investments in deep geothermal align with its heating transition goals; streamlined permitting enables faster growth



Munich-Schäftlarnstraße Deep Geothermal Project



6 wells completed at a depth of **3,000-4,000 meters**



50 MWt output at a reservoir temperature of **~100°C**



Highest availability of all heating plants in Germany



Bavarian geothermal systems have achieved COPs **up to 36**

Policy Strengths of Germany's Legislative Changes*

1

Simplified and digitalized approval procedures

2

Maximum deadlines for approval procedures

3

Geothermal classified as a paramount public interest

*Policy uncertainty in the early stages of the new government may increase investor uncertainty

Sources: [Updated map shows over 150 geothermal projects in Germany in planning phase](#) (ThinkGeoEnergy, 2025); [Germany aims for 100 new geothermal projects by 2030](#) (ThinkGeoEnergy, 2022); [Germany's Climate Action Programme 2030](#) (Clean Energy Wire, 2019); [Germany approves legislation package](#) (ThinkGeoEnergy, 2024); [New German coalition puts climate protection on back burner](#) (Heinrich Böll Stiftung, 2025); [Schäftlarnstraße | Germany](#) (Erdwerk, 2025); [Geothermal plants in Bavaria, Germany recognized for performance, efficiency](#) (ThinkGeoEnergy, 2024).
 Credit: Una Oljaca, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

E In the Netherlands, streamlining permitting processes is a priority as strong policy frameworks for geothermal energy use emerge

🎯 National Target 🏛️ Policy Architecture

- 23% of national heat from geothermal by 2050
- €2B in grants (2023) → 18+ projects funded
- Supports target of 55-60% CO₂ reduction by 2030
- Roadmap: 6.8 PJ (2022) → 200+ PJ (2050)
- Risk coverage: 5% underperformance insured
- SDE++: CO₂-reduction subsidy — makes geothermal cost competitive

📄 Policy and Permitting Bottlenecks

- | | |
|---|---|
| <p>Policy misalignment</p> <ul style="list-style-type: none"> The Mining Act is unclear on heat zones, permits, and sector overlap. Follow-up permit criteria remain vague, stalling progress. | <p>Permitting delays</p> <ul style="list-style-type: none"> 22 SDE++ projects are at risk of a 3- to 5-year delay. Delays erode investor trust; industry calls process “disastrous.” |
|---|---|

🏗️ Case Study: TU Delft Geothermal Doublet

Project overview	Strategic relevance
Delivers ~95% of TU Delft’s heat demand	Acts as model for scaling urban geothermal
Supplies TU Delft and part of Delft city with 25 MW of geothermal heat	Proves viability of geothermal heating in urban settings
Integrated geothermal, HT-ATES, and heat pump technologies	Showcases smart system integration
Managed by TU Delft, Shell, EBN (state owned), Aardyn	As public-private model, improves scalability and financial viability
Funded by Dutch Research Council and EPOS-NL (EU geoscience data infra.)	Anchors geothermal in NL and EU research agendas; enhances EU-wide data sharing

Observations

- The TU Delft project advanced despite permitting delays, enabled by public co-investment and subsidies, showing the power of targeted support.
- The project demonstrates urban geothermal viability and underscores the urgency of Mining Act reform to unlock future projects at scale.

Policy Asks:

- Develop geothermal-specific permitting track and harmonize legal frameworks to reduce intersectoral conflicts.
- Accelerate project timeline, with Germany’s success with Mining Act reform acting as a model.
- Strengthen public-private partnerships to de-risk and accelerate rollout.

Sources: [Geothermal industry in the Netherlands has promising potential for strong growth](#) (ThinkGeoEnergy, 2025); [Geothermal Energy – In the Starting Blocks for Strong Growth](#) (Geothermie Nederland, 2023); [A Research and Energy Production Geothermal Project on the TU Delft Campus](#) (Vardon et al., 2023).
 Credit: Shubhangi Prasad, Pia Doris Morrow, and Gernot Wagner. [Share with attribution](#): Wagner et al. “Geothermal Heating and Cooling,” Columbia Business School Climate Knowledge Initiative (10 March 2026).



Geothermal Heating and Cooling Finance



Key messages Finance

Residential (small-scale) GHPs systems

- By 2050, millions of U.S. homes and businesses could adopt geothermal heat pumps with a positive lifetime payback. To reach this, the industry must grow **10% plus 2% per year** and install GHPs in **7 million homes and businesses by 2035**.
- GHPs cost more than conventional HVAC systems, but tax credits can reduce upfront costs and improve access. **Without incentives, ROI is 3 to 4%; with federal credits, ROI rises to 6 to 7% and can reach 13 to 14% in states like Massachusetts.** Tax incentives are key to reaching the DOE's goal of 7 million homes and businesses by 2035.


District GHPs systems

- GHP district systems are growing in the U.S., with over **20 installed as of 2023** – first on college campuses and now expanding to communities and mixed-income housing. Campus pilots show **30 to 65% annual energy savings** and **19 to 45% lower emissions**, proving performance at scale. Federal incentives are helping make GHPs cost competitive, enabling wider deployment through investment, development, and public-private partnerships.

Private sector trends

- Geothermal startups attracting the most funding are those with innovations in closed-loop systems, horizontal drilling, and dispatchable clean energy.
- Investors are favoring scalable, flexible geothermal tech that serves large, reliable off-takers (like data centers) or enables mass adoption via affordability and ease of deployment.
- Rising startups like Dandelion Energy aim to bring geothermal mainstream – like Tesla for EVs and Sunrun for solar – **by simplifying adoption, cutting costs, and building trust.**

Not one size fits all: Geothermal projects globally leverage different financing options

	Description		Advantages and Challenges	Example
 Public-Private Partnerships	Combines government funding with private equity/debt	 	Leverages both public oversight and private sector efficiency. Involves complex coordination and legal frameworks.	Kenya's Rift Valley development (World Bank support) Large-scale power generation and infrastructure projects (2019-present)
 Green Bonds	Debt instruments for renewable projects	 	Attracts investors seeking green investments; scalable. Dependent on investor confidence and credit ratings.	Iceland's geothermal expansion via bonds Utility-scale geothermal expansions (2018-present)
 Government Grants	Federal and state funding for R&D and deployment	 	Non-dilutive funding; promotes innovation and early-stage support. Often limited in size and competitive to obtain.	U.S. DOE \$200,000 grants for geothermal heating & cooling tech. Pilot/demo projects, new tech in heating & cooling (grants announced in 2020)
 Concessional Loans	Low-interest loans from development banks	 	Reduces financing cost for developing countries. Can lead to debt accumulation; tied to lender conditions.	Philippines' geothermal sector (international aid) Exploration, drilling, and plant development in emerging markets (2010-2015)

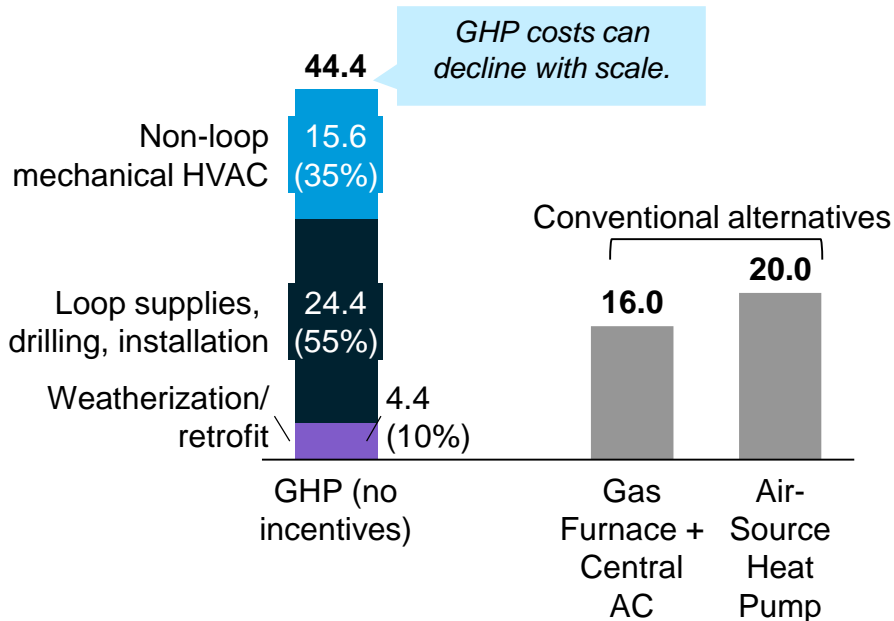
Sources: [Kenya Geothermal Report](#) (World Bank, 2015); [Green Bond Report](#) (Landsvirkjun, 2018); [Geothermal Grant](#) (U.S. DOE, 2020); [Tiwi-Makban Project](#) (ADB, 2010).

Credit: Faradisa Anintya, Pia Doris Morrow, and [Gernot Wagner](#). Share with attribution: Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

GHPs require incentives to overcome high upfront costs — but deliver long-term returns that pay for systems over their lifetime

Est. median CapEx of HVAC U.S. residential (\$K/household)

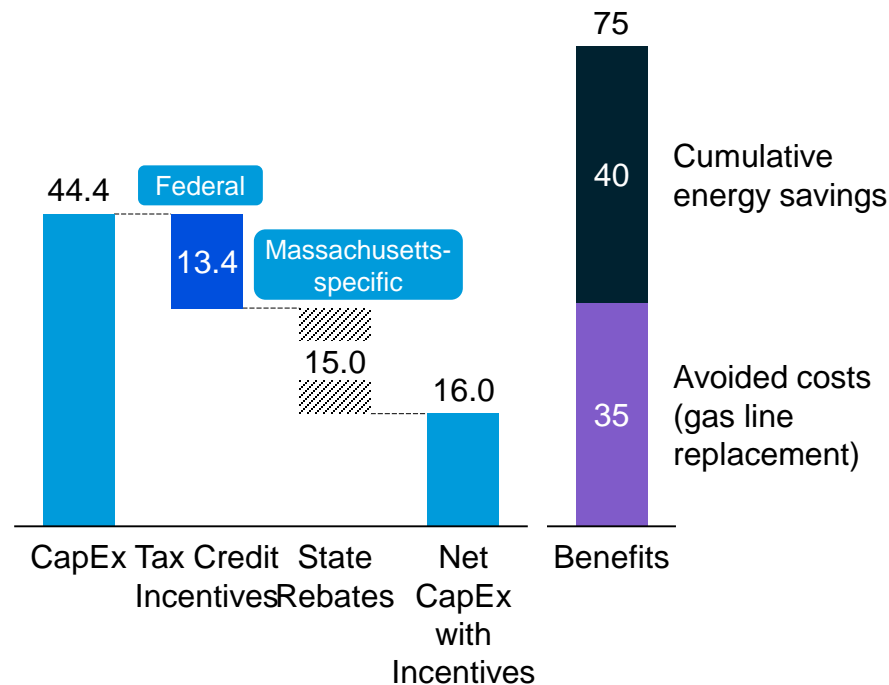
~4 ton/household capacity assumption



Key forecasts:

NREL projects that **costs could decrease ~20-30%** with expanded pilots, workforce training, thermal energy networks, and standardization.

Est. cost and benefit across GHP lifetime (20 years) (\$K/household)



Key assumptions:

- GHP installation capacity: 3 to 5 ton/household (urban to suburban).
- Estimated annual energy savings with GHP installed: \$1.5K-\$2.5K/household.
- Incentive is 30% federal ITC.

Observations

All U.S. states:

- ROI **without** tax credit: **3-4%**
- ROI **with** tax credit: **6-7%**
- Massachusetts specific:
- ROI with tax credit and state rebates: 13-14%
- Tax credits help break the biggest barrier – high upfront costs – making GHPs more accessible and financially viable.
- Incentives are key to unlocking mass adoption and reaching DOE's Liftoff goal of **7 million homes by 2035**.

Sources: [Pathways to Commercial Liftoff: Geothermal Heating and Cooling](#) (DOE, 2024); [GeoVision](#) (NREL, 2020); [Residential Energy Consumption](#) (EIA, 2021); [GHP Installation](#) (Energy Sage, 2023); [HVAC Installation Cost](#) (HomeAdvisor, 2023).

Credit: Faradisa Anintya, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Different incentives created to overcome structural barriers of GHP installation at residential scale

Barriers of GHP at residential scale

High upfront cost: Installation often exceeds **\$30K**, deterring homeowners despite long-term savings.

Site and installation challenges: Vertical loops need deep drilling and permits; horizontal loops require large land area, limiting feasibility.

Lack of awareness: Many homeowners don't know geothermal is an option or don't understand the benefits.

Expertise gaps: Installer expertise is regionally uneven, leading to inconsistent quality and higher risk; availability of trained drillers and installers is a major bottleneck; and current drilling capacity is dominated by water well and oil and gas industries.

Incentives across different countries for homeowners

United States

- **Federal:** Homeowners can receive a **30% tax credit on GHP installations** (2022-2032) via the Residential Clean Energy Credit, with a gradual decrease in 2033-2034.
- **Massachusetts-specific:** Substantial rebates on GHP installations via the Mass Save program.
 - Whole-home systems: **Up to a \$15,000 rebate**; partial-home systems: **\$2,000** per ton, up to **\$15,000**; income-eligible households: enhanced rebates up to **\$25,000**.
 - Rebates are **complemented by a 30% federal tax credit and 0% interest Mass Save HEAT Loan** (up to **\$50K** over seven years) to help cover installation costs.

Canada

- **Federal:** Homeowners can receive **\$125 to \$5,000 grants for eligible retrofits** (including GHP and air-source), plus **\$600** for energy evaluations, as well as **interest-free loans** up to **\$40K** with a 10-year term to help finance GHP installations via the Canada Greener Homes programs.
- **Ontario-specific:** HRS (Home Renovation Savings) Program offers up to **\$12,000 for ground source** and **\$7,500** for air-source heat pumps, based on system size and current heating.
- **Toronto-specific:** HELP (Home Energy Loan Program) provides up to **\$2,500 in rebates for cold-climate systems**, stackable with federal incentives.

Germany

- Offers subsidies up to **€18,000** for ground source (geothermal) heat pumps; scheme is scheduled to run until 2030.

France

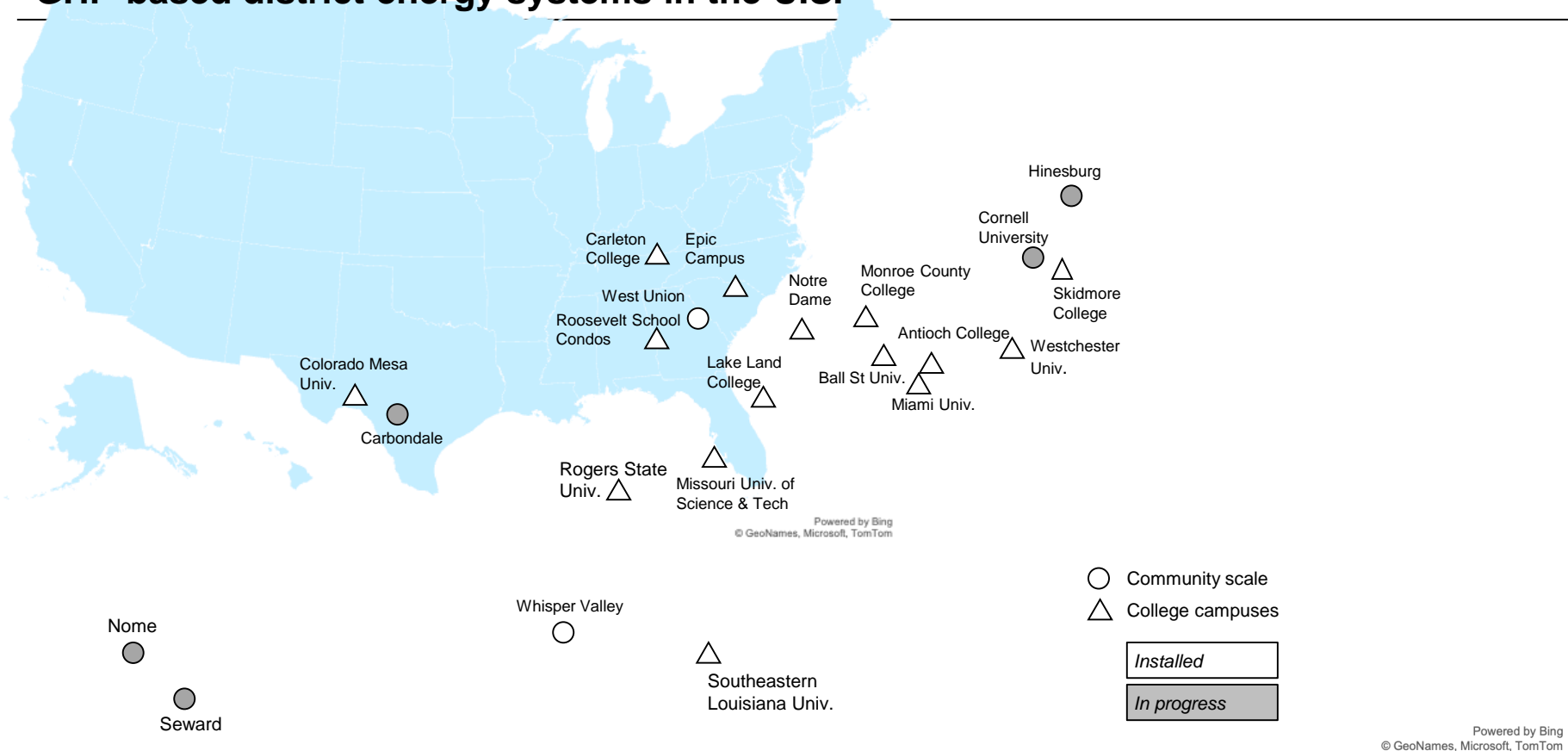
- Grants up to **€15,000** for GHPs, with the amount based on family income under the MaPrimeRénov Scheme.

Sources: [Pathways to Commercial Liftoff: Geothermal Heating and Cooling](#) (DOE, 2024); [Annual Impact Report](#) (Mass Save, 2024); [Greener Homes Grant](#) (NRCan, 2025); [Rebate Saving Program](#) (HRS, 2025); [HELP](#) (City of Toronto, 2025); [Heat Pump Subsidies](#) (European Commission, 2024).

Credit: Faradisa Anintya, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

GHP district heating & cooling is moving from pilot campus use to community-scale clean infrastructure

GHP-based district energy systems in the U.S.



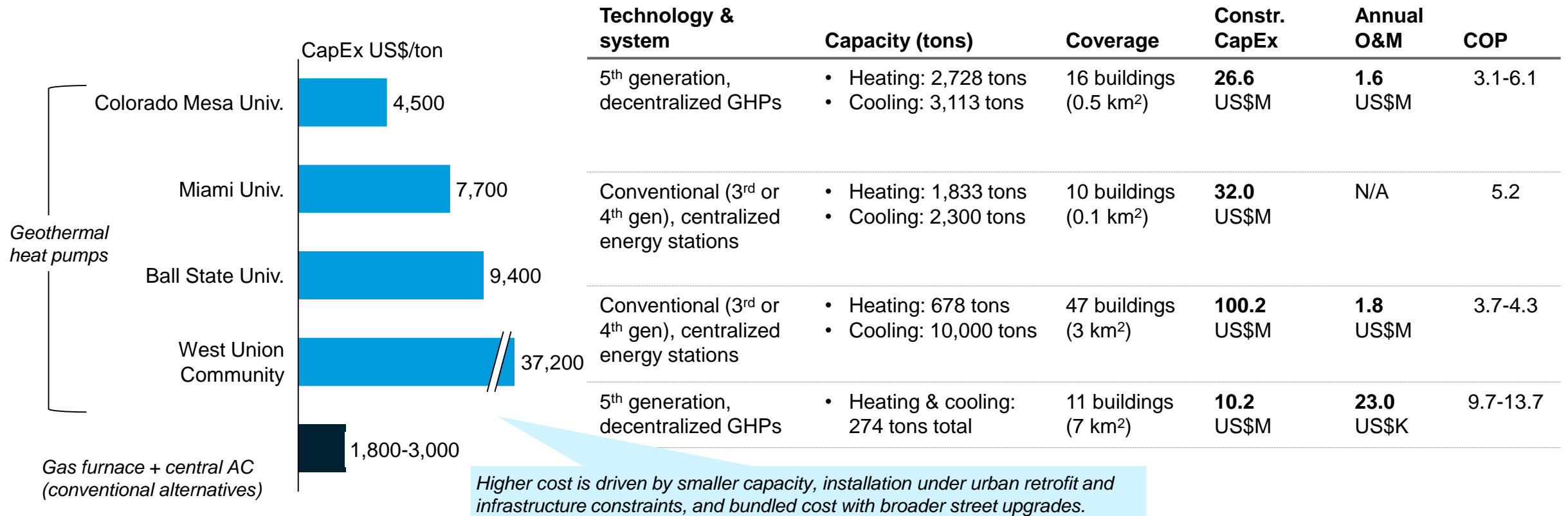
Observations

- As of 2023, there were **>20 GHP-based district energy systems** in the U.S., with the majority located on college campuses (as pilot projects); there has also been growing deployment in communities (e.g., Whisper Valley, Texas) and mixed-income housing developments.
- **Technology:** A mix of fourth- (centralized) and fifth-generation (decentralized) is ideal for mixed-use or retrofit-heavy districts where flexibility and building-level control are critical.
- **Cost and performance:** The average construction cost is **\$3,050/ton (equal to ~\$870/kW_{th})** with COP of 4.7; there are no performance or cost differences between fourth- and fifth-gen systems.
- **U.S. government support:** DOE is funding pilot systems in Alaska, Colorado, Vermont, and Oklahoma, many in underserved or rural communities; DOE also is supporting feasibility/design for **11 new systems**. NREL has built:
- **dGeo:** Modeling tool to assess shallow geothermal market potential
- **LeGUp:** Performance model for fifth-gen systems to support scale-up
- The U.S. is moving from campus pilots to **mainstream community deployments**, opening opportunities for investment, development, and public-private partnerships.

Sources: [Geothermal District Heating & Cooling](#) (NREL, 2023).

Credit: Faradisa Anintya, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Successful district-scale GHP pilots demonstrate strong performance, resulting in cost savings and emission reductions



Stronger rationale to push GHP district on a commercial scale: (1) **Proven impact from campus pilot:** 30-65% annual energy savings, 19-45% annual carbon emission reductions. (2) **Federal incentives make GHPs more cost competitive:** Commercial and utility-scale GHP systems benefit from a 10% federal tax credit and accelerated depreciation – businesses may deduct 40% of system costs upfront – making district-scale deployment significantly more financially attractive and helping construction costs compete with conventional systems like gas furnaces and central AC.

Sources: [Geothermal District Heating & Cooling](#) (NREL, 2023).

Credit: Faradisa Anintya, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Overcoming challenges and barriers to GHP adoption on a district scale requires more than financial incentives

Barriers to GHP at district scale

High upfront cost: Drilling and piping push GHP install costs to ~\$3,050/ton, above central AC and gas furnace (\$1,800 to \$3,000/ton).

Efficiency risk from oversizing: Conservative sizing can overshoot demand, which wastes energy and raises loop temps, as seen at Ball State. Avoiding this requires accurate load forecasts, soil analysis, and precise system modeling.

Urban retrofit complexity: Retrofitting GHPs in dense areas is challenging due limited space for boreholes, utility conflicts, and disruption to roads or buildings.

Workforce gap: There is a shortage of skilled professionals with expertise in GHP design, installation, and long-term maintenance.

Incentives across different countries for commercial/district GHPs

United States

- 30% federal investment tax credit for commercial, nonprofit, municipal, and multifamily geothermal heat pump systems; includes accelerated depreciation for for-profit businesses.
- New York state: Additional **25%** state tax credit (up to **\$5,000**) via NYSERDA, plus rebates and financing under NYS Clean Heat.
- Innovative financing tools such as C-PACE, long-term, low-interest loans repaid via property tax; large-scale loans/guarantees for geothermal heating & power infrastructure through DOE Loan Programs Office.

Norway

- Enova-funded support for district heating & cooling network construction and expansion, and local renewable heat plants (e.g., GSHPs, thermal storage, waste heat recovery).
- Retrofit grants: Up to **25%** of costs, capped at **NOK 100-150K**.
- Includes free technical advisory (Enova Answers) and low-interest Husbanken loans for large projects.






United Kingdom

- Boiler Upgrade Scheme: Successor to the Renewable Heat Incentive, supporting the shift from fossil fuel heating to low-carbon heat pumps or biomass boilers.
- Applies to small and medium non-domestic buildings (e.g., offices, schools, community halls). Offers **£7,500 grants** for ground or air-source heat pumps (**≤45 kWth**).

China

- Low-interest loans for small and medium-size enterprises in geothermal project development. Select city-level subsidies (e.g., Tianjin): Up to **\$3,700** for heat pumps to support coal-to-electric transitions.

Rising geothermal startups with innovations and scalable technologies have attracted the most funding

	Focus	Product and Target Market	Key Tech/ Differentiator	Recent Transactions
Small scale, residential	 Heating & Cooling	Residential geothermal HVAC systems; simplified drilling and installation Targets single-family homes, small buildings	Alphabet X spinoff; 3,000+ installations ; streamlined installation process	\$134.5M raised
	 Heating & Cooling	Advanced drilling, subsurface modeling for affordable geothermal urban/commercial HVAC Targets residential developers, property owners	Aims to make installations "so affordable" developers can generate strong ROI; active in CO, UT regions	\$12M Series A (Jan. 2025)
Large utility scale	 Heating & Cooling, Power Generation	Eavor-Loop closed-loop system , no need for aquifers or volcanic heat	Makes geothermal viable in non-traditional locations; scalable technology	\$504M+ raised; plants in Canada, Germany
	 Heating & Cooling, Power Generation	Geopressed geothermal and energy storage to power data centers	Secured a major contract with Meta for a 150 MW facility	<i>Info not available</i>
	 Heating & Cooling	Manufacturing of heating and cooling systems (especially for the concrete industry); advanced heat pumps and chillers designed for commercial, industrial, and other sectors.	Innovative, fully electric HVAC solution (e.g., ChillMaster product line)	Acquired by Swegon (Feb. 2025)

Geothermal startups **attracting the most funding focus on innovations like closed-loop systems and dispatchable clean energy**. Investors favor **scalable, flexible technologies** aligned with high-growth sectors and reliable off-takers (e.g., data centers).

Sources: [Geothermal Transactions](#) (Pitchbook, 2025), [Financial Times](#) (2024); [Sage Ecosystem](#) (ThinkGeoEnergy, 2024); [Fervo Energy](#) (Business Wire, 2025); [American Geothermal Acquisition](#) (Cision News, 2025).

Credit: Faradisa Anintya, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Dandelion Energy aims to make residential GHPs mainstream



Company Profile

- Based in Mount Kisco, New York.
- Founded in 2017 as a spinoff from Alphabet's X lab (formerly Google X).
- Raised **\$100M+** funding from investors including GV, NEA, Breakthrough Energy Ventures.
- Has ~150 employees (as of 2023), including in-house drillers and HVAC installers.
- Positions geothermal like a scalable tech product, not a one-off construction job.
- Aims to bring geothermal mainstream – like Tesla for EVs or Sunrun for solar – by simplifying adoption, cutting costs, and building trust.

Key pain points

- **High reliance on fossil fuels:** Millions of U.S. homes, especially in the Northeast, still depend on fuel oil or propane for heating, which are both expensive and carbon-intensive.
- **Barriers to geothermal adoption:** Traditional geothermal systems were expensive, required complex custom installations, and had limited consumer awareness.

Product & solutions

- **Vertically integrated solution** for residential geothermal heating and cooling, including:
- **Ground-loop installation** using Dandelion's proprietary drilling technology.
- A high-efficiency heat pump replaces both the furnace and AC.
- **Software and financing: \$0-down financing plans** to tackle the barrier of \$30K+ upfront cost.

Impact generated

- Over **2,000+ systems installed**, primarily in New York, Connecticut, and Massachusetts. Expansion continues in the Northeast U.S., where homes are older, heating needs are higher due to the colder climate, and fossil fuel use is prevalent.
- Impact per home: Homeowners **typically save \$1,000 to \$2,000 per year** on energy bills after switching from oil/propane. Each installation reduces **~80% of a home's carbon emissions** from heating and cooling.

Future opportunities

- Well-positioned to **leverage the IRA 30% tax credit** and state-level rebates (e.g., Mass Save rebates in Massachusetts, NYSERDA in New York).
- Potential for **expansion into other states** (e.g., Pennsylvania, Illinois).
- **A workforce trained in geothermal-specific roles**, including drill operations and clean HVAC installation, created an asset.

Sources: [Dandelion Heating & Cooling](#) (Dandelion Energy, 2025).

Credit: Faradisa Nintya, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal Heating and Cooling Deployment





Site suitability and feasibility assessment

- Successful deployment **hinges on six core factors**: Available land area for horizontal/vertical loops, soil composition and thermal conductivity, building heating and cooling loads, groundwater availability (for open-loop systems), geological stability (seismic activity, faults), and underground utilities.
- Underground utility mapping tools like NREL's dGeo model and Multicriteria Decision Analysis frameworks assess geospatial feasibility and local economic impacts.

Design optimization and system engineering

- A case study with **90 boreholes at 500 feet** served **132 apartments in 28 buildings**. Key design inputs include **soil thermal data, heating and cooling loads, and code compliance**. Maximizing **HDPE piping and grout conductivity** reduces borehole length and **CapEx**. Accurate modeling of **peak outdoor air loads** and **heat pump energy use (COP)** ensures system efficiency.

Permitting, mobilization, and deployment barriers

- U.S. projects face **45-month average permitting** involving **14+ agencies**; globally, timelines range from **four to eight years**. Geothermal heating and cooling systems rely on **smaller drills and shallower boreholes**, easing deployment compared to power systems. Equipment mobilization is highly sensitive to permitting delays, affecting logistics and cost.

Community engagement, education, and safety

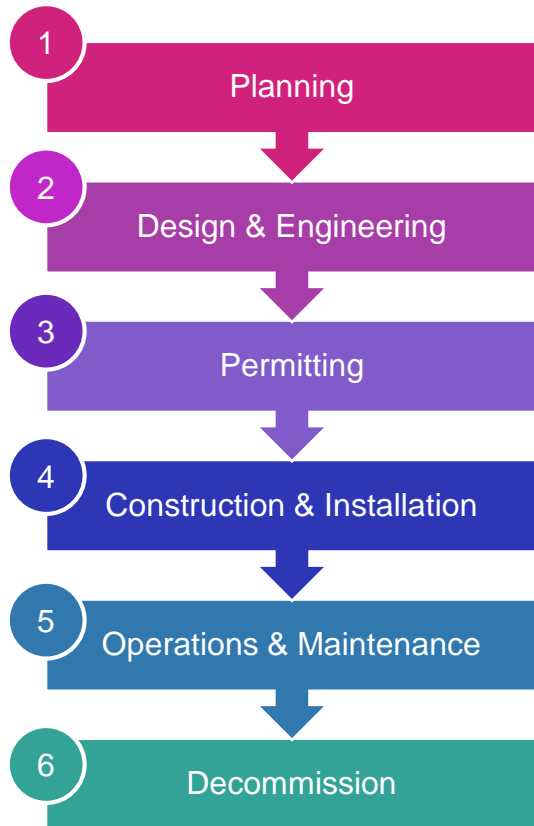
- Early outreach (e.g., **town halls, school visits, open houses**) builds trust and understanding. Shared value strategies include **heat networks, job training, and revenue sharing**. Cultural sensitivity is essential near **Indigenous lands**, requiring co-development, not just consultation.
- Worker protection: **OSHA standards (1910.132, 1926.55)** govern PPE, silica, and hot pipe hazards. Costliest injuries include **amputations (\$126,033)** and **burns (\$52,222)**.

Lifecycle O&M and responsible decommissioning

- Monitoring includes **temperature probes, flow rates (e.g., 180 L/min)**, and pressure controls. Failure risks include probe malfunction, leaks, and mechanical wear. **Annual maintenance (\$300 to \$500)** avoids repair costs **>\$2,000** and extends system life. Decommissioning safeguards against **groundwater contamination**, ensures **land restoration** and meets variable regulatory requirements. Early planning and budgeting is critical for compliant closure.

Identifying key stakeholders is crucial to successful deployment of a geothermal heating & cooling project

Key deployment stages and stakeholder engagement map

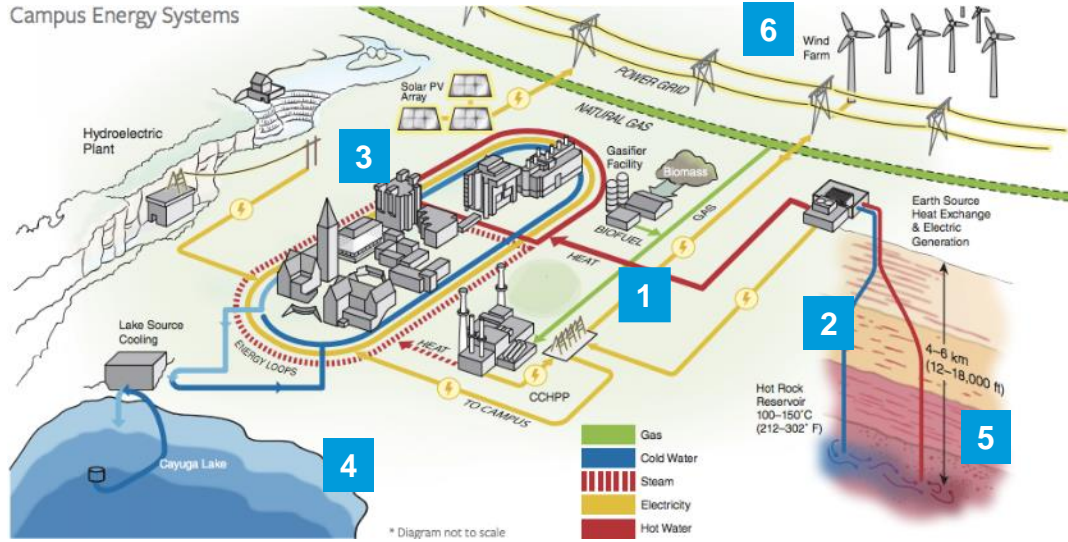


Stage	Key stakeholders	Key activities
1	Site owners/building operators	<ul style="list-style-type: none"> Provide site access and building data
1	Geologists and geothermal consultants	<ul style="list-style-type: none"> Conduct subsurface and thermal analysis, execute feasibility assessment
1	Local utilities	<ul style="list-style-type: none"> Assess infrastructure for integration
1	Community organizations	<ul style="list-style-type: none"> Facilitate local engagement and feedback
1	Project developers and investors	<ul style="list-style-type: none"> Initiate and fund planning
2	Local, state, and environmental regulators	<ul style="list-style-type: none"> Approve land use and drilling activities, ensure compliance
2	Legal advisors	<ul style="list-style-type: none"> Prepare and submit legal compliance documents
3	Engineers and HVAC designers	<ul style="list-style-type: none"> Design system layout and HVAC compatibility
3	Software modelers	<ul style="list-style-type: none"> Run thermal simulations to optimize performance
3	Building architects	<ul style="list-style-type: none"> Incorporate system into building design
4	Drilling contractors	<ul style="list-style-type: none"> Drill boreholes and install piping systems
4	Construction crew	<ul style="list-style-type: none"> Install mechanical and electrical infrastructure
4	Site safety and quality assurance officer	<ul style="list-style-type: none"> Ensure field safety and risk compliance
5	Facility managers and maintenance contractors	<ul style="list-style-type: none"> Oversee operation, handle routine servicing and repairs
6	Local authorities	<ul style="list-style-type: none"> Authorize decommissioning procedures
6	Restoration contractors	<ul style="list-style-type: none"> Restore landscaping and ecological balance

Sources: CKI analysis (2025).

Credit: Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

1 Requirements for site suitability and risk avoidance



Cornell University Geothermal Plan

- 1 Available Land Area:** Sufficient space is crucial for ground loops (horizontal and vertical) depending on site needs.
- 2 Soil Composition and Thermal Conductivity:** The type of soil and its heat transfer ability play a significant role in the systems efficiency.
- 3 Building Heating & Cooling Loads:** The buildings' type and size must match the buildings' energy requirements.
- 4 Ground Water Availability:** Ground water is necessary for open-loop systems; quality and availability must be assessed.
- 5 Geological Conditions:** Faults and areas with high seismic activity can impact drilling capabilities and system performance.
- 6 Underground Utilities:** The location of existing utilities must be carefully considered to avoid drilling conflicts.

*List is relevant for residential, commercial, and public-private use.

Frameworks for site suitability assessment:

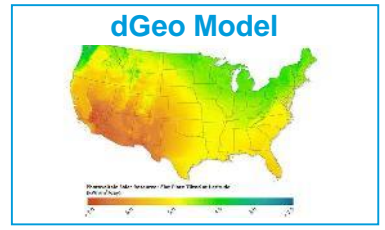


dGeo Model

NREL model, uses a high-resolution geospatial database to evaluate the feasibility of geothermal heat pumps in specific regions

NREL's WIRED Model Suite

Suite of models by NREL, designed to evaluate the local economy-wide impacts of geothermal heat pump installations, district heating and cooling, and power generation plants



Sources: CKI analysis (2025); [Cornell wants to drill 2 to 4 miles underground for enhanced geothermal heating](#) (Ars Technica, 2016); [Multi-expert multi-criteria decision analysis model](#) (Nature.com, 2022); [Distributed Generation Market Demand Model](#) (NREL, 2025); [Geothermal Data and Tools](#) (NREL, 2025).
 Credit: Zacharia Thurston, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner et al. "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

1 The key to community acceptance lies in educating stakeholders about the benefits of geothermal energy

Key community challenges during the planning phase of geothermal heating and cooling projects



Drilling concerns

Fear of drilling, induced seismicity, or visual or noise concerns during drilling



Lack of understanding

Misconceptions about environmental impact and technology



Land use conflicts

Disputes over subsurface rights, private wells, or land devaluation



Access inequity

Upfront costs as a barrier, lack of financing options for low-income households



NIMBY (not in my backyard)

Support in principle, but resistance to installations near homes or schools



Cultural sensitivities

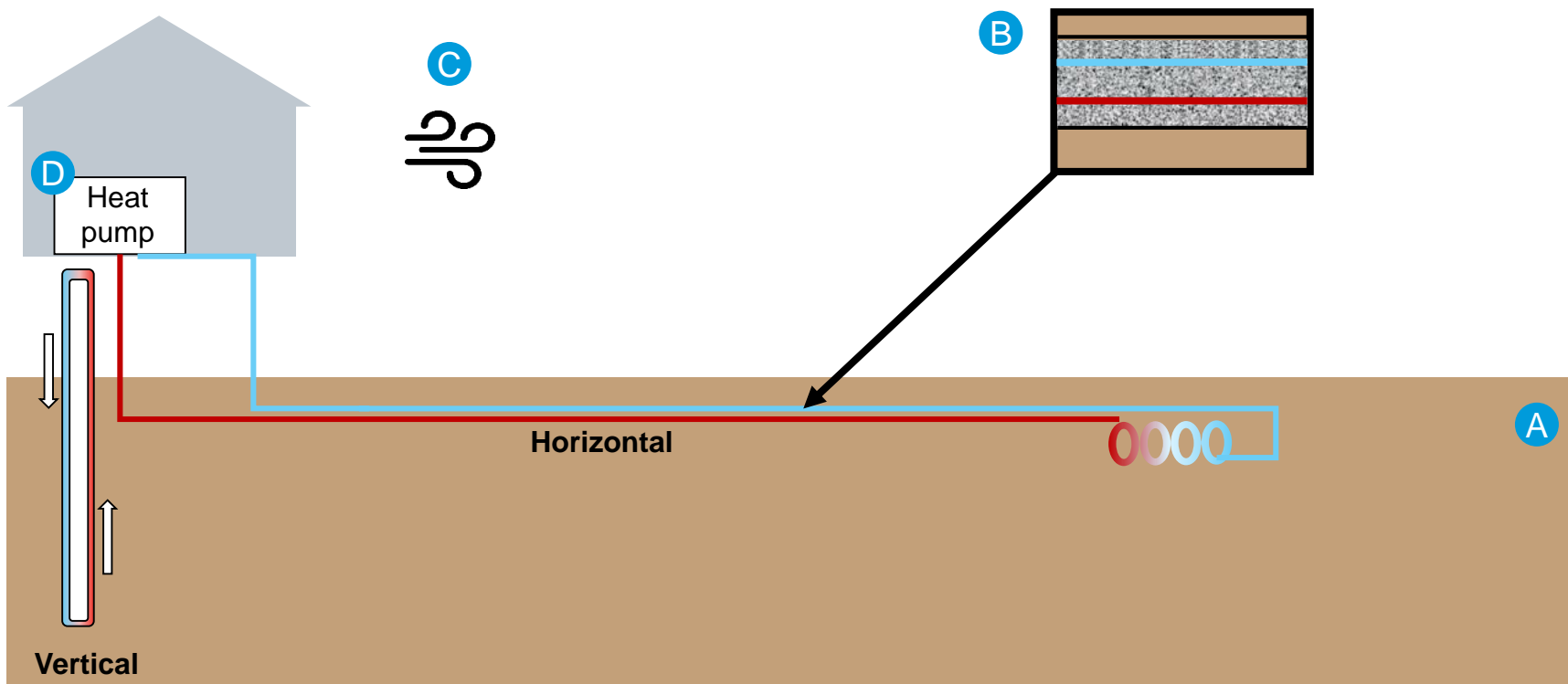
Projects intersect with culturally significant lands or sacred Indigenous sites

Mitigation Strategies

- **Early Engagement:** Involve communities in town halls, school visits, and open houses before drilling begins.
- **Transparent Communication:** Clear info on safety, benefits, and impacts to demystify the technology.
- **Shared Value:** Offer community heat networks, job training, or revenue sharing.
- **Cultural Sensitivity:** Especially when operating on or near Indigenous land, it is crucial to co-develop, not just consult.
- **Robust Compensation Models:** This includes compensation for land use, disruption, or visual impact.

2 Several site-specific factors dictate the design and economics of a GHP system

Typical geothermal heat pump system



Several design criteria are critical to GHP system designers:

- A Soil characteristics** – Allowable drill depths, soil thermal conductivity, and soil composition influence the heat transfer characteristics of geothermal reservoir.
- B Piping and grouting** – Grouting and HDPE thermal conductivity need to be maximized to minimize total borehole length (to reduce project CapEx).
- C Outdoor air peak load** – Determined by measuring the maximum amount of heat the GHP system would need to transfer during the hottest and coldest periods of the year.
- D Heat pump energy load** – Dictating the system's overall coefficient of performance (COP), energy load for compression and pumping compared to total heat transfer capabilities determines the energy costs of the system.

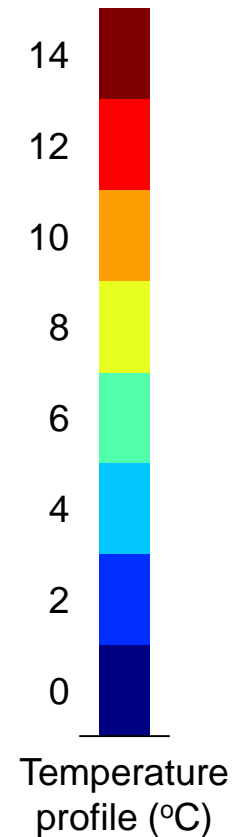
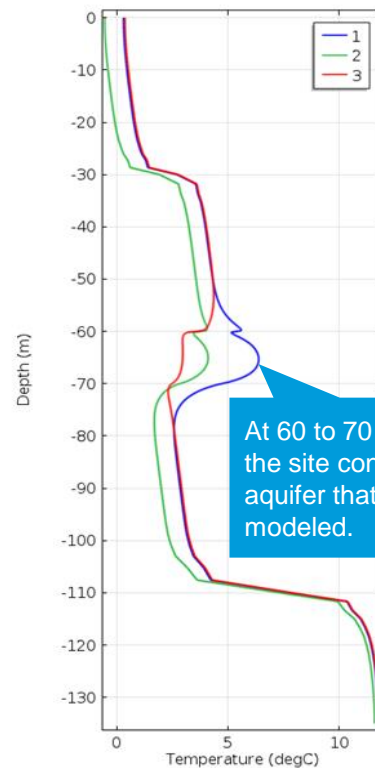
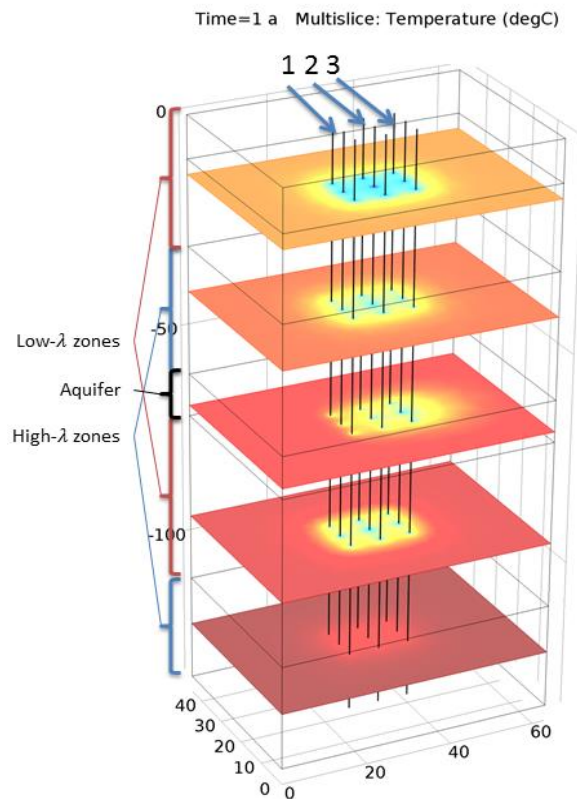
Highlight: GHPs can cut energy bills by up to 65% compared to traditional HVAC systems and typically recoup their upfront cost within 10 years through energy savings.

Sources: [Six steps for designing ground heat exchangers](#) (CSEmag, 2017).

Credit: Hassan Riaz, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

2 COMSOL Geothermal Heat Transfer Models can predict temperature profiles of geothermal heat sources

Temperature profile of a shallow 130-meter vertical GHP system with a 3-part HDPE piping system



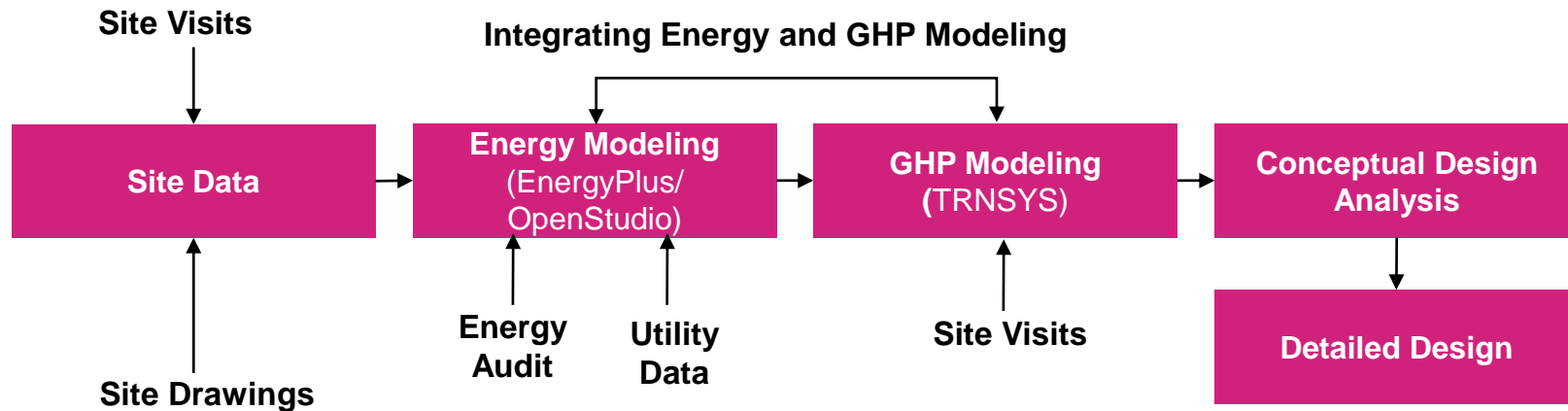
- Through **computational thermodynamics**, the temperature profile of a simulated vertical **ground source heat pump** system can be determined.
- Based on **peak HVAC load requirements** and **closed-loop heat transfer properties**, the borehole length can be optimized using the simulated temperature profile.
- **Upstream oil and gas reservoir modeling expertise** is transferable to larger commercial and industrial geothermal projects.
- **Thermal interference effects** — such as heat drawdown between closely spaced boreholes — can reduce efficiency and must be accounted for in system design.
- **Subsurface groundwater flow** significantly influences heat recovery rates, underscoring the need for accurate **multiphysics simulation** in layered geological settings.

Sources: [Modelling Geothermal Processes with COMSOL Software](#) (COMSOL, 2014).

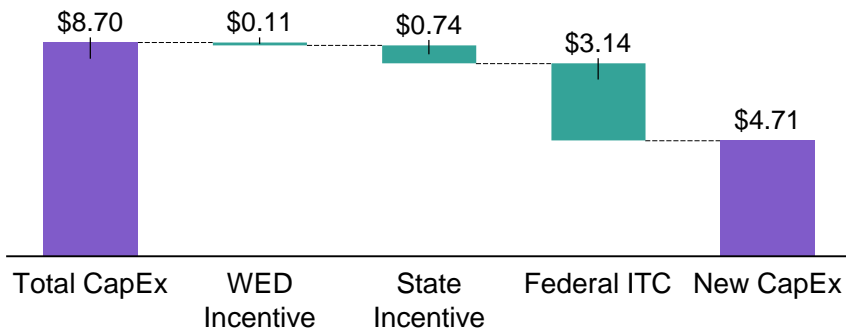
Credit: Hassan Riaz, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

2 Utilizing effective siting and design methodologies to design a CapEx-efficient geothermal system

Design Process Overview



Project Financials (units in millions)



Key Project Facts



- 31%
Reduction in tenants'
heating bill

- \$12.9 million
Savings in 30-year
lifetime costs vs. gas
retrofit

Observations

- The community geothermal design case study used effective siting and design methodologies to design a CapEx-efficient geothermal system.
- The total system will supply heating to 132 apartments in 28 buildings. Project specifics include:
 - Drill 90 500-foot boreholes
 - Construct pump house
 - Distribute water/glycol fluid to apartments
 - Retrofit apartments with water-source heat pumps
- The UConn Institute for Advanced Systems Engineering and LN Consulting led the engineering design work. Design factors included:
 - Heating and cooling loads
 - Soil thermal data
 - Applicable codes

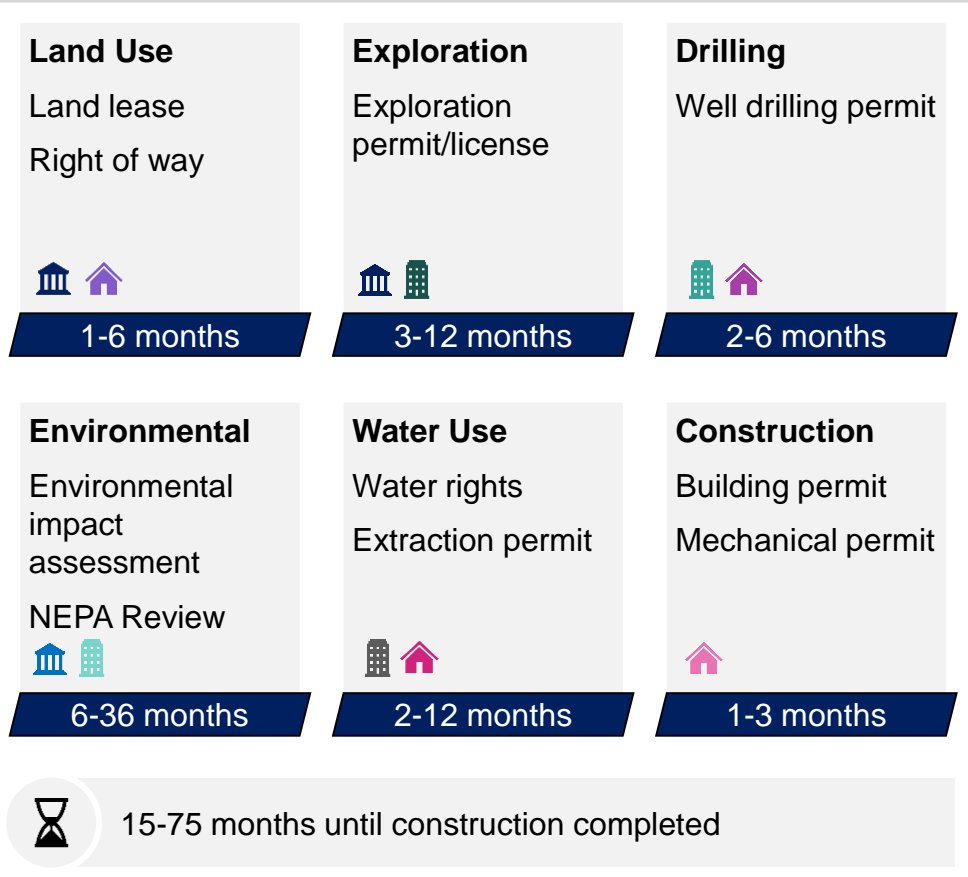
Sources: [Connecticut Community Geothermal Case Study](#) (Connecticut DOEP, 2024).

Credit: Hassan Riaz, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

3 The average permitting process in the U.S. takes 45 months on average and includes 14+ responsible agencies

Permitting process in the U.S.

Until construction completion



If hybrid power generation



Multilevel responsible agencies

Federal agencies

- Bureau of Land Management (for federal lands)
- Environmental Protection Agency
- Federal Energy Regulatory Commission (for power)
- Public utility commissions, if it involves district heating sales

State agencies

- Department of Natural Resources
- State water resource agencies
- State environmental agencies
- Department of Water Resources
- Department of Environmental Conservation

Local agencies

- County zoning offices
- County drilling permits
- Municipal water authorities
- County building departments
- Local utilities

Sources: [Permitting for Geothermal Power Development Projects](#) (DOE, n.d.); [Assessment of Economic Impact of Permitting Timelines on Produced Geothermal Power in Imperial County, California](#) (Idaho National Laboratory, 2022); [2021 U.S. Geothermal Power Production and District Heating Market Report](#) (NREL, 2021); [Geothermal Permitting and NEPA Timelines](#) (NREL, 2014).
 Credit: Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

3 Permitting leaders are streamlining processes, while challenges arise for countries with fragmented processes

Best practices and challenges by countries

Best practice: Streamlined

Iceland



- Centralized under the National Energy Authority (Orkustofnun); a national priority
- Simple property rights: Landowner owns resources on private land
- Long-established legal and technical frameworks
- 6-12 months

Sweden



- Clear distinctions for shallow vs. deep geothermal
- Simple notification process for most residential/medium-depth systems
- One main ordinance governs process (1998:899)
- 1-3 months (shallow); up to 6-12 months for deeper systems or protected zones

France



- Simplified in 2023 to halve permitting times
- Coordinated support from ADEME (environment/energy agency)
- Clear licensing system under Mining Code for deep geothermal
- 1-2 years (previously longer)

Challenged: Fragmented

USA



- Jurisdiction split among federal (BLM, EPA), state (natural resources, water rights), and local (zoning/building)
- NEPA reviews add years unless expedited
- Each project requires navigating at least 5-7+ agencies
- 5-10 years (worst case); with expedited reforms (2025), aim for 1-2 years

Türkiye



- Multiple layers including provincial and national agencies
- Inconsistent enforcement, political/ bureaucratic delays
- Water, drilling, and land permits handled by separate ministries
- 2-5 years depending on project and province

Netherlands



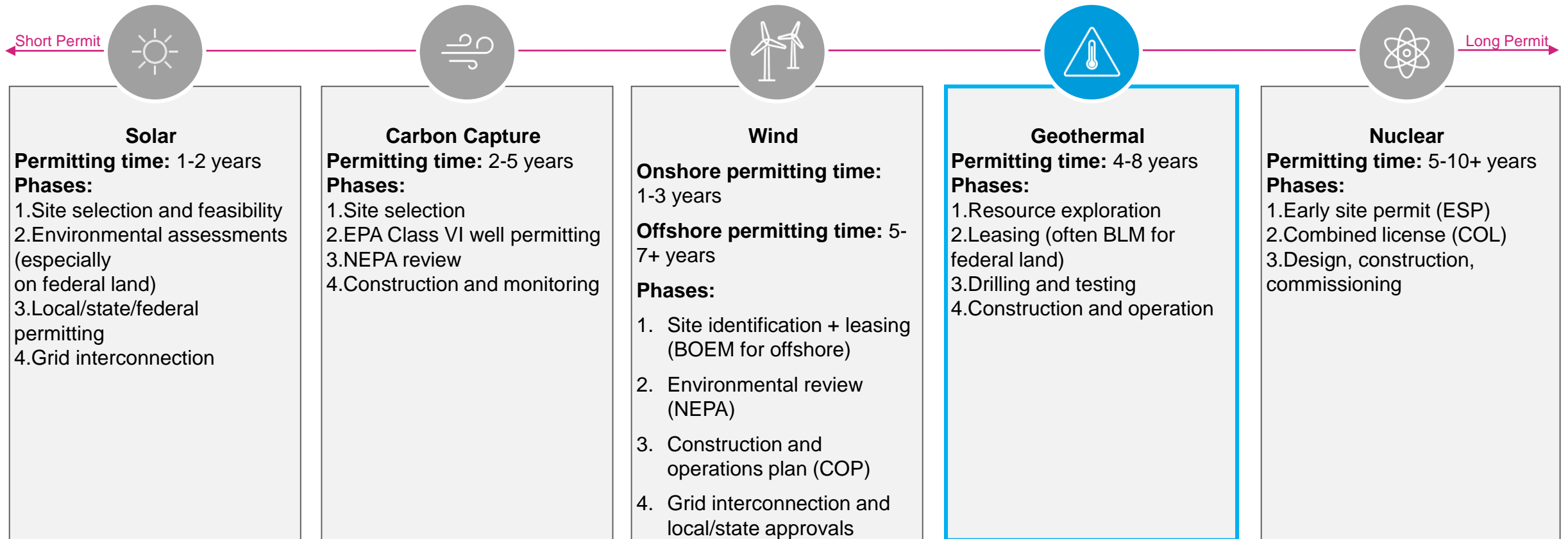
- Dual licensing under the Mining Act and the Environmental Licensing Act
- Coordination needed between Ministry of Economic Affairs and State Supervision of Mines
- 3.5-9.5 years depending on depth, location, and complexity

Sources: [Licences and applications](#) (Orkustofnun, n.d.); [The Future of Geothermal Energy](#) (IEA, 2024); [France announces simplification measures for geothermal permitting](#) (ThinkGeoEnergy, 2024); [Permitting for Geothermal Power Development Projects](#) (DOE, n.d.); [Geothermal Transparency Guide](#) (VNF, 2017).

Credit: Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

3 Alongside nuclear energy, geothermal power has the longest permitting timelines among all renewable energy sources

Best practices and challenges by renewables



Sources: [Assessment of Economic Impact of Permitting Timelines on Produced Geothermal Power in Imperial County, California](#) (Idaho National Laboratory, 2022); [The Future of Geothermal Energy](#) (IEA, 2024); [2021 U.S. Geothermal Power Production and District Heating Market Report](#) (NREL, 2021).
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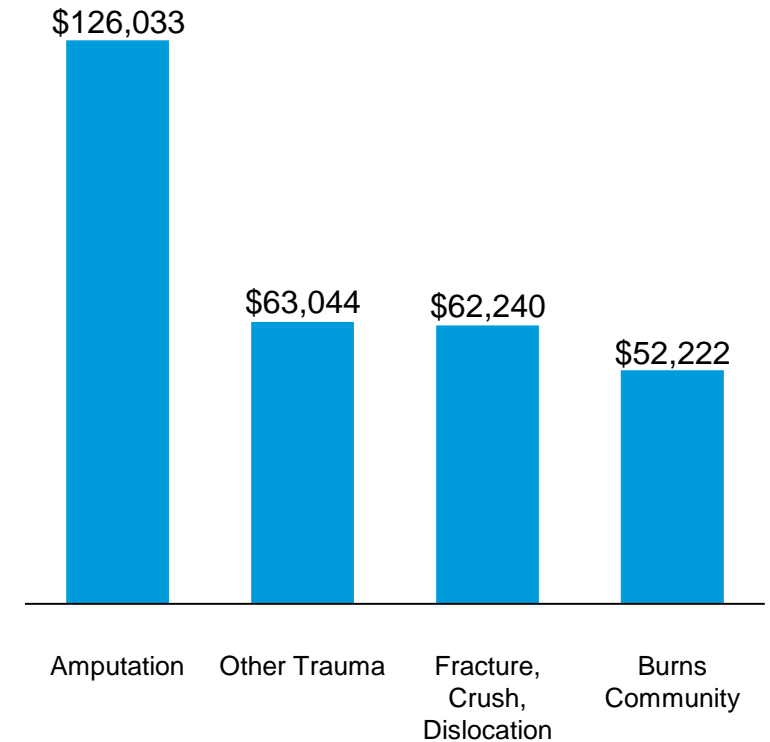
4 Geothermal installation workers face hazards including drilling accidents, heat exposure, and confined space risks

OSHA regulations require employers to protect workers by providing proper PPE, guarding hot pipes, and limiting exposure to hazardous

Hazards

<p>Trenching and excavation dangers: Cave-ins have caused fatal incidents.</p>
<p>Exposure to hot water and steam: Risk of severe burns from sudden heat release.</p>
<p>Toxic gas exposure: Hydrogen sulfide leaks may cause respiratory distress or collapse.</p>
<p>Confined space hazards: Chemical fumes and oxygen depletion may lead to serious illness.</p>
<p>Slips and falls: Workers risk falling into hot water pools or other hazards at remote sites.</p>
<p>Mechanical Injuries: Equipment malfunctions and handling heavy tools can cause fractures and other injuries.</p>

Injury Data

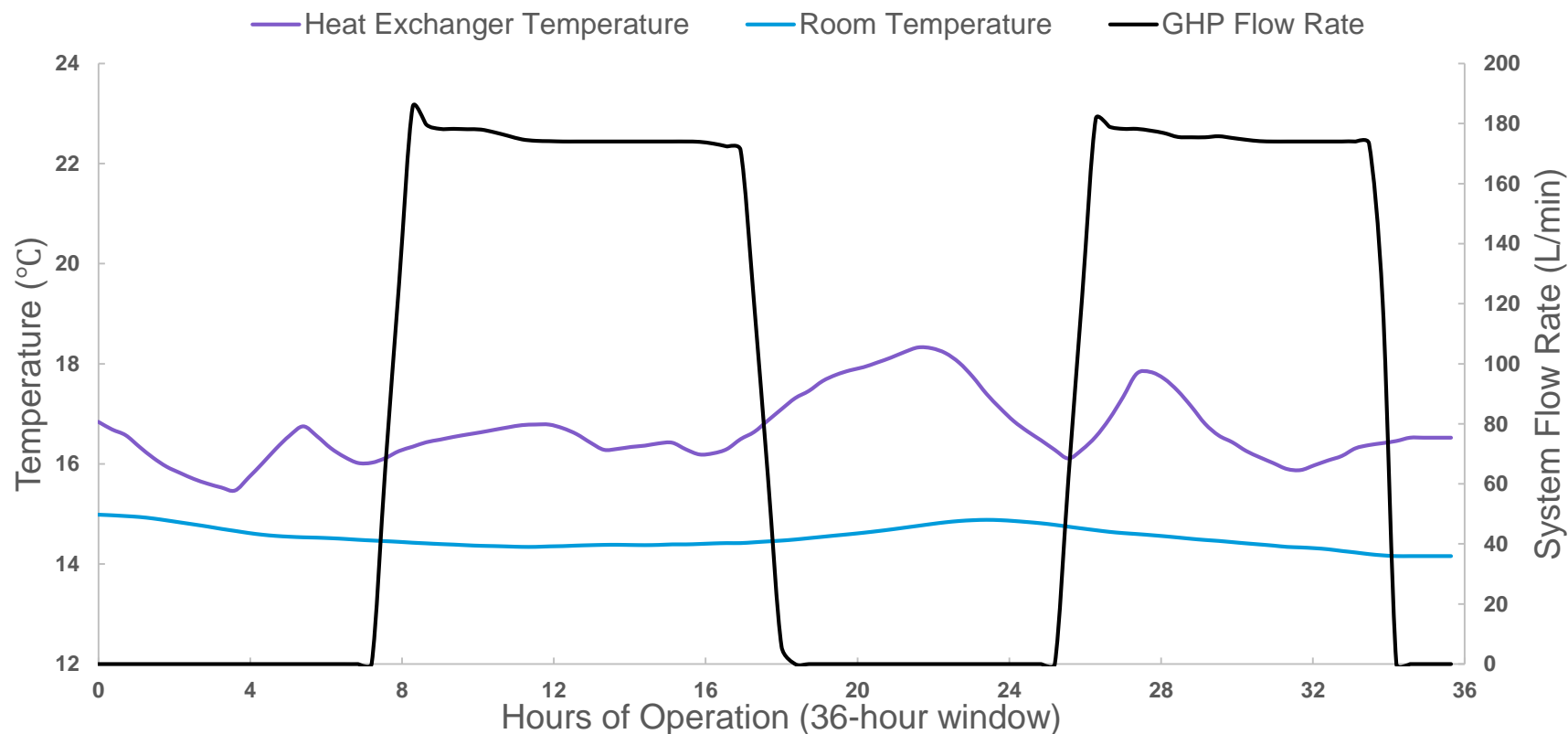


OSHA requires workers to have personal protective equipment: **1910.132(a)**; keep a distance of 15 inches to 7 feet from hot water pipes: **1910.261(k)(11)**; limit exposure to an 8-hour working window **29 CFR (1926.55, 1910.1000)**.

Sources: [OSHA Archive](#) (OSHA.gov, 2009); [Green Job Hazards](#) (OSHA.gov, 2025); [Geothermal Project Safety](#) (IGSHPA.org, 2025); [EUR-Lex](#) (OSH Directive, 2025); [EUR-Lex](#) (Machinery Directive, 2025); [EUR-Lex](#) (Pressure Equipment Directive, 2025).
 Credit: Zacharia Thurston, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

5 Critical parameters like temperatures, system pressure, and flow rates need to be monitored

Temperature vs. system flow rate during 36 hours of a GHP system operation in Korea



GHP system monitoring includes:

- **Temperature set points:** Primarily temperature in the internal environment. Based on specified target temperatures, actual temperatures are continuously measured for deviance using probes.
- **System-level controllers:** Primarily pressures and flow rates of the heat pump loop. As seen in the study shown left, the heat pump system is activated to release **180 L/minute** once the control room temperature falls **below 14.5°C**.
- **Risk factors:** Temperature probe failure, mechanical leaks, and more can affect system operation.
- **Main service providers and players:**



Sources: [Open-source IoT monitoring system of a shallow geothermal system for heating and cooling year-round in Korea](#) (Energy, 2022).

Credit: Hassan Riaz, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

5 Consistent maintenance checklists can help minimize lifetime OpEx

Key parameters and checklist

Level of Importance



Low



Moderate



High

Parameter	Overview	Schedule	Conducted by	Importance to System
Check and replace air filters	Inspect filters monthly and replace as needed	Monthly	Owner	M
Monitor system performance	Monitor energy bills for inconsistency	Monthly	Owner	L
Inspect coils	Check air handler and heat pump coils for dirt/debris	Biannual	Owner	M
Clean condensate drains	Inspect condensate drains for any clogs and leaks	Biannual	Owner	H
Inspect ductwork	Look for visible signs of damage or disconnections	Biannual	Owner	M
Test thermostat	Verify thermostat is accurately reading temperature	Biannual	Owner	L
Refrigerant level check	Get technician to verify refrigerant levels	Annual	Technician	H
Electrical component inspection	Conduct comprehensive testing of electrical components	Annual	Technician	M
Ground loop pressure test	Check for proper pressure for efficient heat transfer	Annual	Technician	M
Heat pump performance evaluation	Schedule professional testing of heating & cooling modes	Annual	Technician	H
Ductwork cleaning	Have professional inspect and clean ductwork	Annual	Technician	H

A GHP system's overall maintenance costs and reliability can be optimized through proactive owner engagement:

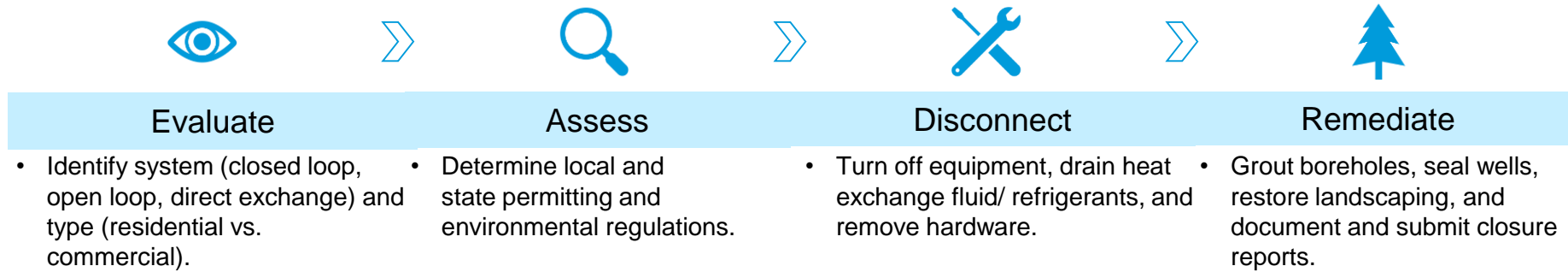
- **Integrate GHP maintenance into facility management:** For commercial facilities with regular maintenance staff, critical areas such as testing refrigerant and examining leaks should be included in maintenance checklists.
- **Monitor performance:** Observe GHP performance and track utility consumption for efficiencies, engaging with trusted technicians for any adjustments needed.
- **Budget for routine service:** Annual maintenance that requires technicians can cost **\$300 to \$500** per year, but that service extends GHP system life and reduces the need for eventual equipment replacement or repairs that can cost **more than \$2,000**.

Sources: [Geothermal System Maintenance: Tips and Best Practices](#) (EnvirotechGeo, 2024).

Credit: Hassan Riaz, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

6 Adhering to guidelines prevents groundwater contamination and ensures quality of land and reuse

Proper decommissioning is essential to protect groundwater, comply with local regulations, and ensure safe removal of equipment and fluids



System Type	General Decommissioning Steps
Open Loop	<ol style="list-style-type: none"> Cut well 4 feet below surface. Fill well with gravel, clean sand, or stone. Fill upper 10 feet with cement/6% bentonite and allow overflow, preventing water contamination. Compact soil above well cutoff.
Closed Loop	<ol style="list-style-type: none"> Remove and dispose of heat exchange fluid per state and local guidelines. Excavate hole at least 5 feet around well. Fill loop with high-solids bentonite slurry and allow for overflow, preventing water contamination.
Direct Exchange	<ol style="list-style-type: none"> Follow the first two steps of closed-loop decommissioning. Fill loop with cement grout and allow for overflow, preventing water contamination.

Observations

Decommissioning geothermal systems is critical to prevent or control for:

- Groundwater contamination
- Restoration of land usability
- Adherence to regulatory requirements enforced by various levels of government

While the core objectives of decommissioning are consistent, permitting requirements, timelines, and costs vary significantly by jurisdiction and project scale, making planning and budgeting essential to successful project closure.

Sources: [Con Edison Clean Heat Program Non-Residential Decommissioning Checklist](#) (Con Edison, 2025); [Guidelines for Ground Source Heat Pump Wells](#) (Mass.gov, 2013).

Credit: Zacharia Thurston, Pia Doris Morrow, and [Gernot Wagner](#). [Share with attribution](#): Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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CKI Geothermal Team

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Appendix

Glossary (1/2)

CKI Guideline for Geothermal Terms

Baseload power

Electricity supplied consistently over time to satisfy the minimum level of demand

Peaker plant

A power-generation facility that is used only during periods of high electricity demand (peak loads) rather than continuously

Hydrothermal: Conventional geothermal

A geothermal system in which naturally occurring heat, fluid, and rock permeability are present, allowing heat extraction without major engineering of the reservoir

Dry steam power plants

A geothermal plant type in which steam (rather than hot water) from the reservoir is piped directly to a turbine to generate electricity

Flash steam power plants

A geothermal plant type in which high-pressure hot water from underground is brought to the surface, the pressure drops, water “flashes” into steam that drives a turbine, and remaining fluid is often reinjected

Binary cycle power plants

A geothermal plant in which geothermal fluid (often lower temperature) transfers heat to a secondary “working fluid” via a heat exchanger; the working fluid vaporizes and drives a turbine, while the geothermal fluid remains in a closed loop and is reinjected

Next-generation geothermal

An umbrella term for geothermal approaches beyond conventional hydrothermal resources; that is, systems using engineered reservoirs, closed loops, or other technologies to expand geothermal potential

Closed-loop geothermal systems (CLGS)

Geothermal systems in which the working fluid is circulated through sealed loops of pipe drilled into hot rock, extracting heat by conduction rather than relying on natural rock permeability or fluid pathways

Enhanced geothermal systems (EGS)

A method to develop geothermal energy in hot but low-permeability rock by artificially creating or improving the permeability (for example via hydraulic stimulation) so that fluid can circulate and extract heat

Advanced geothermal systems (AGS)

Often used interchangeably with closed-loop systems, geothermal systems that are engineered and do not depend on naturally favorable permeability or hydrothermal fluids

Superhot rock geothermal

Geothermal systems operating at very high temperatures (for example >400°C), often in rock that may reach or exceed super-critical conditions, thus offering a high-potential energy yield per well

Glossary (2/2)

CKI Guideline for Geothermal Terms

Frontier technologies

Emerging and experimental geothermal technologies beyond current commercial practice, including advanced drilling, novel stimulation techniques, and reservoir-creation methods (*please refer to technologies below*)

Magma-based geothermal

Geothermal systems that aim to extract heat directly from molten or partially molten rock (magma) or adjacent high-temperature zones; a higher-risk/higher-reward approach in the geothermal field

Geopressured geothermal

Geothermal systems in sedimentary basins where hot fluids are under high pressure (geopressure), sometimes containing dissolved gas (e.g., methane), which can provide combined heat and gas resource potential

Directional drilling

A drilling technique in which the wellbore is steered off vertical (horizontal or angled) to reach target zones of heat, fluid, or permeability that are not directly beneath the surface well pad

Hydraulic fracturing

A stimulation technique in which fluid is injected at high pressure into rock to open or expand fractures, thereby creating or enhancing permeability so that fluid can circulate; used in EGS development

Plasma drilling

A drilling method under development in which plasma (ionized gas) is used to erode or vaporize rock ahead of the drill bit, aiming for faster penetration in very hot or hard rock

Thermal spallation

A drilling technique under development in which rapid heating of rock causes spalling, rapid flaking, or fracturing of the rock surface, to assist borehole advancement in high-temperature conditions

Millimeter-wave drilling (Gyrotron)

A drilling technique under research using high-power electromagnetic waves at millimeter wavelengths (often from a gyrotron) to heat or vaporize rock ahead of the drill, to enable drilling in extreme rock/temperature environments

Laser-assisted drilling

A drilling technique under development in which lasers are used to ablate or weaken rock ahead of the drill bit, thereby improving the drilling rate or reducing bit wear in hard/high-temperature formations