Columbia Business School
Climate Knowledge Initiative

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Geothermal Power

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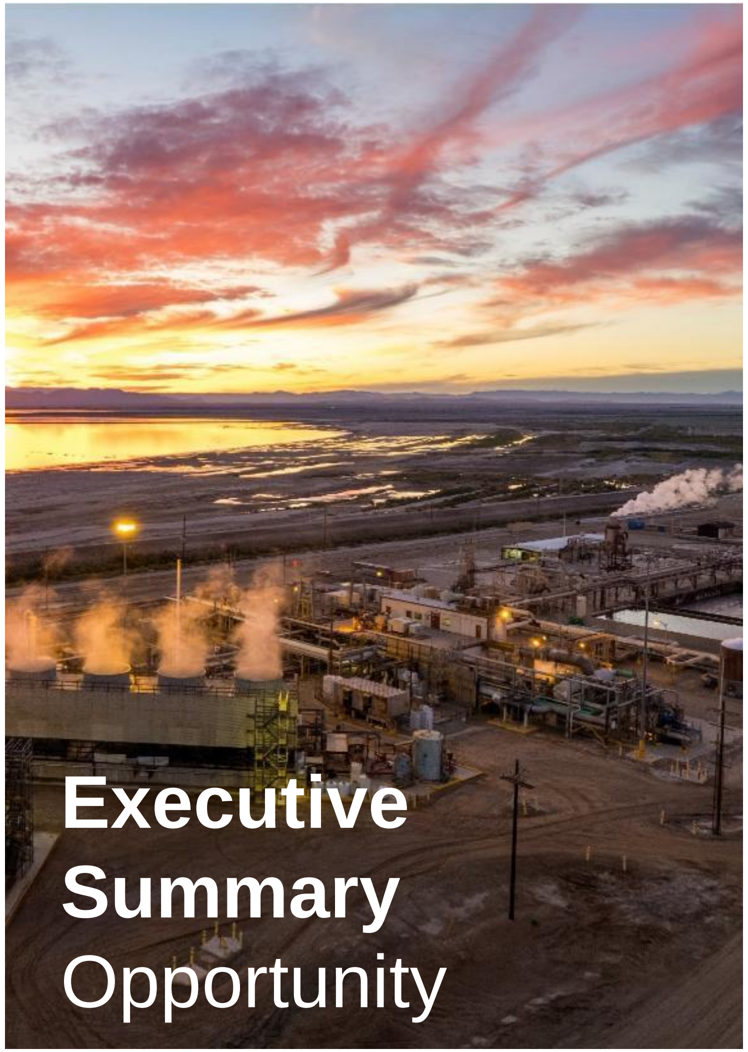
Geothermal Opportunity



Executive Summary 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.

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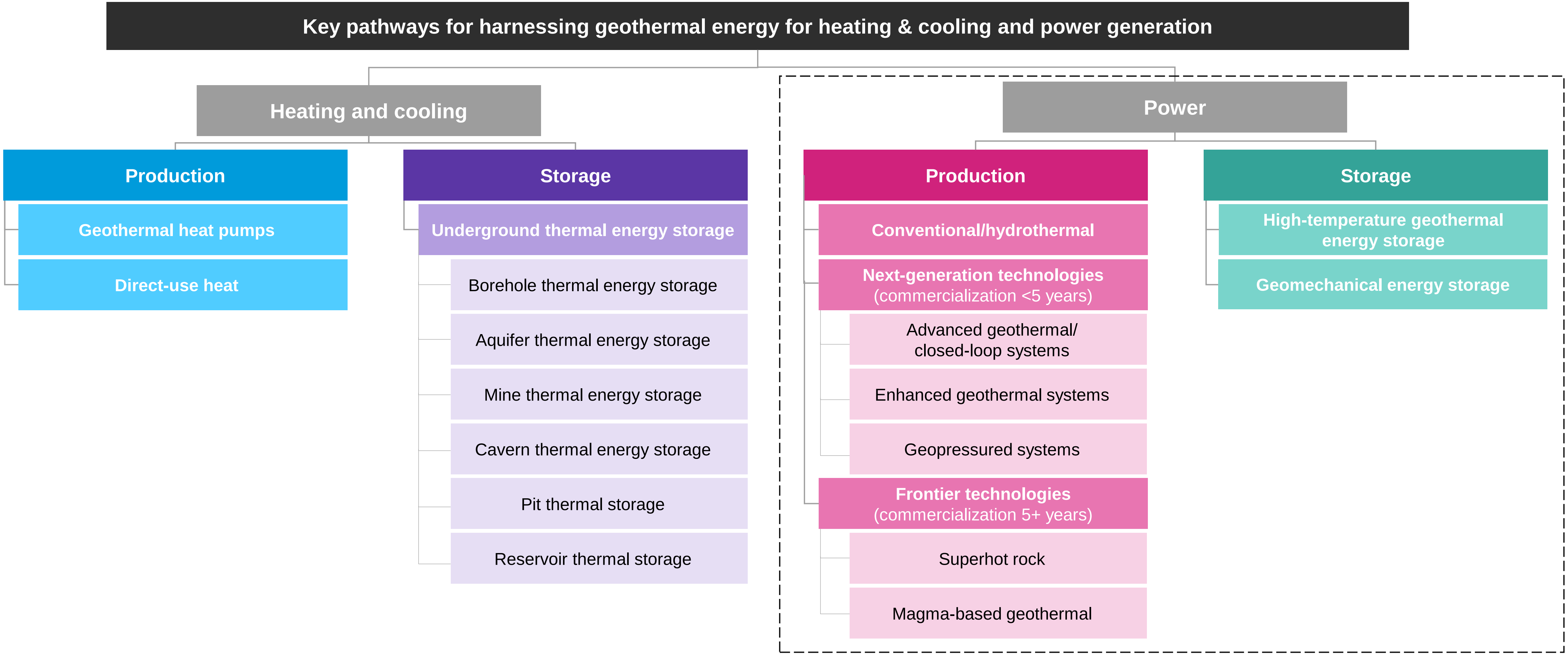
Geothermal energy technologies span heating & cooling and power generation, with conventional approaches most widely deployed



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

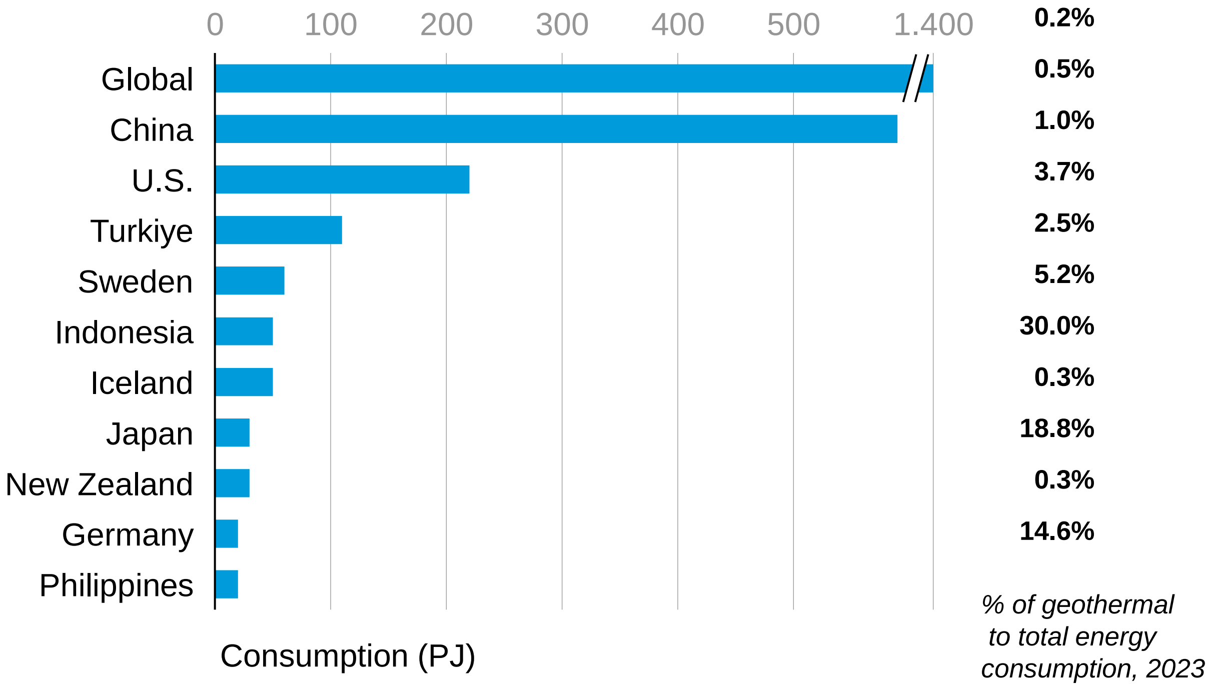
- **Heating and cooling**
  - **Production**
    - **Geothermal heat pumps**
    - **Direct-use heat**
  - **Storage**
    - **Underground thermal energy storage**
      - Borehole thermal energy storage
      - Aquifer thermal energy storage
      - Mine thermal energy storage
      - Cavern thermal energy storage
      - Pit thermal storage
      - Reservoir thermal storage
- **Power**
  - **Production**
    - **Conventional/hydrothermal**
    - **Next-generation technologies** (commercialization <5 years)
      - Advanced geothermal/ closed-loop systems
      - Enhanced geothermal systems
      - Geopressured systems
    - **Frontier technologies** (commercialization 5+ years)
      - Superhot rock
      - Magma-based geothermal
  - **Storage**
    - **High-temperature geothermal energy storage**
    - **Geomechanical energy storage**

Sources: Underground Thermal Energy Storage (Nature, 2012); Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); The Future of Geothermal Energy (IEA, 2024).

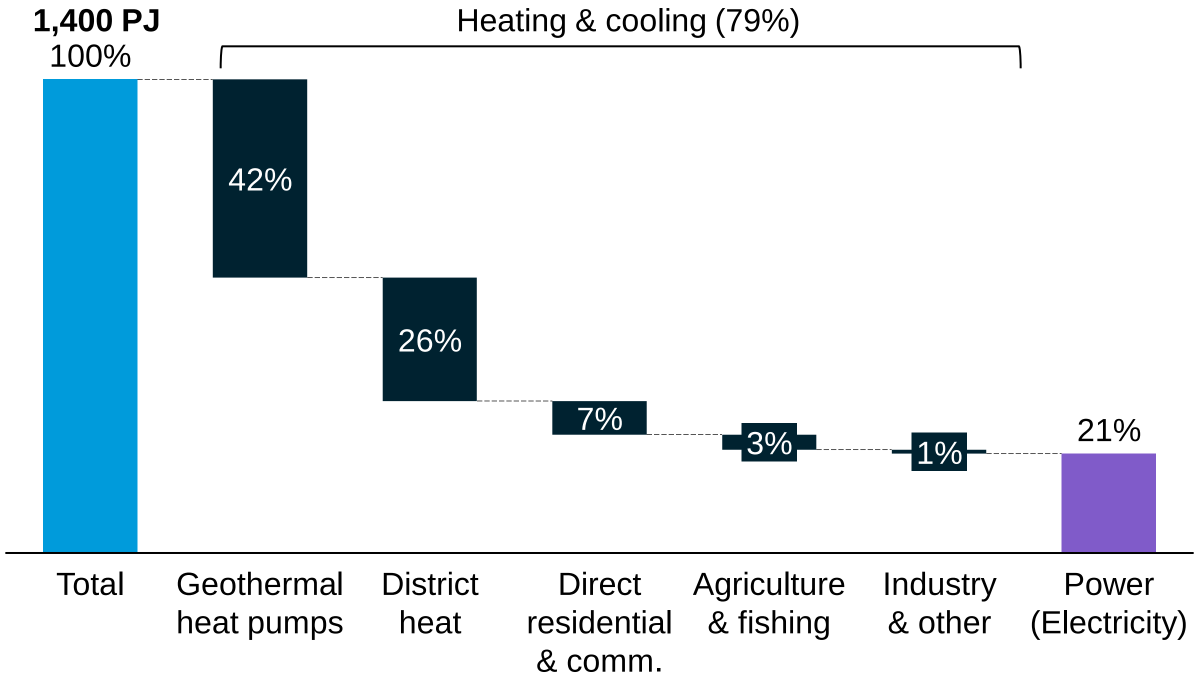
Credit: Sevgi Helin Tilkicioglu, Una Oljaca, Pia Doris Morrow, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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



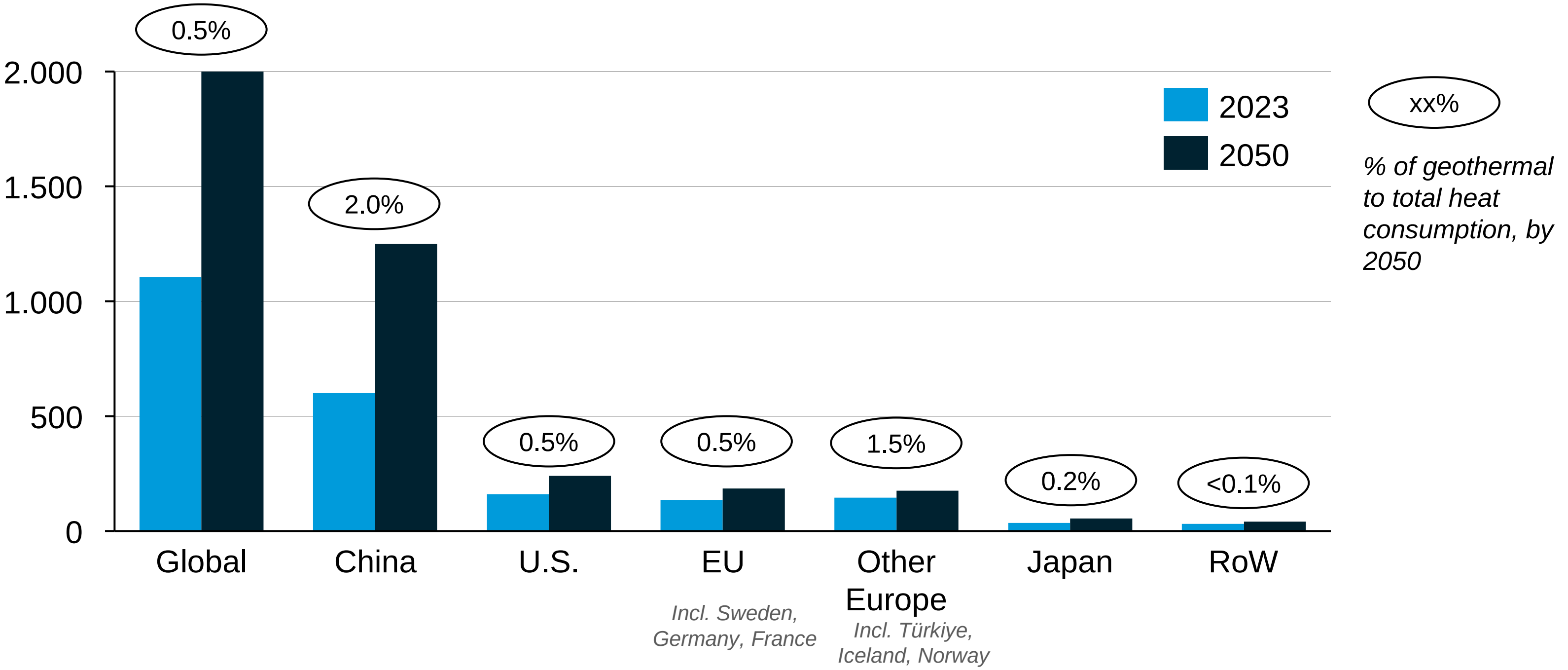
- **Heating: China** is the most significant country, accounts for nearly 50% of global geothermal final energy consumption, dedicated entirely to **space heating.**
- **Electricity:** The **U.S., Indonesia, Türkiye, the Philippines, and New Zealand** generate **two-thirds of global geothermal electricity**,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

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

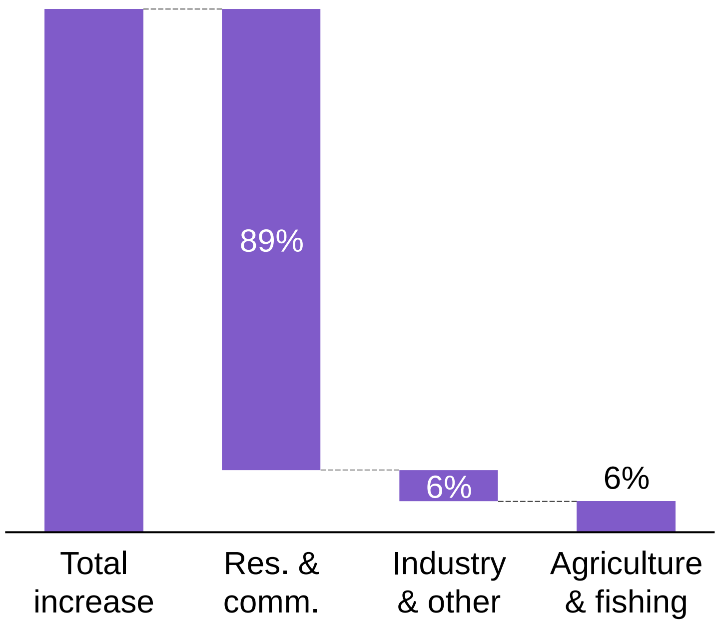
Credit: Faradisa Anintya, Pia Doris Morrow, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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



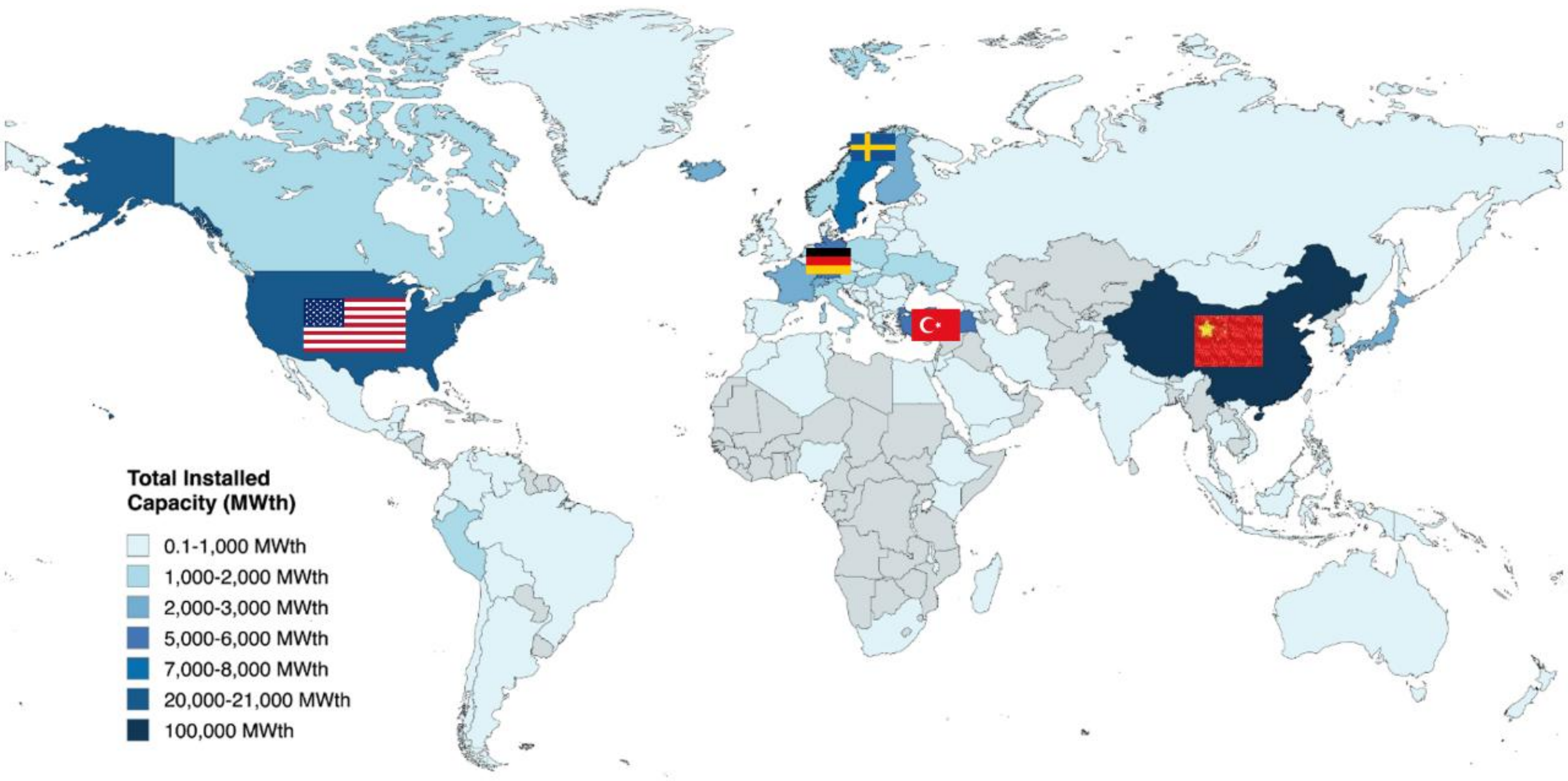
- Geothermal heating use **doubles in 2050** under a realistic government Stated Policies Scenario (STEPS), with China as the biggest source of growth. Yet, it remains **only 0.5% of total heat consumption globally**.
- From the use-case perspective, nearly **90% of geothermal heating consumption comes 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 Power," 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 >90ºC is **~320 TW**, while the potential for <90ºC 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).
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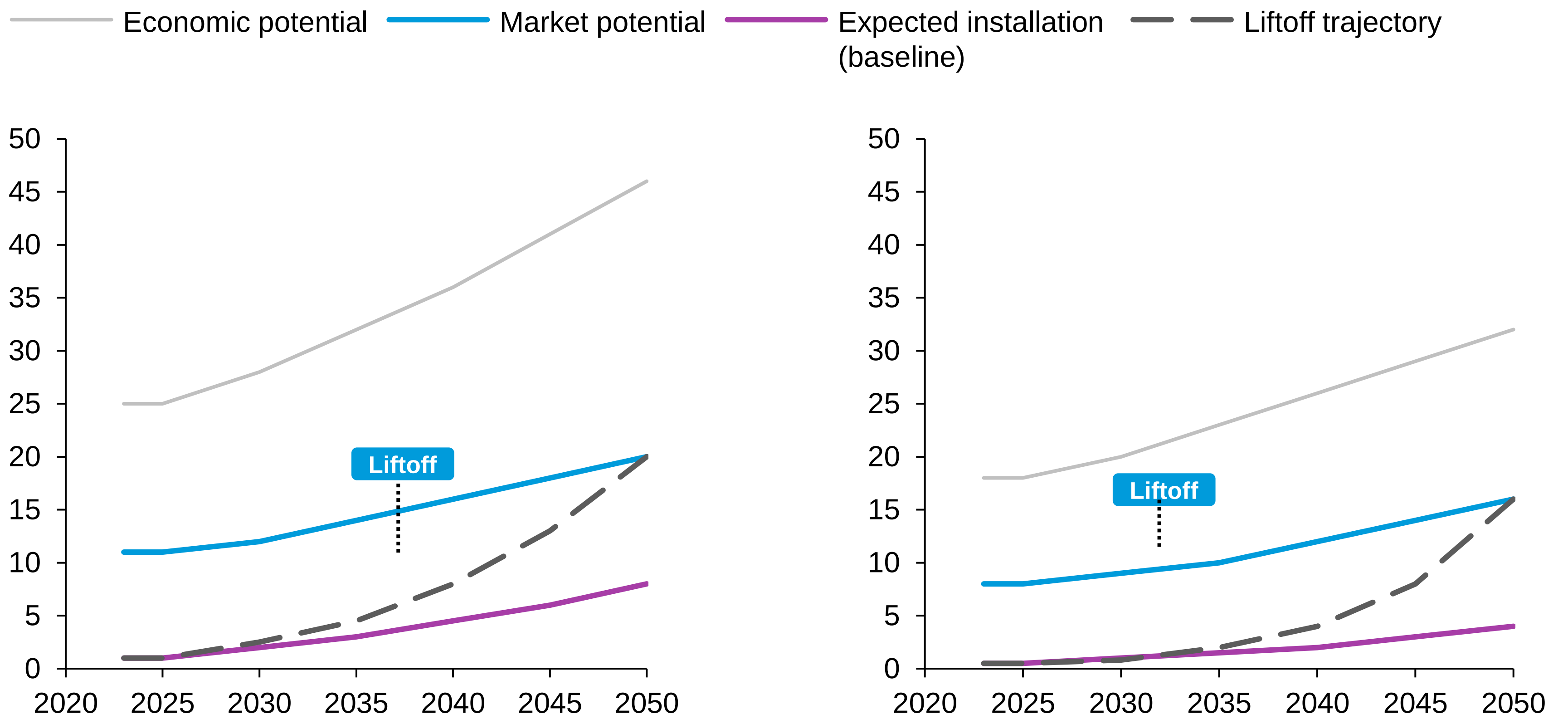
GSHPs could reach millions of U.S. homes by 2050, enabled by tax incentives, business innovation, and workforce development

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

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



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.

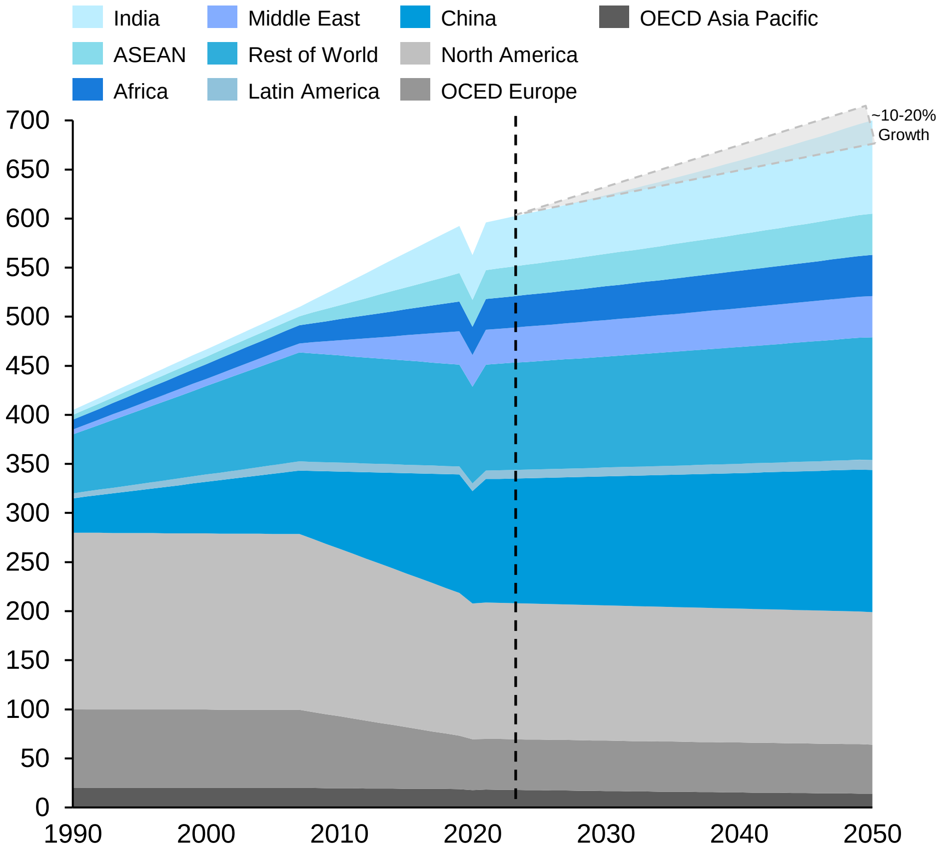
Sources: Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); The loophole that can give clean heat a boost under Trump (Canary Media, 2025).

Credit: Faradisa Anintya, Pia Doris Morrow, Zacharia Thurston, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," 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

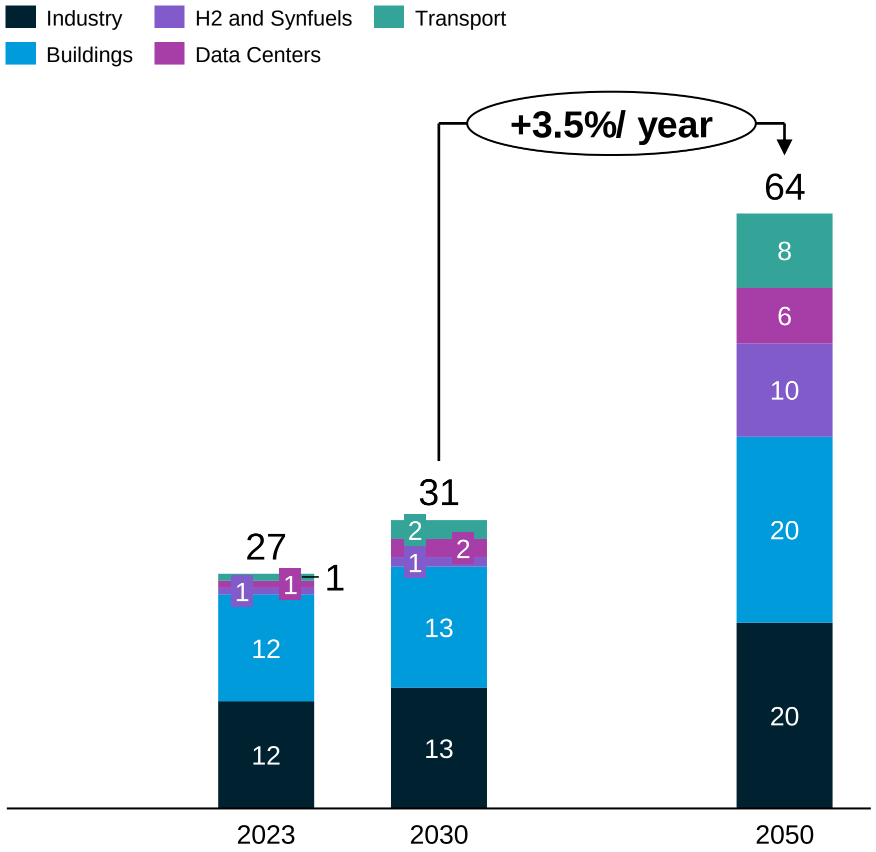
India, ASEAN*, Africa, and the Middle East will be responsible for ~65-95% demand growth

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 ~**10 to 20%**, with ~**65 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 10% 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.**

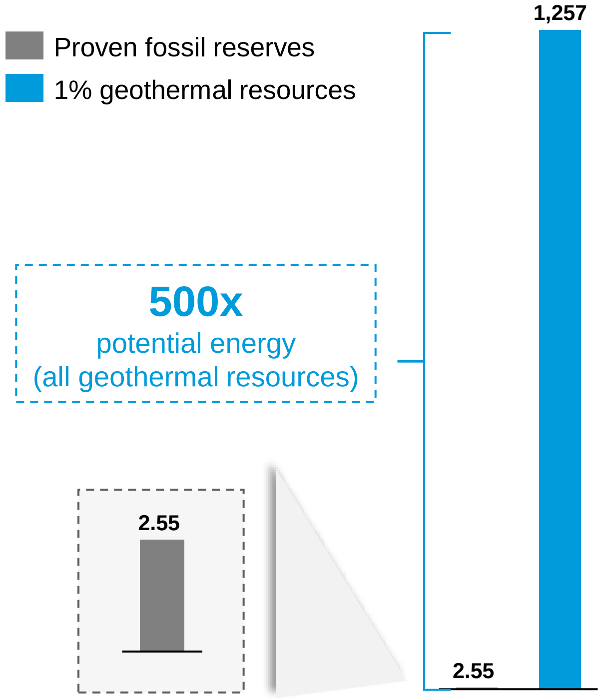
*Association of Southeast Asian Nations

Sources: Global Energy Perspective (McKinsey, 2024); Cumulative Investment for Next Generation Geothermal 2025-2050, (IEA, 2024).

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

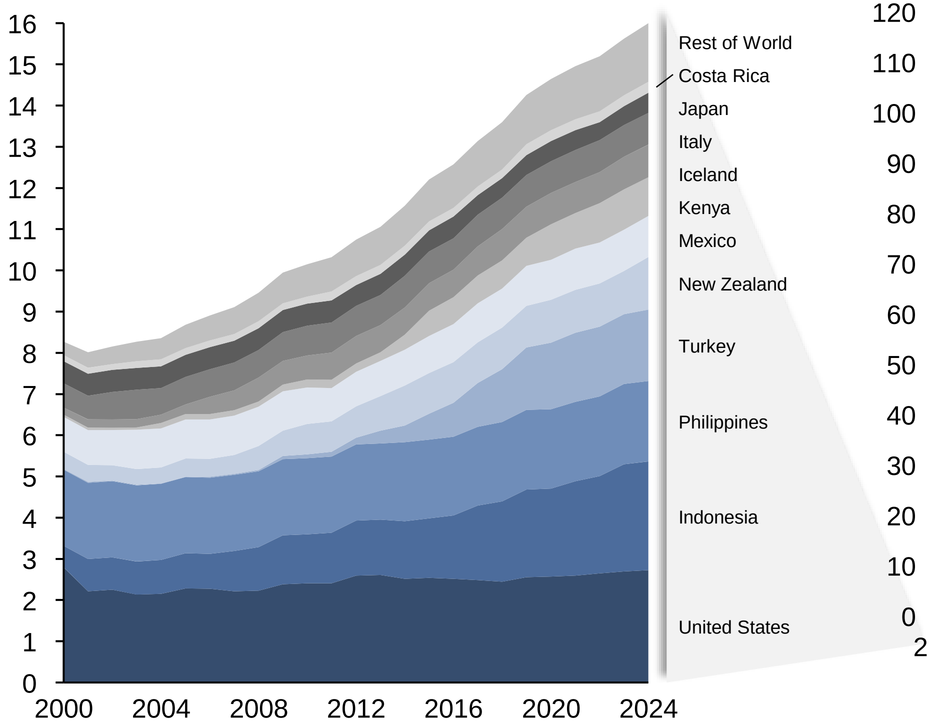
With vast untapped thermal resources and emerging technological advancements, geothermal power is primed for a breakout decade

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

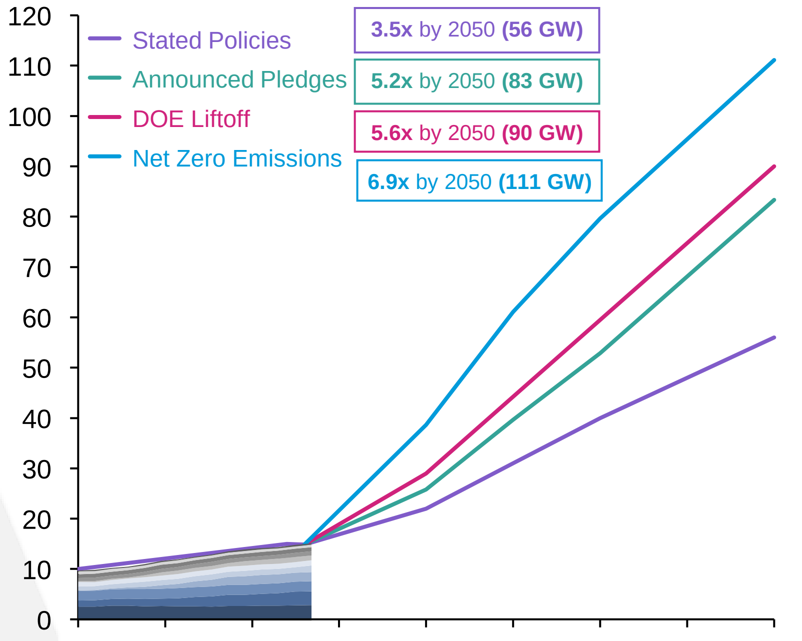


500x
potential energy
(all geothermal resources)

Historical installed geothermal capacity by country, GW



Projected global geothermal under different scenarios, GW



3.5x by 2050 **(56 GW)**

5.2x by 2050 **(83 GW)**

5.6x by 2050 **(90 GW)**

6.9x by 2050 **(111 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.

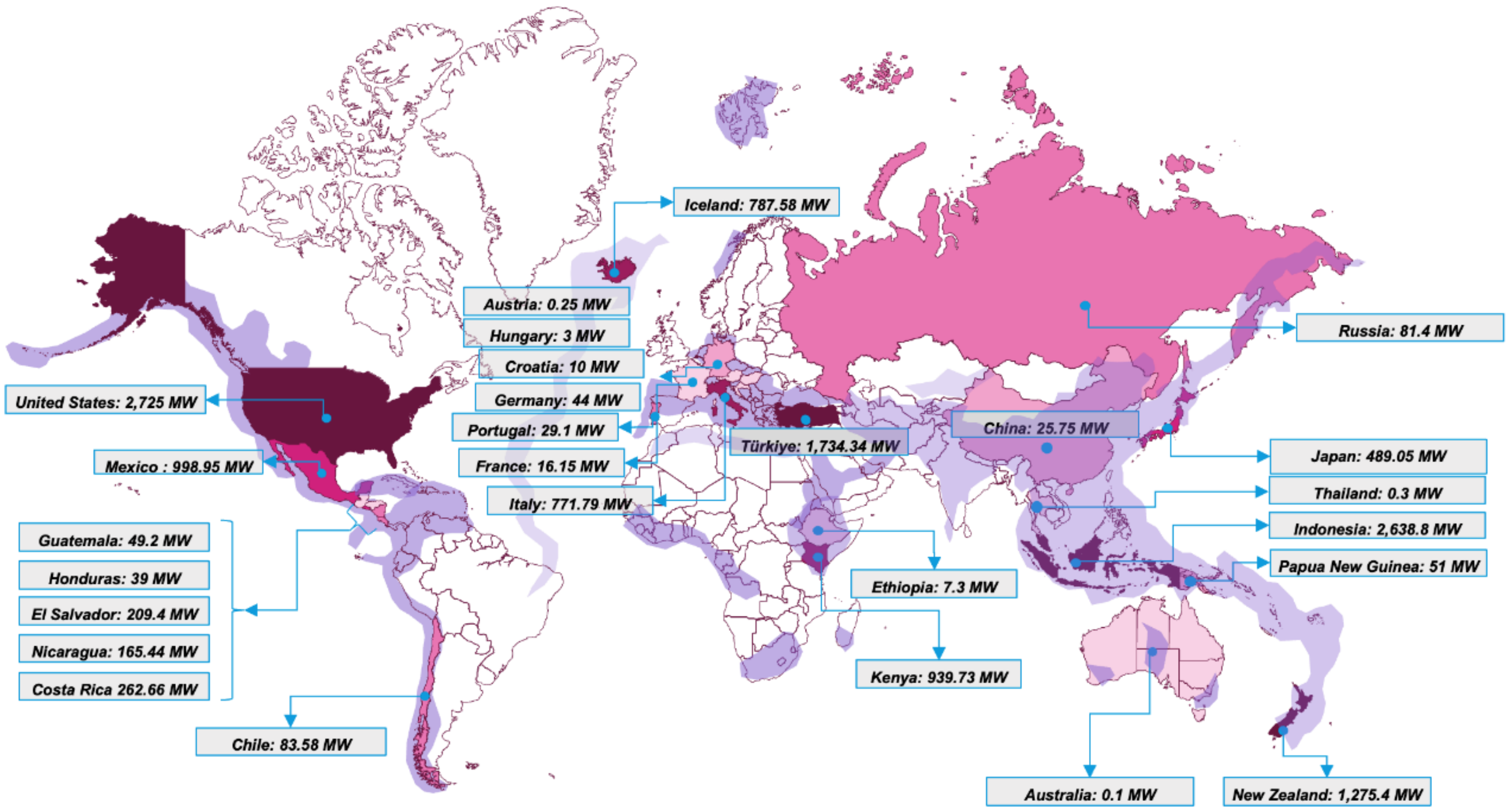
*One barrel of oil/gas is roughly equivalent to 1.7 MWh. There are about 1.5 trillion proven reserves of oil/gas x 1.7 MWh = 2.55 trillion MWh of potential fossil energy remaining (50-year supply remaining).

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).

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

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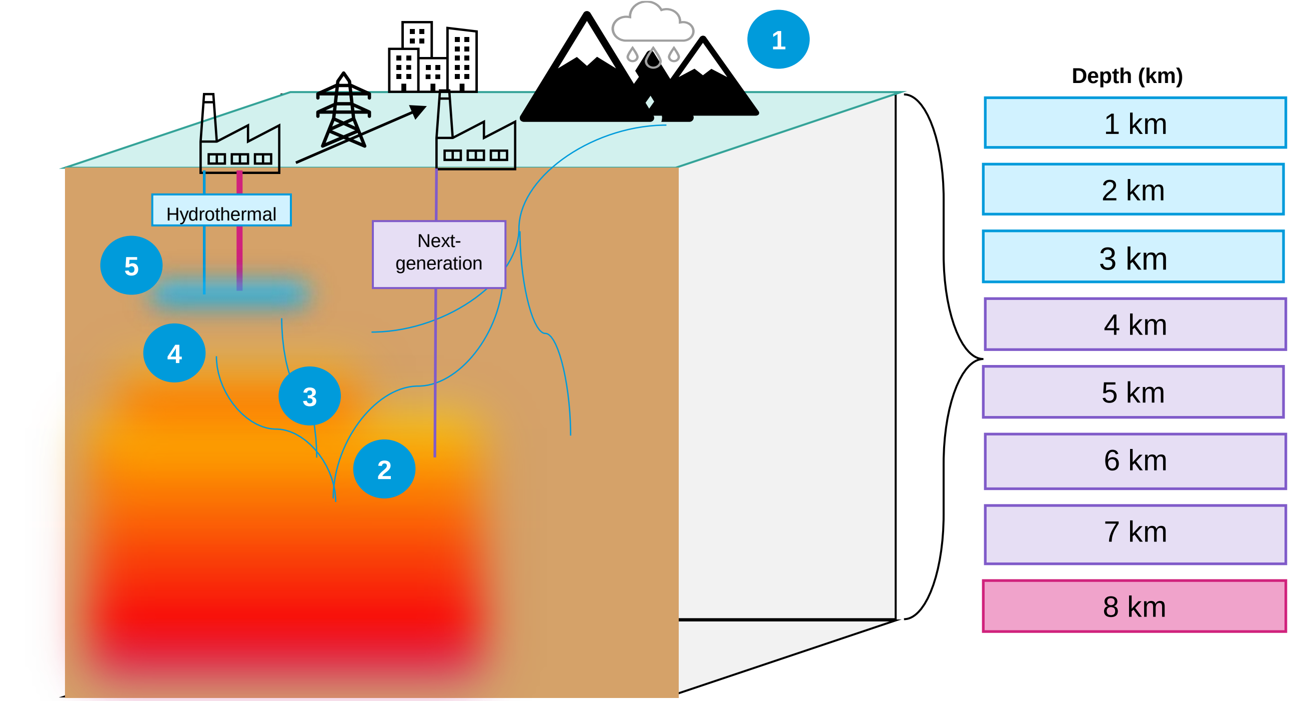
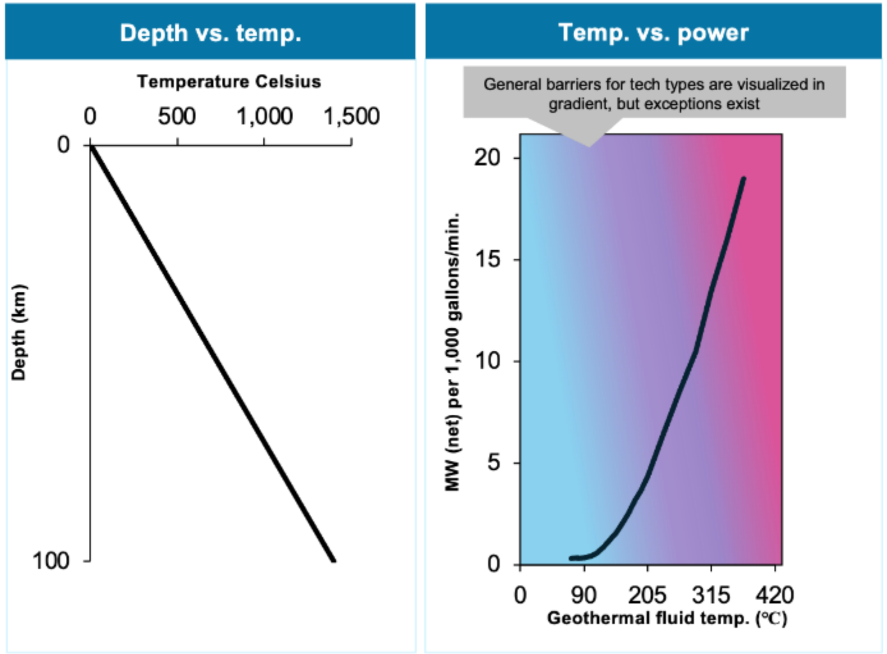
Next-generation technologies enable deeper drilling to unlock greater power potential

Heat reservoir formation process and access

1. Rainfall flows from higher elevations into the ground.
2. Water is heated by surrounding rock.
3. Water travels through faults and fractures.
4. Permeable rock traps and stores rising hot water or steam.
5. Geothermal reservoir is formed.



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



Tech type	Depth & temp. (ranges depending on location)	Power potential
Hydrothermal	~1-3 km, 90-370℃ (some may exceed)	●●●○○
Next-generation	~5-7.5 km, 120-370℃	●●●●○
Superhot rock	~7.5+ km, +400℃	●●●●●

*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).

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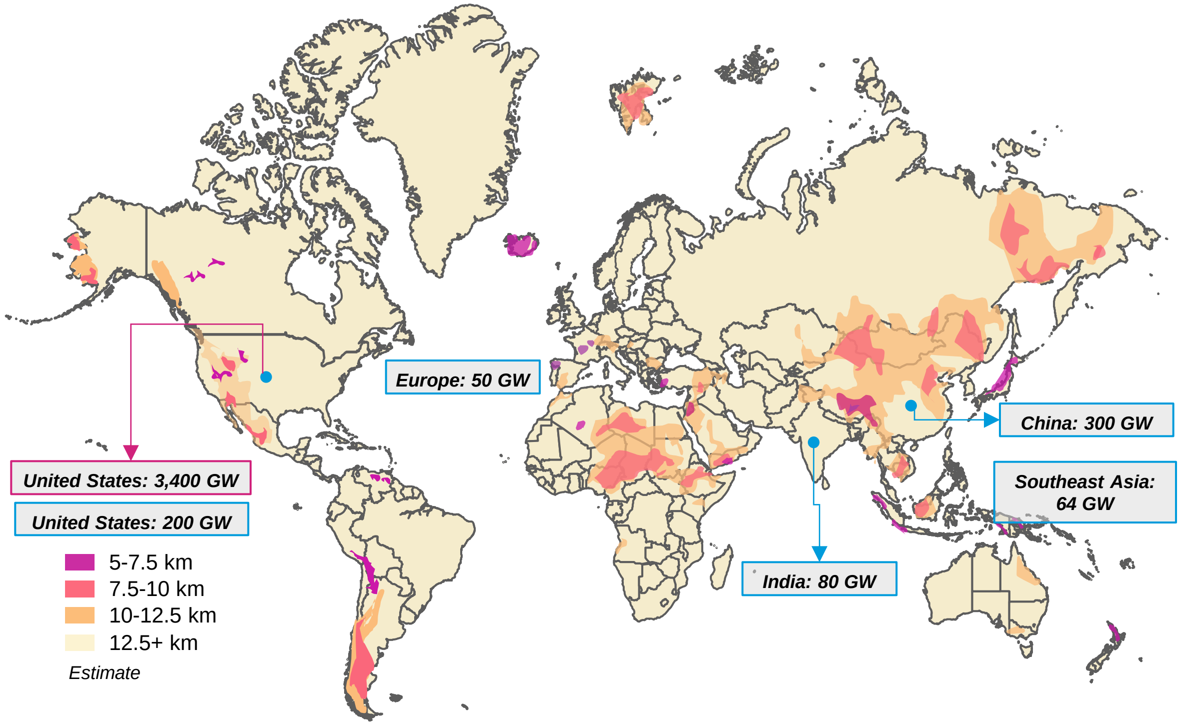
Next-generation drilling unlocks globalized clean energy access, with notable overlap in emerging economies by 2050

Global EGS hotspots concentrated in emerging economies

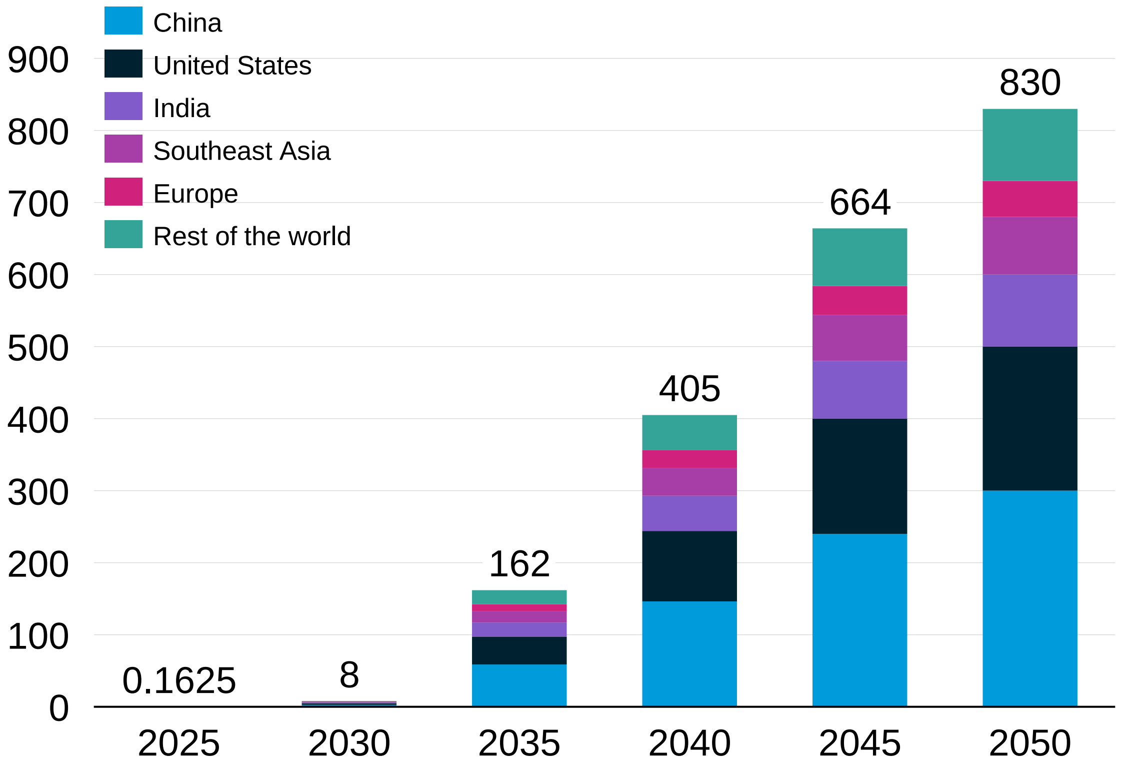


Project InnerSpace

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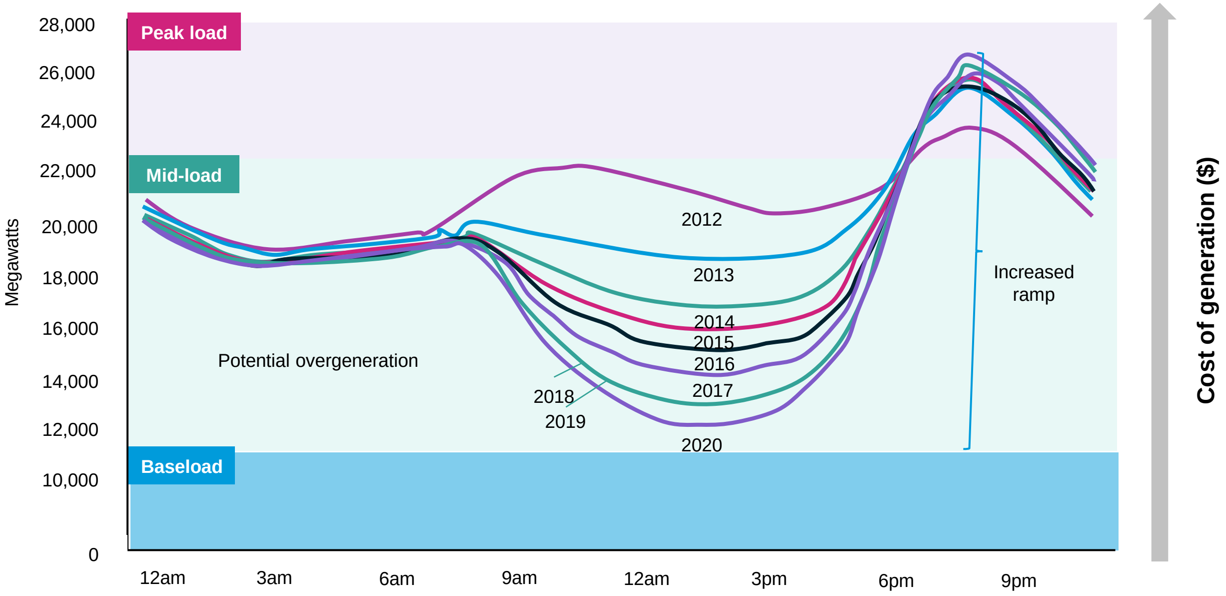
Geothermal power offers clean baseload capacity to replace retiring coal plants and prevent overreliance on peaker plants

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

Hourly net load (year average) in California



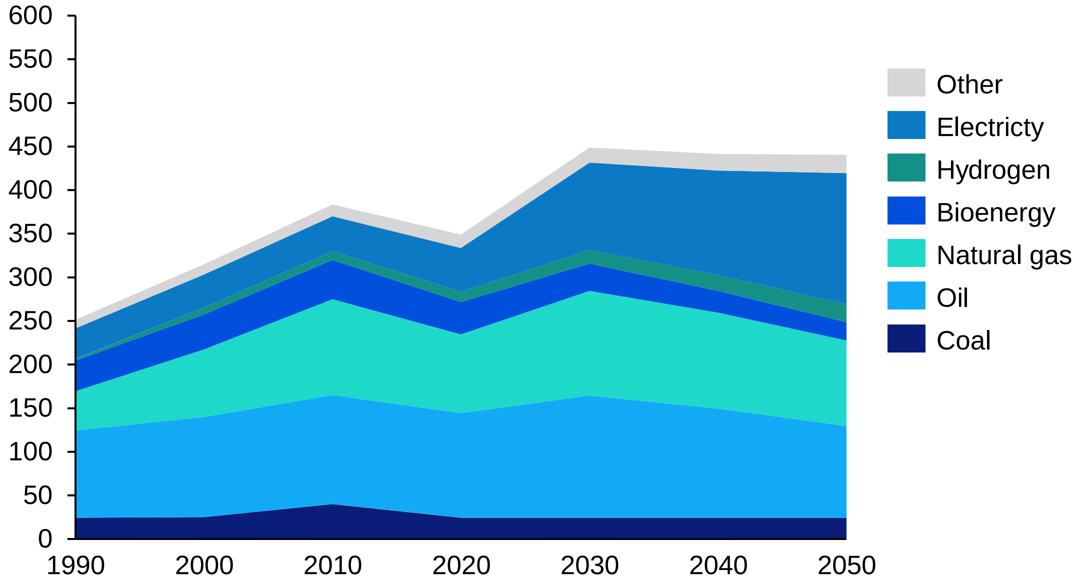
What is baseload?

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

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

Heavy dependence on intermittent renewables without baseload capacity threatens grid reliability

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



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 Power," 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

Major Barriers

Barrier	Description	Impact on Deployment	Emerging Solutions
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).

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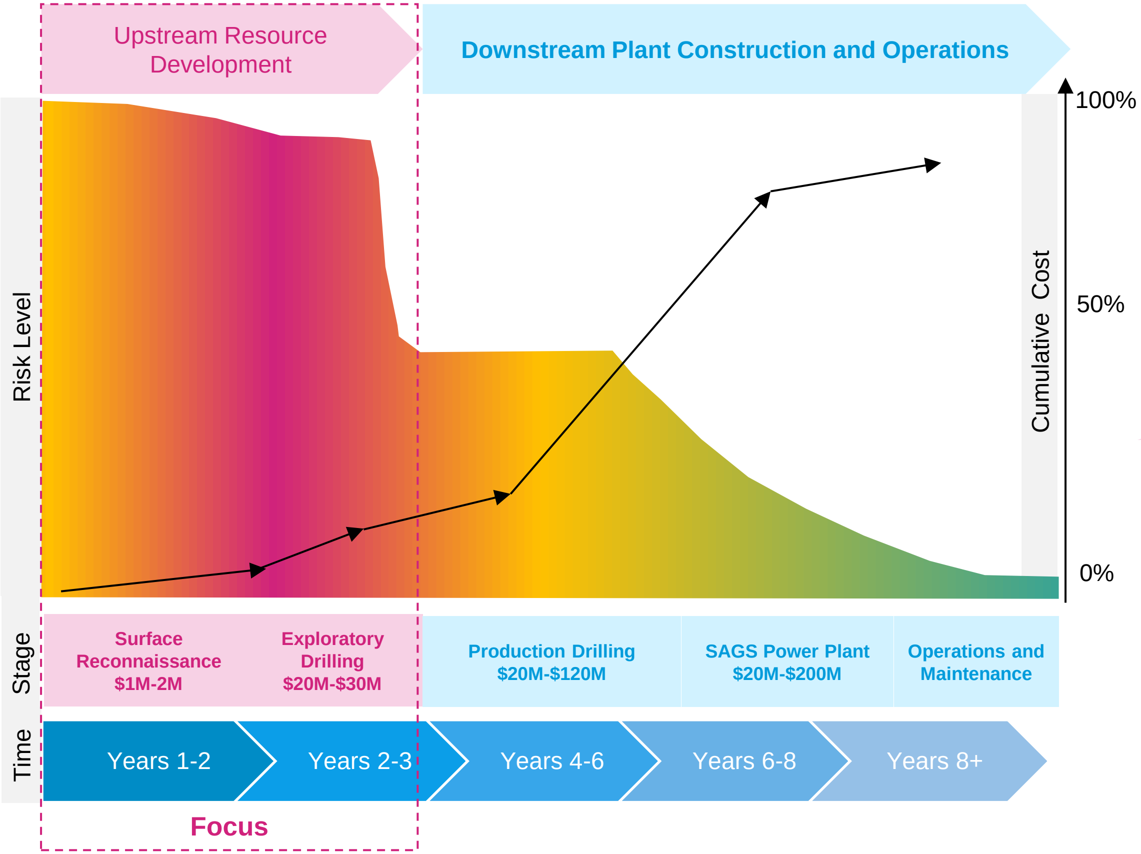
Exploratory drilling carries the highest project development risk, which can be reduced through advanced subsurface modeling

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



Stage	
Surface Reconnaissance $1M-2M	Years 1-2
Exploratory Drilling $20M-$30M	Years 2-3
Production Drilling $20M-$120M	Years 4-6
SAGS Power Plant $20M-$200M	Years 6-8
Operations and Maintenance	Years 8+

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.

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*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

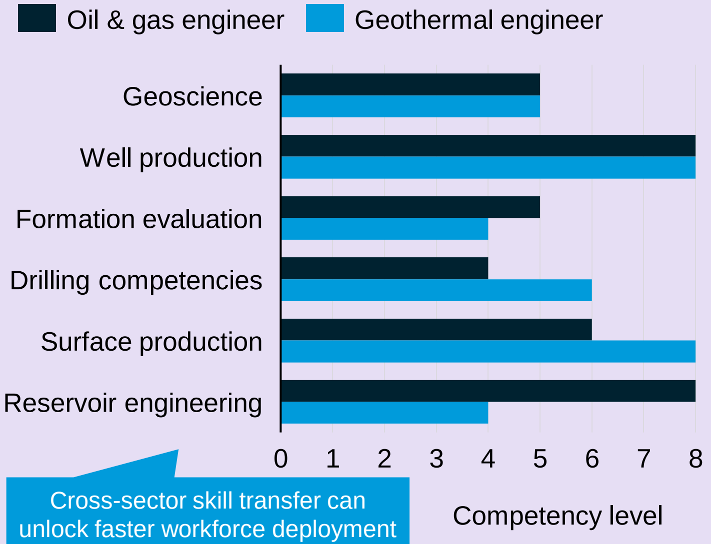
Simulation and zonal isolation techniques from O&G enhance reservoir longevity and reinjection efficiency.

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

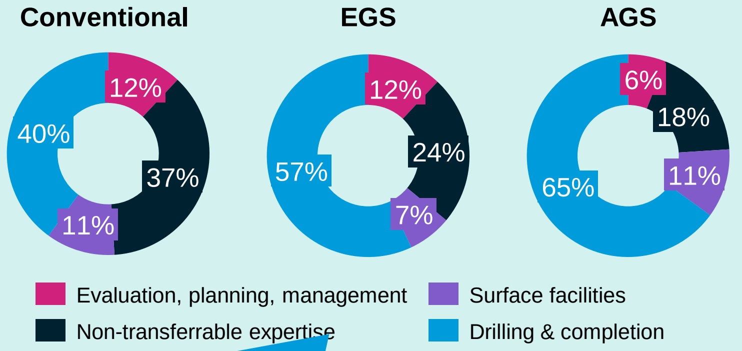
Iceland: Integrated geothermal-O&G training pipeline

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.

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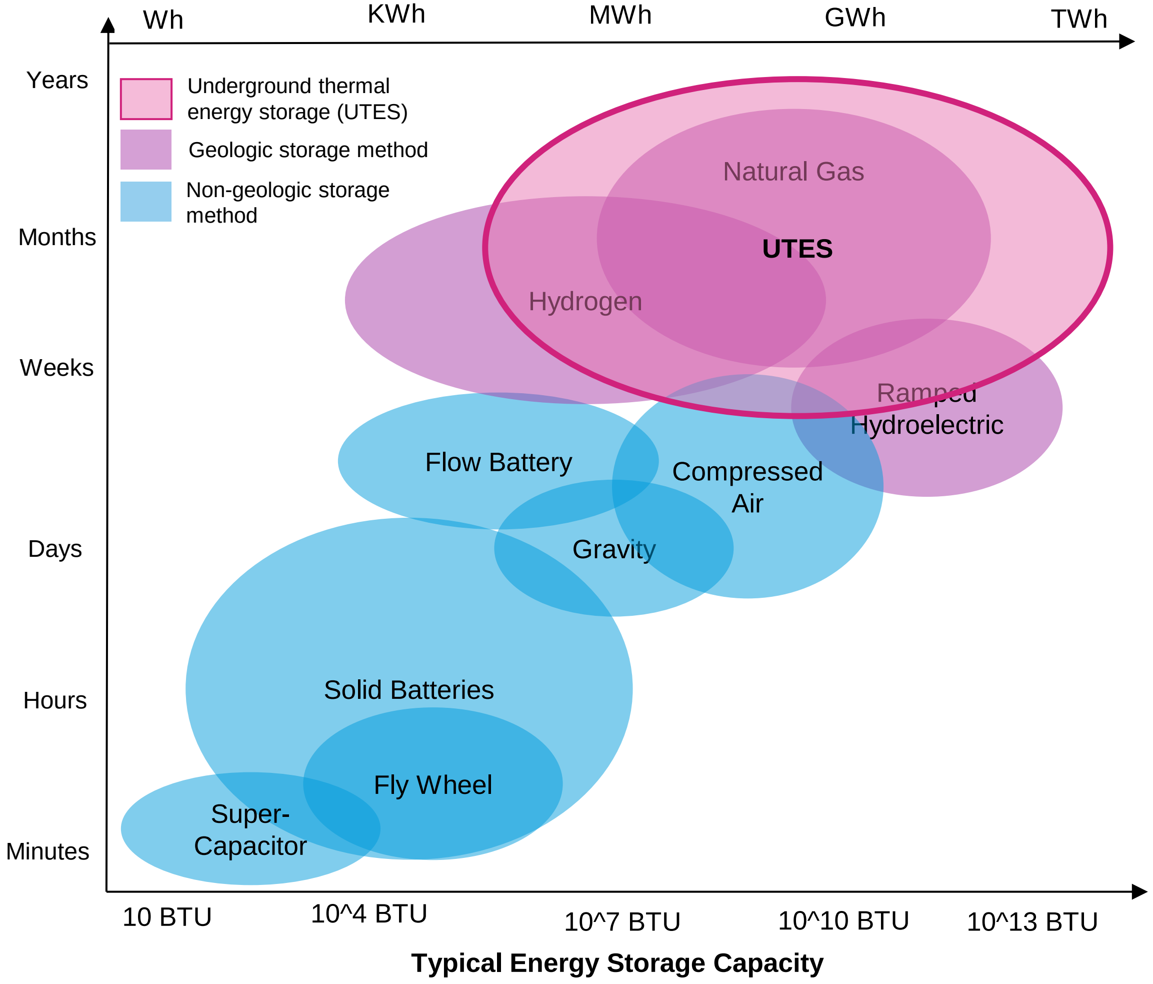
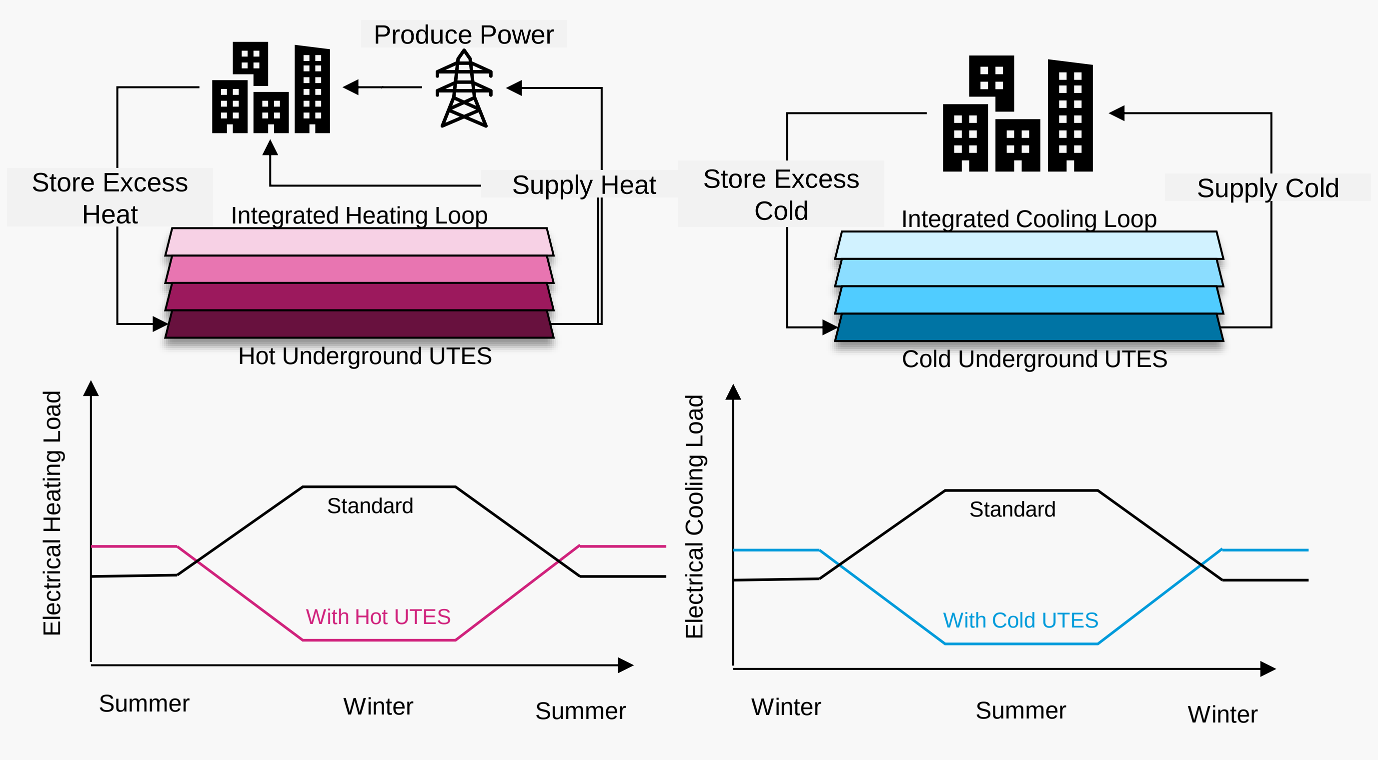
*Competency levels based on SPE competency matrices.

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 Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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





Both systems can coexist regardless of season due to the earth's insulating properties, but storage of excess heat and cold will be more likely during the summer and winter, respectively (i.e., lakes in the summer vs. winter).

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).

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

Columbia Business School
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Geothermal Power Technology

Key messages

Technology

Traditional **hydrothermal geothermal** taps naturally occurring hot water and steam reservoirs near the surface. These mature systems provide **reliable, low-cost baseload power** but are geographically limited to areas with accessible heat and permeability.

Petrothermal (enhanced or engineered geothermal systems) use advanced drilling and stimulation to access **dry, hot rock at greater depths**, creating artificial reservoirs where none existed. This breakthrough could unlock geothermal potential worldwide, independent of surface resource availability, making geothermal energy a truly global rather than niche solution.

At extreme depths and temperatures (>400°C), **superhot rock systems** could generate **5 to 10 times more energy per well** than conventional geothermal. These projects promise **ultraefficient, zero-emission power**, though they remain in early demonstration phases.

Modern drilling techniques — some borrowed from the **oil and gas industry** — include **directional drilling, hydraulic fracturing, and plasma or millimeter-wave drilling**. These techniques are driving **cost reductions and deeper resource access**, expanding geothermal's viable footprint.

Geothermal brines are rich in **critical minerals** such as **lithium, manganese, and zinc**, enabling **co-production of clean energy and essential materials** for batteries and energy storage. This overlap strengthens geothermal's strategic value across the **energy transition supply chain**.

Artificial intelligence and machine learning are transforming exploration by **analyzing geophysical data, seismic imaging, and well logs** to identify optimal drilling zones, predict subsurface conditions, and reduce exploration risk and cost.

Nuclear and geothermal are the only **scalable, zero-carbon baseload technologies** capable of providing continuous power independent of weather, season, or geography. Nuclear fusion innovation has found cross-sector use cases in drilling applications aiming to induce capabilities to melt granite and basalt.

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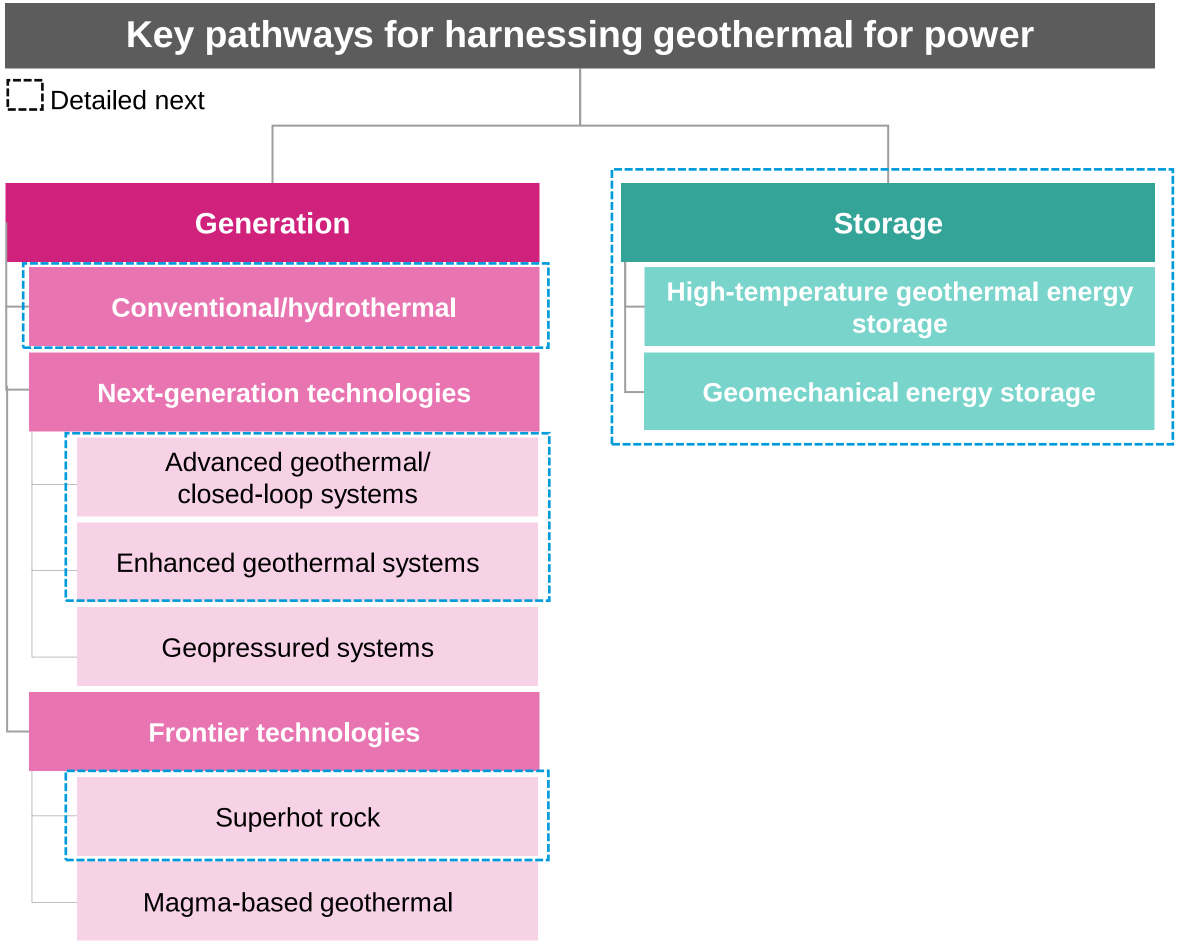
Conventional hydrothermal systems tap natural reservoirs; next-generation technologies reach broader heat resources



Key pathways for harnessing geothermal for power

⬚ Detailed next

- **Generation**
  - Conventional/hydrothermal
  - Next-generation technologies
    - Advanced geothermal/ closed-loop systems
    - Enhanced geothermal systems
    - Geopressured systems
  - Frontier technologies
    - Superhot rock
    - Magma-based geothermal
- **Storage**
  - High-temperature geothermal energy storage
  - Geomechanical energy storage

The three most important criteria to generate geothermal power are heat, fluid requirement, and permeability

	Conventional/ hydrothermal	Next-generation/ frontier technologies
Heat (varies by depth)	85-180°C+ 0.1-4.5 km	>200°C 2-10 km
Fluid	Required	Can be injected or circulated in closed loop
Permeability	Required	Created via stimulation or closed loop

Sources: The Future of Geothermal Energy (IEA, 2024); Exploring geothermal energy-based systems: Review from basics to smart systems (Renewable and Sustainable Energy Reviews, 2025).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

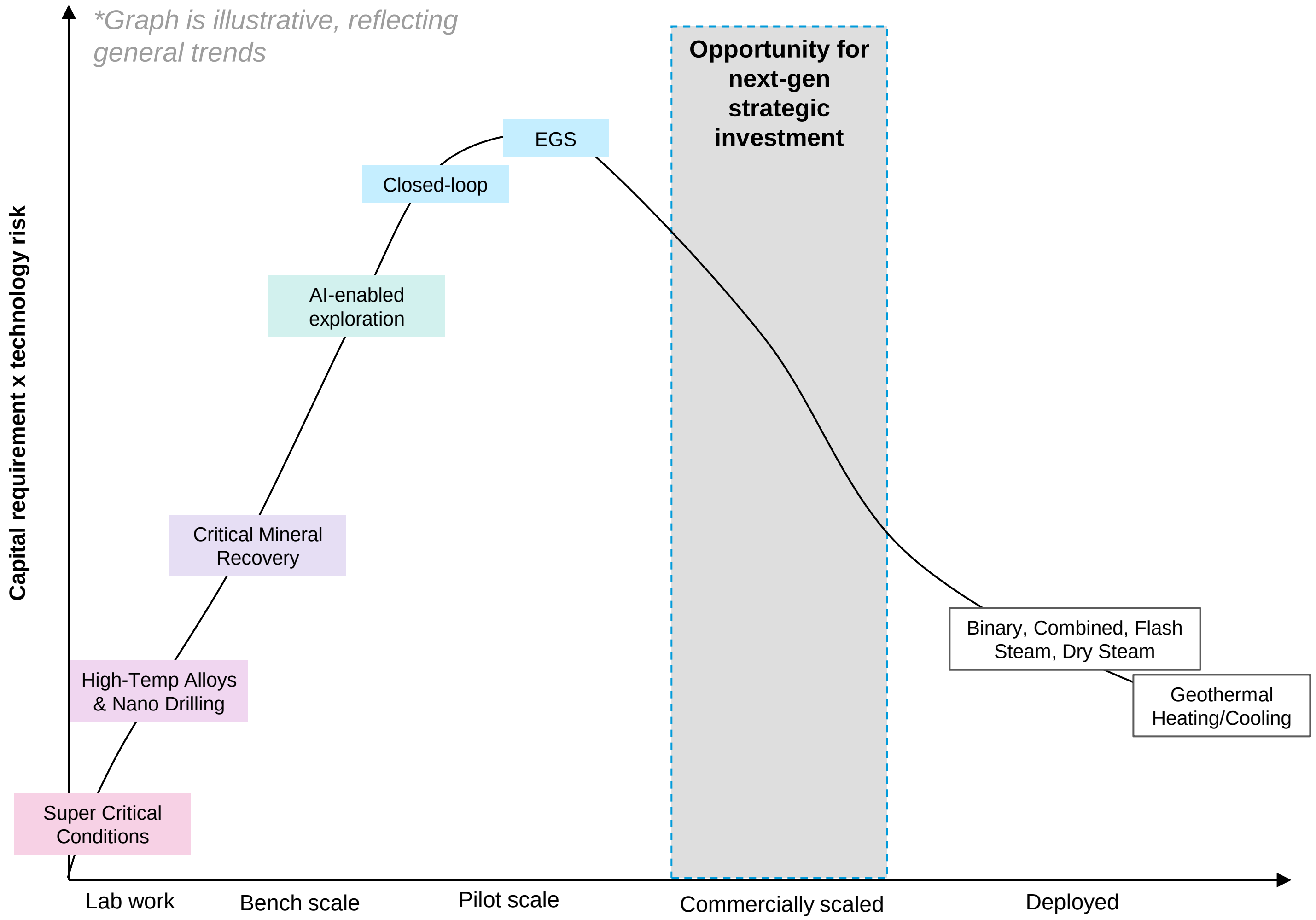
Next-generation geothermal technologies advance scalability, while conventional geothermal remains the most cost effective

	Conventional (Hydrothermal)	**Next-Generation**		**Frontier**
	Dry Steam, Flash Steam, Binary Cycle	**Enhanced Geothermal Systems (EGS)**	**Closed-Loop Geothermal Systems (CLGS)**	**Superhot Rock Geothermal**
Description	Naturally occurring geothermal reservoirs are accessed, with hot water circulating in permeable rock. Open fluid circulation through the system.	Engineered reservoirs are created via hydraulic, chemical, or thermal stimulation of rock to increase permeability and enable open fluid circulation.	Hot rock is accessed via wellbores in a closed-circuit system. Working fluid is used to extract heat via conductive heat transfer.	Superhot rock resources (>400°C) at great depth are accessed. Water is circulated through natural or engineered fractures to produce supercritical fluid for power generation.
Advantages	Well-developed, niche technology for power generation and heating & cooling.	Synergies with oil & gas technology have improved flow rates and flow consistency; greater geographic reach.	Minimal environmental impact, lowest water use, potential for use in unproductive conventional geothermal wells and abandoned oil & gas wells.	Highest energy density among geothermal technologies; location independent.
Barriers	Geographical constraints, geological uncertainty regarding reservoir productivity.	Concerns over induced seismicity, water use, and water contamination.	Engineering challenges including maintaining heat flow rates and reducing drilling costs.	Requires long development time and high cost; extreme drilling challenges and equipment limitations.
Depth	50-300 meters	2,000-4,000 meters	Typically, below 5,000 meters	5,000-15,000
Location Suitability	Extraction limited by natural reservoir dependence.	Flexible siting	Flexible siting	Flexible siting
Scalability	Limited due to geographic constraints.	Highest commercial readiness among next-generation geothermal technologies.	Dependent on technological advancements and cost reduction.	Lowest technological readiness.
Cost	New plants commissioned in 2021 demonstrated an LCOE of $0.068 per kWh.	Current cost ~$0.225 per kWh; U.S. DOE target for LCOE of $0.045 per MWh by 2035.	Current cost ~$0.293 per kWh, with potential cost reductions to $0.08 to $0.09 per MWh by 2035.	Not commercial yet (not producing power, in research phase).

Sources: Global Geothermal Market (IRENA, 2023)*;* The Future of Geothermal Energy (IEA, 2024)*;* Barriers to Next-Gen Geothermal (IFP, 2023); Next-Generation Geothermal Can Help Unlock 100% Clean Power (NREL, 2024); Next-Generation Geothermal: Considerations and Opportunities (WRI, 2024); Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024).

Credit: Una Oljaca, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Next-generation geothermal technologies are reaching the brink of commercialization, presenting an opportunity for strategic investment



**Graph is illustrative, reflecting general trends*

Innovation in geothermal power is scaling quickly, attracting a large volume of diverse investments

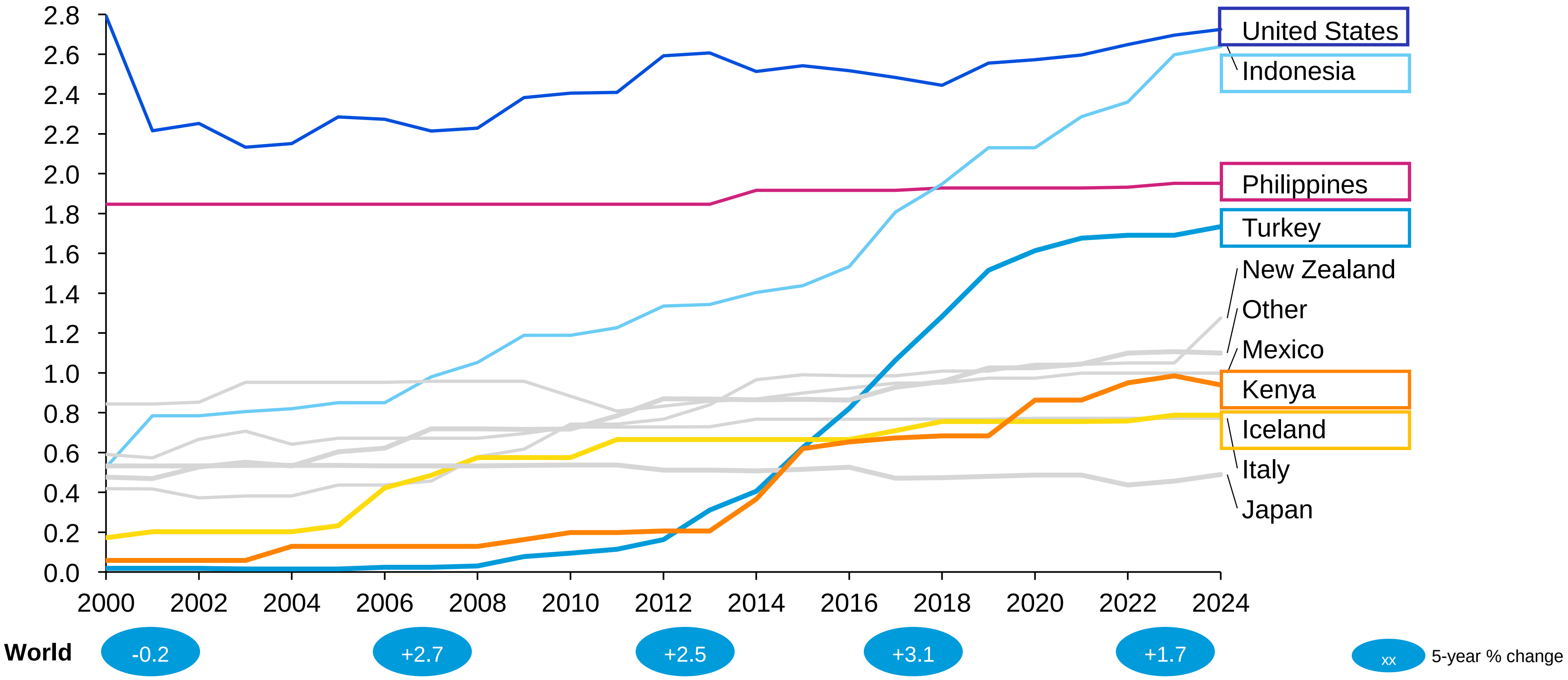
Technology	Funding	Key Barriers
Super-Critical Conditions	$82M+ – NZ Regional Infrastructure Fund	Extreme T/P drilling; material durability; limited demos; high CapEx.
High-Temp Alloys and Nano Drilling	$4M+ – DOE FOAs, VC pilots (e.g., Hephae $4M)	Costly R&D/testing; limited alloy supply chain; expensive field trials.
Critical Mineral Recovery	$1.63B+ – CA geothermal lithium (e.g., ATLiS)	Scale-up challenges; brine management; permitting; price volatility.
AI-Enabled Exploration	$200M-$1.2B+ – VC, corporate, grants (Zanskar ~$40M; Microsoft & G42 $1B)	Sparse data; limited field validation; physics-ML integration; regulatory trust.
EGS Closed-Loop	$900M+ private (5 years); DOE: $165M (2022), $44M (FORGE 2023); $14.2M (2024), $60M (2024)	**EGS:** Seismicity; stimulation efficiency; well integrity; financing. **Closed-loop:** Technology validation; sustained heat output; drilling cost; permitting.

Sources: Geothermal Energy, Turning up the Heat (Kearny Foresight, 2023); $10M to drill into science of one of worlds hottest (Newsroom, 2025); Hephae energy raises $4M for high-t drilling technology (ThinkGeoEnergy, 2024); California geothermal lithium project secures $1.36B direct loan (ThinkGeoEnergy, 2025); The Hottest Energy in Tech (Baseload Capital, 2025), Biden-Harris administration invests $60M (Climate Program Portal, 2024); DOE announces $44M in EGS Funding (Utah FORGE, 2023); Is geothermal energy ready to make its mark in the US power mix? (McKinsey, 2025), DOE Announces $14.,2 M for EGS (DOE, 2024); DOE to invest up to $165M to advance geothermal energy deployment (DOE, 2022).

Credit: Zacharia Thurston, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Conventional geothermal capacity has nearly doubled since 2000, reaching ~15 GW; growth has slowed in the past five years

Global geothermal power installed capacity by country, *GW*

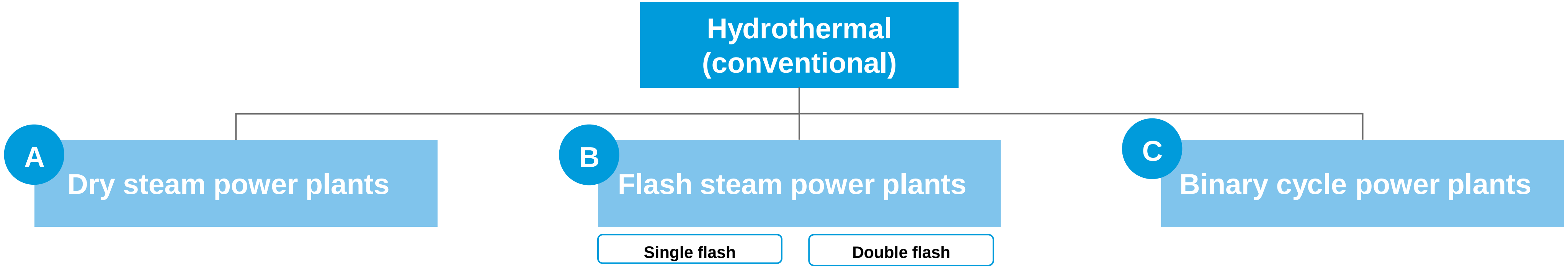


Observations

- Nearly all commercial geothermal power plants today are hydrothermal.
- Hydrothermal systems are mature and commercially proven, but they are location constrained, typically requiring shallow, naturally occurring reservoirs near tectonic plate boundaries.
- Conventional hydrothermal capacity grew rapidly between 2015 and 2020, but expansion has slowed in recent years, potentially due to these geographic limitations.
- Countries like Indonesia, Türkiye, and Kenya have recorded the fastest growth because they still possess large untapped resources. However, early leaders such as the United States and the Philippines have seen slower expansion in recent years as their most accessible fields are already developed.

Sources: Installed geothermal energy capacity (Our World in Data, 2024).
Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Conventional geothermal energy can utilize all three power plant design methods, each suited to different temperature ranges



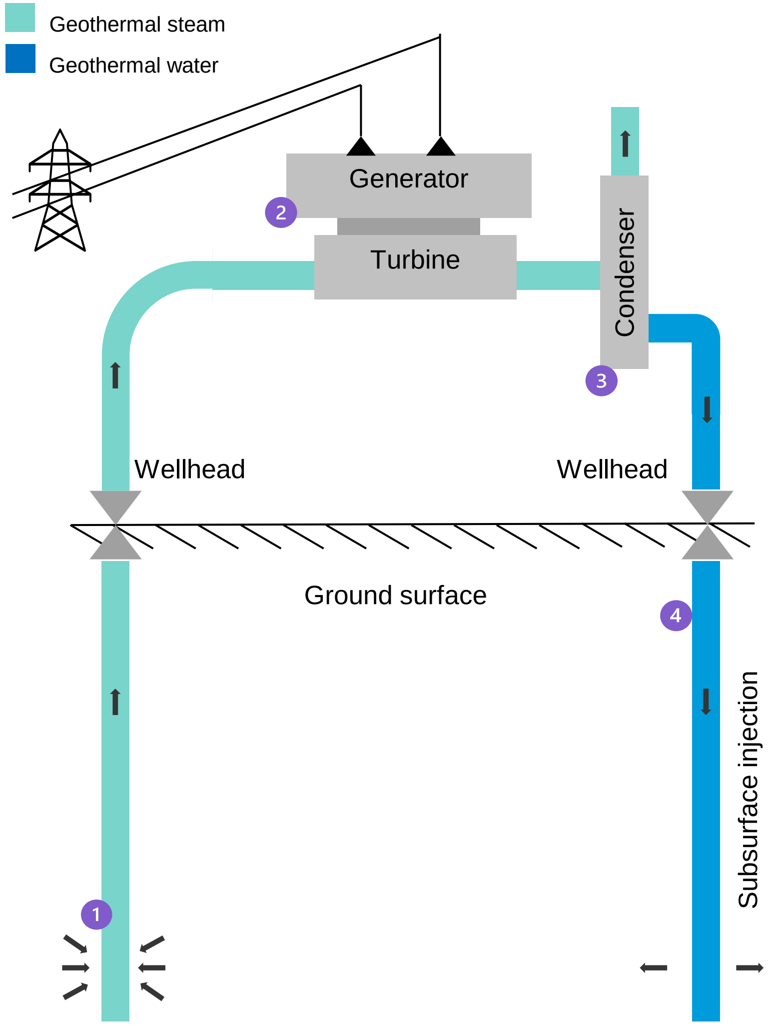
Hydrothermal (conventional)

- **A** Dry steam power plants
- **B** Flash steam power plants
  - Single flash
  - Double flash
- **C** Binary cycle power plants

	A Dry steam power plants	B Flash steam power plants: Single flash	B Flash steam power plants: Double flash	C Binary cycle power plants
Global capacity, %	23%	42%	19%	14%
Advantages/ disadvantages	⊕ Proven and mature technology ⊕ Lower plant complexity ⊖ Rare resource availability ⊖ Resource depletion risk ⊖ Potential emissions	⊕ Most common technology ⊕ High efficiency ⊖ High temperature requirement ⊖ Mineral scaling and corrosion ⊖ Water management challenges		⊕ Lower temperature requirement ⊕ Closed secondary loop ⊖ Lower efficiency ⊖ Higher CapEx and OpEx ⊖ Secondary fluid risks
Temperature range, °C	180+	150-200	180-220	85-170
Efficiency, %	20-30	25-35	30-40	10-20
LCOE, $US/MWh *(Conservative estimate, 2030)*	TBU	~56		~84

Sources: Technology Baseline (NREL, 2025); Exploring geothermal energy-based systems: Review from basics to smart systems (Renewable and Sustainable Energy Reviews, 2025).
Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

A Deep-dive on technology: Direct dry steam (1/3)



Process

① Hot steam is directly drawn from geothermal reservoirs, and unlike flash or binary plants, **steam is used as it is, without converting hot water first**.

② The steam flows into the turbine, and **as the turbine spins, it drives the generator** to produce electricity.

③ After passing through the turbine, the **lower-energy steam is cooled in a condenser** and condenses back into water.

④ **The condensed water is pumped down through the reinjection** well, which returns the water to the underground reservoir to sustain the geothermal cycle.

Advantages

- **Proven and mature technology** – first geothermal plants (e.g., the Geysers, California) use dry steam
- **Lower plant complexity** – simpler design compared to flash or binary cycle plants

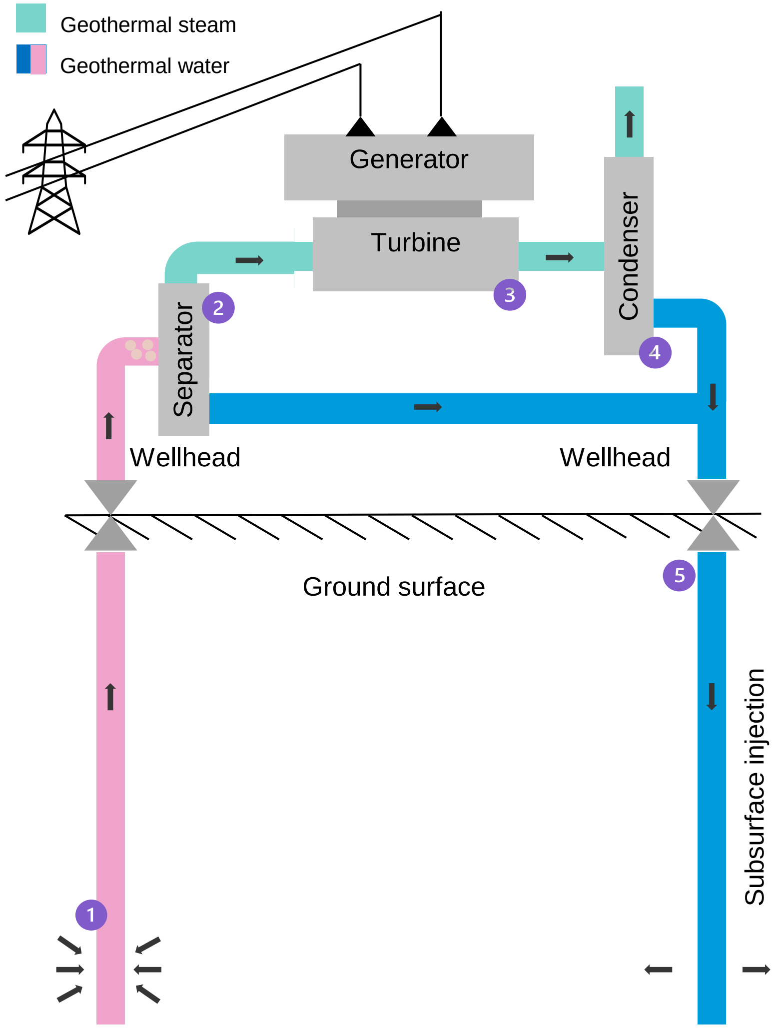
Disadvantages

- **Rare resource availability** – requires underground reservoirs of naturally occurring steam
- **Resource depletion risk** – steam fields may decline in pressure and output over time
- **Potential emissions** – some non-condensable gases (CO2, H2S) released with steam

Sources: Global Geothermal Market and Technology Assessment (IRENA, 2023); Exploring geothermal energy-based systems: Review from basics to smart systems (Renewable and Sustainable Energy Reviews, 2025); Geothermal technology: Trends and potential role in a sustainable future (Applied Energy, 2019).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

B Deep-dive on technology: Single/double flash cycle (2/3)



Process

1. Very hot geothermal fluid is pumped up from deep underground, and **unlike dry steam, it is mostly pressurized hot water** (>180°C).
2. The fluid enters a separator and, as the pressure drops, **part of the hot water flashes (vaporizes) instantly into steam; the remaining stays as water**.
3. The steam flows into the turbine, and **as the turbine spins, it drives the generator** to produce electricity.
4. After passing through the turbine, the **lower-energy steam is cooled in a condenser** and condensed back into water.
5. **The condensed water is pumped down through the reinjection** well, which returns the water to the underground reservoir to sustain the geothermal cycle.

Advantages

- **Most common geothermal technology** – proven at commercial scale worldwide
- **Higher resource availability** – can use hot water reservoirs, which are more common than dry steam
- **High efficiency** – suitable for high-temperature reservoirs (>180°C)

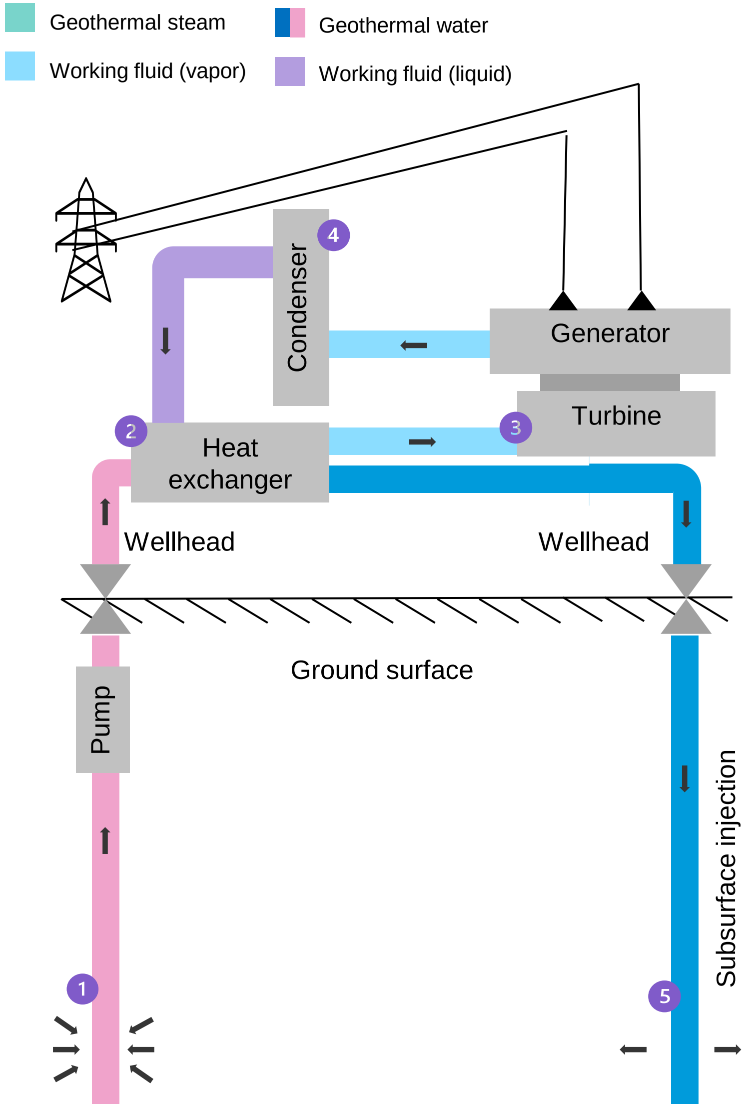
Disadvantages

- **Requires very hot resources** – limited to areas with high-temperature reservoirs
- **Mineral scaling and corrosion** – dissolved minerals in hot water can clog or damage equipment
- **Water management challenges** – large volumes of brine need proper reinjection

Sources: Global Geothermal Market and Technology Assessment (IRENA, 2023); Exploring geothermal energy-based systems: Review from basics to smart systems (Renewable and Sustainable Energy Reviews, 2025); Geothermal technology: Trends and potential role in a sustainable future (Applied Energy, 2019).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

C Deep-dive on technology: Binary cycle (3/3)



Process

① Moderately hot geothermal fluid (usually 100-180°C) is pumped from the underground reservoir.

② The geothermal fluid enters a heat exchanger. **It transfers heat to a secondary working fluid** with a much lower boiling point (often an organic fluid like isobutane or pentane).

③ **The secondary fluid absorbs the heat and vaporizes**. The vapor drives the turbine, which spins the generator to produce electricity.

④ After passing through the turbine, the **secondary vapor is cooled in the condenser** and returns to liquid form.

⑤ The **cooled geothermal fluid is returned to the reservoir** through a reinjection well.

Advantages

- **Can use lower-temperature (100-180°C) resources** – much more widely available
- **Closed secondary loop** – no gases or steam released to atmosphere (very low emissions)

Disadvantages

- **Lower efficiency** – compared to flash and dry steam (extra heat exchange step)
- **Higher CapEx and OpEx** – requires pumps, heat exchangers, and secondary working fluids
- **Secondary fluid risks** – organic fluids can be flammable or toxic if leaked

Sources: Global Geothermal Market and Technology Assessment (IRENA, 2023); Exploring geothermal energy-based systems: Review from basics to smart systems (Renewable and Sustainable Energy Reviews, 2025); Geothermal technology: Trends and potential role in a sustainable future (Applied Energy, 2019).
Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Location dependence is main barrier for conventional geothermal deployment, followed by high upfront costs and low efficiency

Constraint

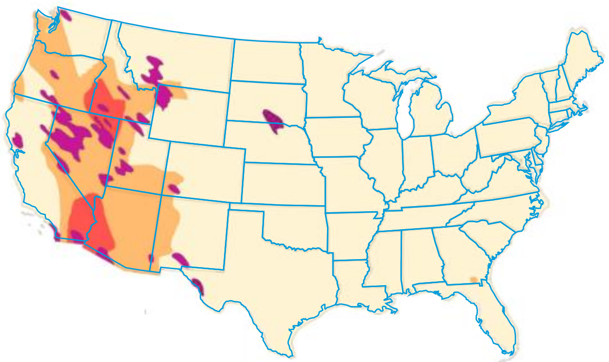
① **Location dependent**

② **High initial investment and cost variance**

③ **Low efficiency considering heat content**

Example

Due to the requirements for heat, fluid, and permeability, hydrothermal resource cluster in specific locations, **especially along tectonic and volcanic belts.**



For example, in the United States, hydrothermal resources are concentrated in the West, particularly in states such as Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming.

2.1 **High initial investment**

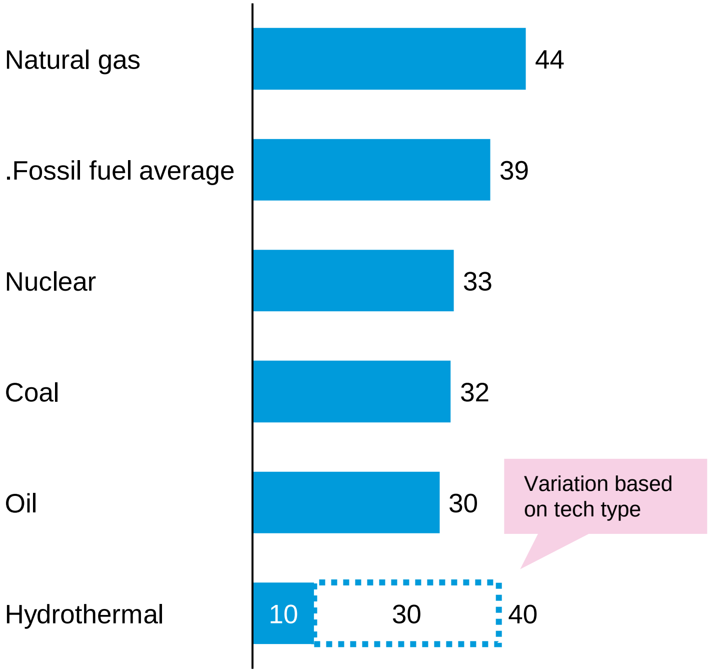
Conventional geothermal, compared with wind and solar, typically requires high upfront capital, has **longer payback periods, and is less modular**.

Roughly 80% of its LCOE comes from CapEx and ~20% from fixed O&M.

2.2 **Exploration risks and cost variance**

Drilling costs comprise some 35 to 40% of the total capital costs of a geothermal project. Thus, drilling hazards such as loss circulation can cause very high variance. For example, the **circulation loss costs in the U.S. in geothermal drilling operations is approximately 10% of overall well costs** and 20% for exploration wells.

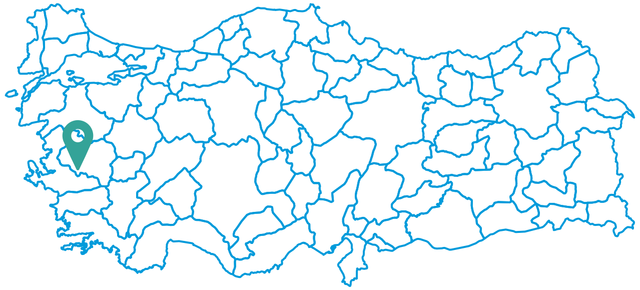
Thermal power plant efficiency in the United States, %, 2023



Sources: Power plant efficiency since 1900 (Boston University, 2023); Success of Geothermal Wells: A global study (IFC, 2013); A review on geothermal wells: Well integrity issues (Journal of Cleaner Production, 2020).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Kızıldere is the largest geothermal power plant in Türkiye, accounting for ~15% of the country's total geothermal power production



Resource characteristics

- Kızıldere I, built in 1984, was the **first conventional geothermal power plant in Türkiye**; Kızıldere III was completed in 2018.
- It is located in Denizli, Türkiye, a region known for **tectonic activity caused by an active continental rift** zone and for the hot springs in Pamukkale.
- The reservoir temperature is **approximately 246°C, with a depth range of 1.9 to 3.4 km**.

Technology & output

- The plant is known for its high-efficiency triple-flash and binary system, operating at an **efficiency rate of about 18%**.
- The overall Kızıldere complex — with Kızıldere I having 15 MW capacity, Kızıldere II 80 MW, and Kızıldere III, consisting of two units, 100 MW and 65 MW — **has a total capacity of 260 MW**.

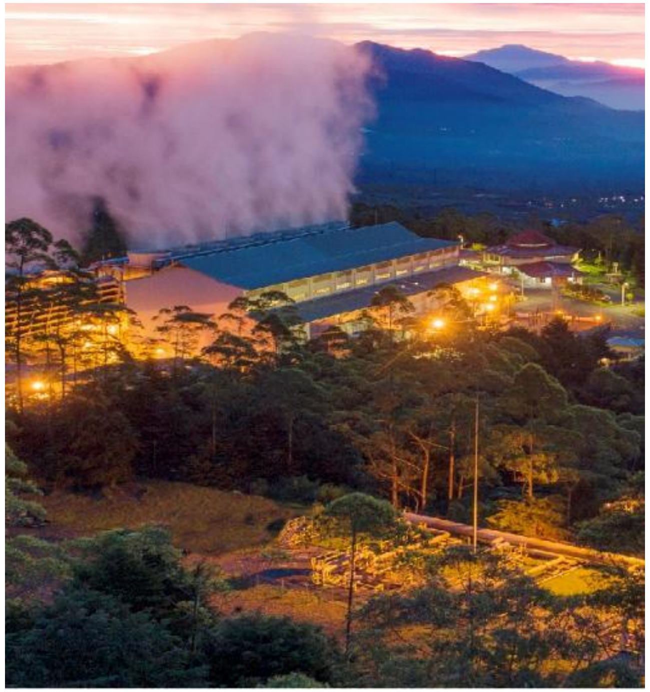
Lessons learned

- After privatization in 2008, Zorlu Enerji acquired ownership and used the initial plant (Kızıldere I) **as a training ground**, building internal expertise over successive phases. Through the expansion to Kızıldere III, the **company relied heavily on prior research conducted during stages I and II by both private companies and government institutions**.
- Zorlu integrated community **benefits early by supplying geothermal heat from Kızıldere I to 2,500 homes in Sarayköy and to greenhouses for agriculture**, strengthening local support and enabling long-term project sustainability.
- The company continuously sought **industrial synergies, capturing naturally occurring CO_2 from geothermal fluids** and supplying it to a nearby dry ice and CO_2 plant, reducing emissions while creating additional economic value.
- Over time, **to address a decline in reservoir pressure, Zorlu redesigned reinjection systems and installed ESPs**, further developing technical expertise and ensuring long-term operational reliability.

Sources: Integrated Annual Company Report (Zorlu Enerji, 2024); Four Decades of Service – Kızıldere Reservoir, Units and Management (GRC Transactions, 2018).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

As a vapor-dominated geothermal system, Darajat faces the risk of reservoir dryout



Resource characteristics

- Located near Mount Kendang in Garut, West Java, **about 1,750 to 2,000 meters above sea level, within a volcanic zone of the Malabar-Papandayan-Kendang complex**.
- The field lies inside a structurally complex area formed by **volcanic activity and faulting that enhances permeability and steam migration**.
- The Darajat reservoir has **1.5 to 3 km depth and temperatures around 240°C**.

Technology & output

- It is a dry-steam power complex consisting of three units **constructed between 1994 and 2009, with a total installed capacity of 271 MW (**Unit I with 55 MW, Unit II with 95 MW, and Unit III with 121 MW).
- Average plant **efficiency is 17 to 18% and capacity factor is 70%, depending on steam pressure**.

Lessons learned

- The project highlighted **the importance of continuous reinjection to stabilize the declining reservoir pressure** observed after the early 2000s, though concerns remain.
- Operational studies found high auxiliary power use reduced efficiency. For example, installing variable frequency drives and Mitsubishi retrofitted turbine upgrades increased **net output by about 8 MW**.
- Ongoing optimization studies **propose hybrid operation with binary cycles to recover waste heat and extend resource life**.

Sources: Star Energy Geothermal (n.d.); Improving the conceptual understanding of the Darajat Geothermal Field (Geothermics, 2018); Press release (Mitsubishi, 2024).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Next-generation technologies enable energy extraction from hot dry rock with little to no natural fluid

	Next-gen technologies		Frontier technologies
	A Enhanced geothermal systems (EGS)	**B** Advanced geothermal (AGS)/ closed-loop systems	**C** Superhot rock geothermal
Definition	EGS creates or improves permeability in hot dry rock to circulate injected fluid between wells.	Closed-loop geothermal circulates a working fluid in sealed pipes to conductively draw heat from hot rock, with no groundwater contact and no reliance on rock permeability.	Superhot rock geothermal taps ultradeep formations where water becomes a supercritical fluid, enabling vastly higher heat and power output than EGS or AGS systems.
Advantages/ disadvantages	⊕ Higher thermal efficiency compared to AGS ⊕ Potentially higher scale ⊖ Seismicity risks ⊖ Reservoir uncertainty ⊖ Water losses	⊕ Geographic flexibility ⊕ No brine requirement ⊕ No seismic risk ⊖ Lower thermal efficiency ⊖ Higher CapEx requirements compared to EGS	⊕ Much higher energy ⊖ Long development time and highest cost requirement ⊖ Extreme drilling challenges and equipment limitations

Sources: The Future of Geothermal Energy (IEA, 2024); Superhot Rock Energy (CATF, 2022).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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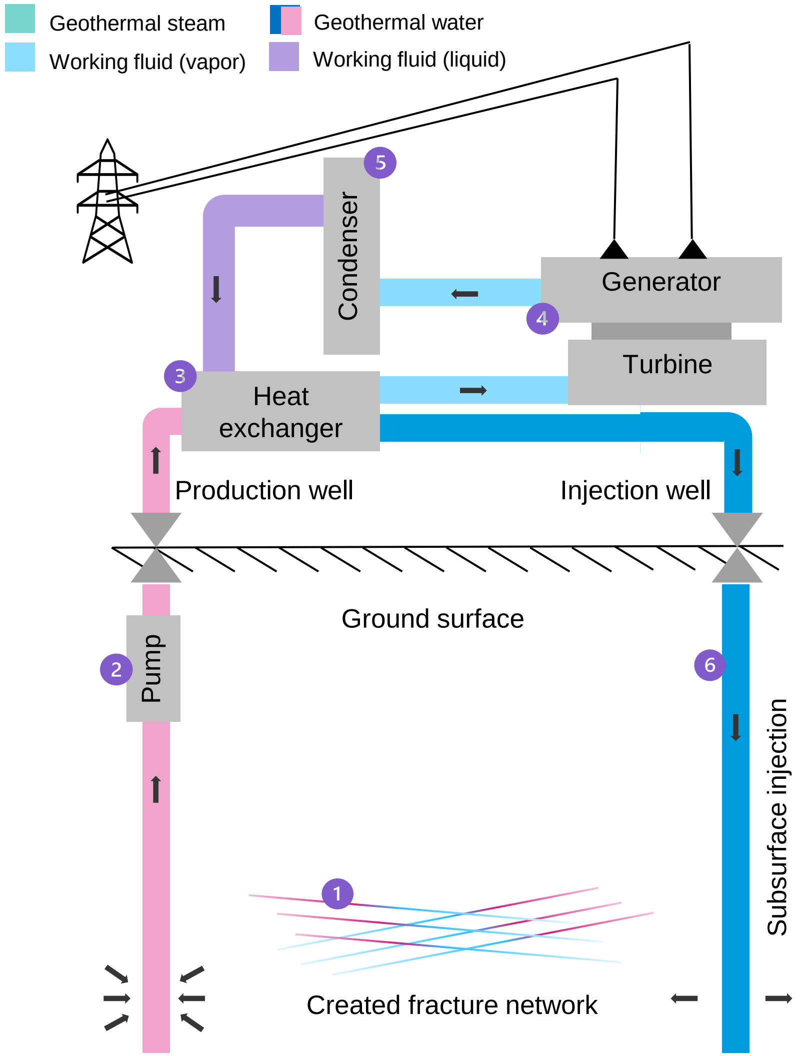
A

Enhanced geothermal systems fracture hot rock to unlock geothermal resources beyond natural hydrothermal zones



Process

① **Pre-production steps:**
- Drill an injection well and a production well into hot, low-permeability rock.
- Perform hydraulic stimulation to create/enhance a fracture connecting the wells.
- Pump water down the injection well.

② **Water flows through the engineered fractures, heating up as it contacts the hot rock**. The heated water returns up the production well to the surface.

③ The geothermal fluid enters a heat exchanger. **It transfers heat to a secondary working fluid** with a lower boiling point.

④ **The secondary fluid absorbs the heat and vaporizes.** This vapor drives the turbine, which spins the generator to produce electricity.

⑤ After passing through the turbine, the **secondary vapor is cooled in the condenser** and returns to liquid form.

⑥ The **cooled geothermal fluid is returned to the reservoir** through a reinjection well.

Advantages

- **Higher thermal efficiency –** direct fluid/rock contact transfers heat more effectively than AGS
- **Potentially higher scale –** compared to AGS, can access vast resources with stimulation
- **Leverages oil & gas skills –** uses drilling, fracturing, and reservoir management expertise of the oil and gas sector

Disadvantages

- **Seismicity risk –** hydraulic stimulation can trigger induced earthquakes, while AGS avoids that
- **Reservoir uncertainty –** fracture networks may close and permeability can decline, which would decrease productivity
- **Water losses –** injected fluid may migrate, unlike with AGS, where working fluid is contained

Sources: The Future of Geothermal Energy (IEA, 2024); A systematic review of enhanced geothermal systems (Geothermal Energy, 2013); Advanced Geothermal Technologies (ThinkGeo, n.d.).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

A

Commercial capacity of global EGS could reach 108 TW by 2050, equivalent to 3.5x current global yearly electricity consumption

Maximum technical potential

The total capacity in theory that could be developed if both economic and water constraints were removed and capacity be limited only by geology, temperature, and drilling depth

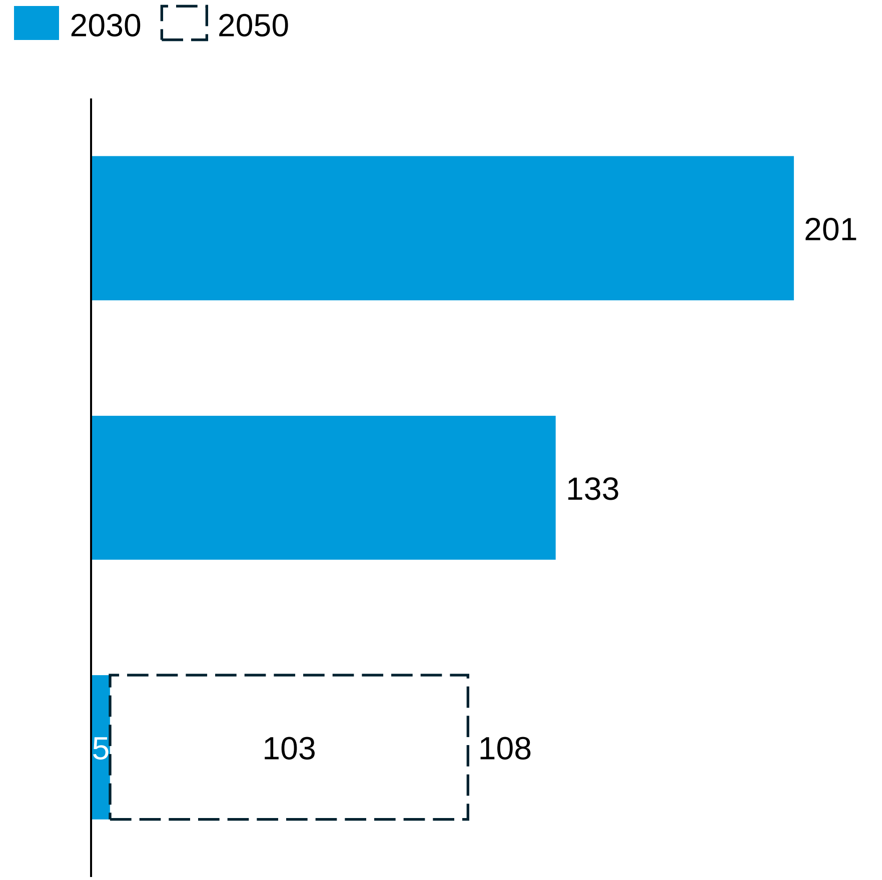
Technical potential

The technically recoverable portion of the EGS resources that could be harnessed, ignoring economic limits but still considering water constraints and other physical feasibility factors

Commercial potential

The economically and environmentally viable portion of the EGS resource that can be developed under current or projected cost and water availability conditions

Estimated global EGS power potential, TW 2030-2050



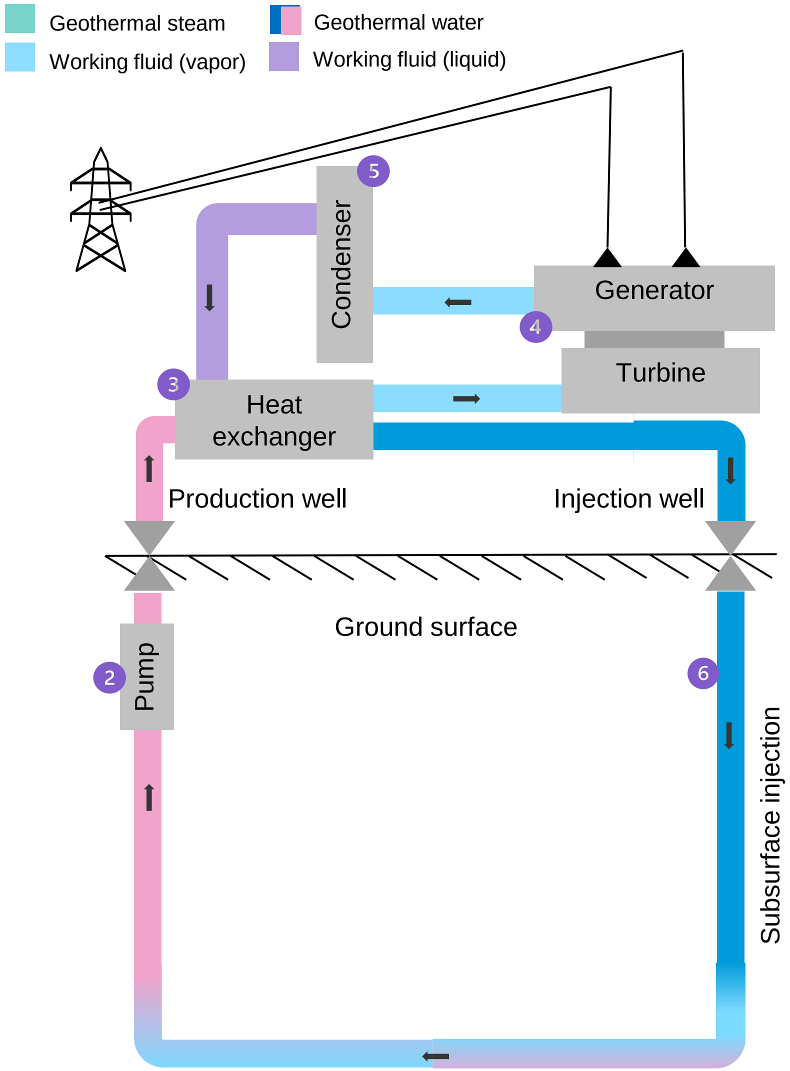
Observations

- Global commercial **EGS capacity could reach ~108 TW by 2050**, increasing from ~5 TW in 2030.
- This is equivalent to **3.5 times current global electricity demand**.
- The technical potential (~133 TW) and maximum technical potential (~201 TW) show that commercial **EGS would utilize about 80% of the technical and approximately 54% of the total theoretical resources by 2050**.

Sources: From hot rock to useful energy: A global estimate of enhanced geothermal systems potential (Applied Energy, 2020).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

B Closed-loop technology circulates fluid through underground pipes, eliminating need for natural reservoirs or fracturing



Process

① **Pre-production step:** A sealed well or **multilateral U-tube is drilled into hot rock.** Unlike EGS, no fractures are stimulated and no reservoir water is used.

② A working fluid **circulates inside the closed loop**, heating as it flows through the hot rock. The heated loop fluid reaches the surface and enters a heat exchanger. **Heat is transferred to a secondary working fluid** with a low boiling point. The secondary fluid vaporizes.

③ The steam flows into the turbine, and **as the turbine spins, it drives the generator** to produce electricity.

④ After passing through the turbine, the **lower-energy steam is cooled in a condenser**, and it condenses back into water.

⑤ **The condensed fluid is pumped** back underground to repeat the cycle.

Advantages

- **No seismicity risk** – avoids because no stimulation or fracture creation is needed
- **No produced brine** – avoids scaling, corrosion, and handling of H_2S or dissolved minerals
- **Geographic flexibility** – can work in low-permeability formations where EGS/hydrothermal are not viable

Disadvantages

- **Lower thermal efficiency** – conductive heat transfer through rock to wellbore is less efficient than fracture-based fluid flow in EGS
- **High CapEx** – requires advanced well design, materials, and long laterals/coaxial wells

Sources: The Future of Geothermal Energy (IEA, 2024); Advanced Geothermal Technologies (ThinkGeo, n.d.).
Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Next-generation pilots to increase avg. capacity over time; cost, geologic variability, and seismicity risks uphold commercialization

■ EGS ■ AGS/closed-loop ■ Superhot rock ■ DOE funded

Projects	Location	Capacity, MW	Deployment date	Status
Chevron New Energies	California, U.S.	20	2029-2033	Planned
XGS Energy (Meta collaboration)	New Mexico, U.S.	150	2027-30	Planned
Mazama Energy	Oregon, U.S.	200	2025-26	Planned
Fervo – Cape Station II	Utah, U.S.	400	2028	Planned
Fervo – Cape Station I	Utah, U.S.	100	2026	Ongoing construction
Eavor Loop – Geretsried	Bavaria, Germany	8.2	2025	Ongoing construction
GEL – United Downs	Cornwall, UK	3-5	2025	Operational
Soultz-sous-Forets	Alsace, France	1.7	2010-present	Operational

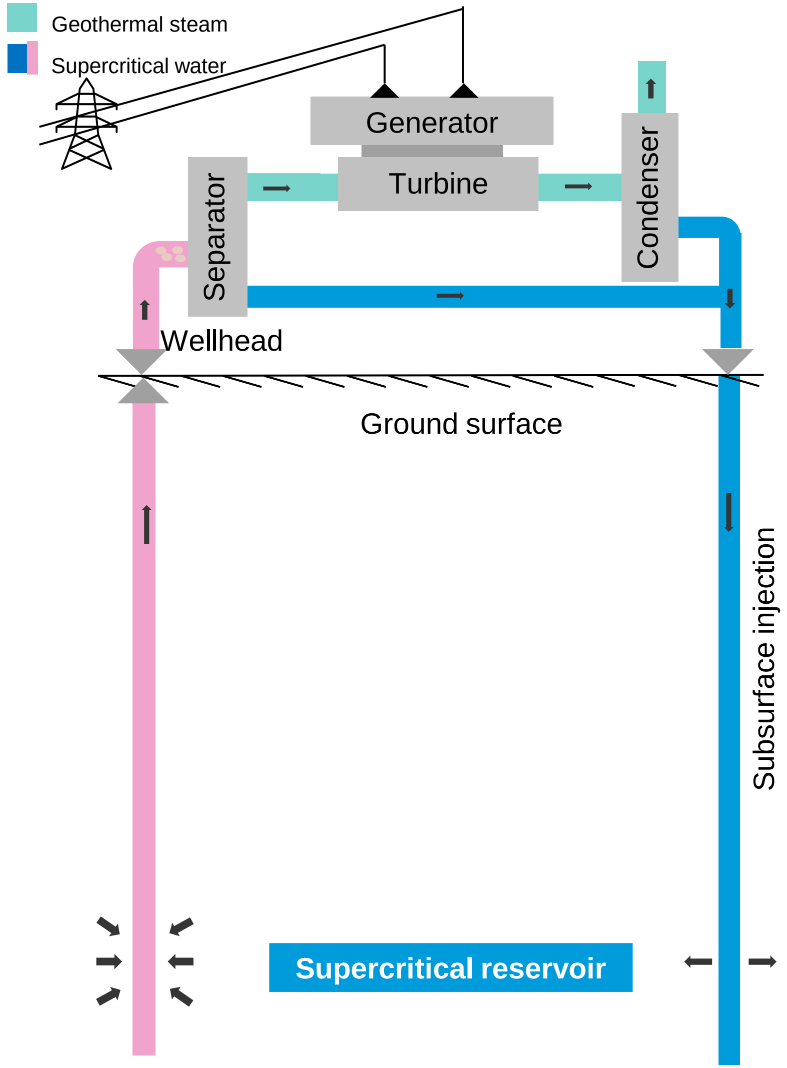
Observations

- Since the 1980s, numerous pilot demonstrations of petro-thermal systems have been conducted. **In addition to the projects shown left, other early pilots**, such as Ormat in the U.S. and Eavor-Lite in Canada, were completed.
- However, the transition from pilot/feasibility studies to commercial-scale deployment is still challenging **due to difficulties in standardization and replication across different geological sites**.
- Also, induced seismicity is posing a significant risk and can decrease public acceptance. For example, “felt earthquakes” led to the shutdown of EGS projects in Basel, Switzerland (2006), and Pohang, South Korea (2017).
- Currently, the U.S. dominates EGS pilot projects, with commercial deployment anticipated in the mid- to late 2030s. DOE took action in 2024 by deciding to support three feasibility projects, with the goal being to cut the cost of EGS by 90% by 2035.

Sources: Enhanced Geothermal Systems (EGS) Pilot Demonstrations (DOE, n.d.); Enhanced Geothermal Systems; Mazama Energy; XGS Energy; Fervo Energy; Eavor Deutschland; The United Downs Geothermal Power Plant, Cornwall, UK (ThinkGeo, 2025); First Year of Operation from EGS geothermal plants in Alsace, France: Scaling Issues (2018).

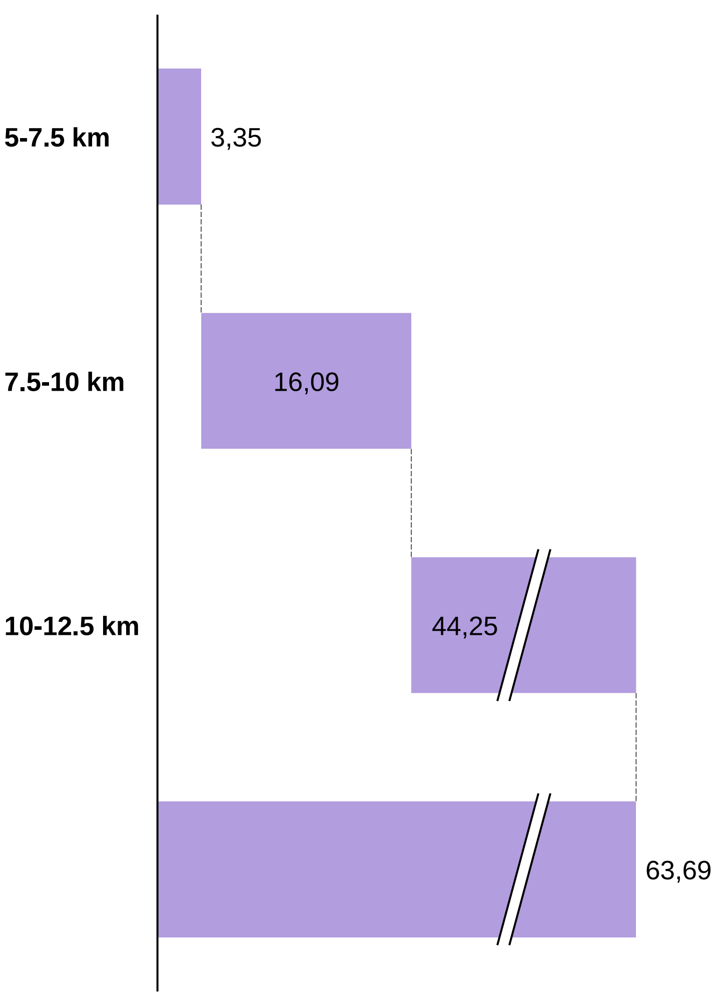
Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

C Superhot rock is the least mature geothermal technology, with capacity to surpass the limitations of hydrothermal and EGS/AGS



How does it work?	- Works by drilling very deep underground and reaching highly heated rocks. When water is injected into these rocks, it changes into a supercritical fluid, a condition that is neither liquid nor steam. Then, the fluid rises to the surface, where electricity is generated using its energy.
How does it differ?	- Compared to hydrothermal, uses supercritical reservoir for power generation instead of naturally occurring water. - Compared to EGS, it reaches to extreme depths to access naturally supercritical, ultra-high-temperature conditions.
What is the potential?	- Nearly unlimited — there are different models but potentially 63 TW
Depth and temperature	- 5-15 km depth - <400°C
Examples	- IDDP 1 & 2 (Iceland) - IDDP-J Project (Japan) - DOE Superhot Rock Initiative (U.S.)

Superhot rock potential, TW by depth



Sources: The Future of Geothermal Energy (IEA, 2024); Advanced Geothermal Technologies (ThinkGeo, n.d.).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

IDDP-1 and IDDP-2 projects in Iceland are pioneering initiatives advancing the global understanding of superhot rock geothermal

Resource characteristics	• **Active volcanic rift systems** (Krafla for IDDP-1 and Reykjanes for IDDP-2). • IDDP-1 was drilled in 2008 to approximately **2.1 km, producing steam at 452°C** (**targeted depth was 4.5 km, but drilling terminated** upon encountering a rhyolitic magma body at temperatures of >900°C). • IDDP-2 was drilled in 2016 **to 4.7 km with temperature measured at 426°C and pressure at 340 bars**, achieving supercritical conditions (formation temperature is estimated to be 500 to 600°C).
Technology & output	• Both IDDP wells were designed for scientific research rather than electricity generation. They were not connected to power plants but demonstrated that **supercritical geothermal fluids exist and can be accessed**. • Injection/tracer tests at IDDP-2 revealed deep fracture connectivity to nearby shallower wells, **supporting the potential for a deep superhot EGS.**
Lessons learned	• IDDP-1 was the world's hottest production well, but due to the **failure of several surface valves in 2012, the well had to be cooled down**, cemented up, and permanently abandoned with a sunk cost of €15M. However, the project proved **magma-enhanced geothermal systems are possible**. • IDDP-2, the deepest well drilled in Iceland, demonstrated that **ultradeep, superhot drilling is feasible** but also revealed significant challenges, including a **casing damage encountered during operations**. • High-temperature, oxygen-rich injection water and **corrosive supercritical reservoir fluids caused rapid casing and valve degradation**, highlighting the need for corrosion-resistant alloys, improved well design, and strict injection-fluid control in future deep geothermal projects. • The IDDP's commitment to open publication and data sharing **established a new international standard**, directly influencing Japan's IDDP-J and the U.S. DOE Superhot Rock initiatives. • IDDP-3 is expected to be drilled in Nesjavellir in 2026, targeting a previously drilled superhot zone, and aims to test improved designs using lessons learned from IDDP-1 and IDDP-2.

Sources: The IDDP success story – Highlights (2021); Corrosion damage of injection string from the deep geothermal well IDDP-2 in Reykjanes Iceland (2019).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal storage for electricity has relatively lower technological readiness compared with heating and cooling applications

	High-temperature geological thermal energy storage	**Geomechanical energy storage**
	Geological thermal energy storage	**Geopressure storage**
Description	Deep geologic reservoirs engineered to store high-temperature heat (often charged by solar or intermittent resources) and discharge as firm power and/or industrial heat	Subsurface reservoirs that store energy as pressurized water in rock and release it through turbines
Usage area	Multi-hour to seasonal storage of electricity and heat	Multi-hour to seasonal storage of electricity and heat
Grid-scale long-duration storage	Yes	Yes
Depth	Deep ~500-3,000 meters	Shallow to deep: ~500-2,500 meters (formation dependent)
Temperature	< 80-250°C	Not temperature-driven; energy stored as pressure, not heat
Example projects	• EarthBridge Energy (Texas) • GeoBattery (West Texas)	• Quidnet Energy (Texas) • Sage Geosystems (Texas)

Sources: A review of Geological Thermal Energy Storage for seasonal, grid-scale dispatching (Renewable and Sustainable Energy Reviews, 2025); EarthBridge; Quidnet; Sage.

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Sage Geosystems is advancing long-duration geothermal storage that can deliver firm, flexible clean power

Resource characteristics

- Sage is **developing projects in Texas**, including its full-scale commercial demonstration near Brooks County.
- The company uses subsurface formations to create **pressure-based energy storage**, not dependent on high geothermal heat.
- Sage's system is designed to work in **sedimentary formations with suitable mechanical properties**, but the company does **not** publicly disclose specific reservoir depths or geology.

Technology & output

- Sage's system, **Sage Geomechanical Energy Storage**, stores energy by injecting fluid into a sealed subsurface reservoir and releases it to generate power through controlled depressurization.
- The company achieved **16-hour-long discharge** in its early Texas pilot.
- In 2023, Sage completed a **200-hour-long storage demonstration**, validating multiday storage.
- Sage plans to deploy a **3 MW commercial project** integrated with ERCOT.

Lessons learned

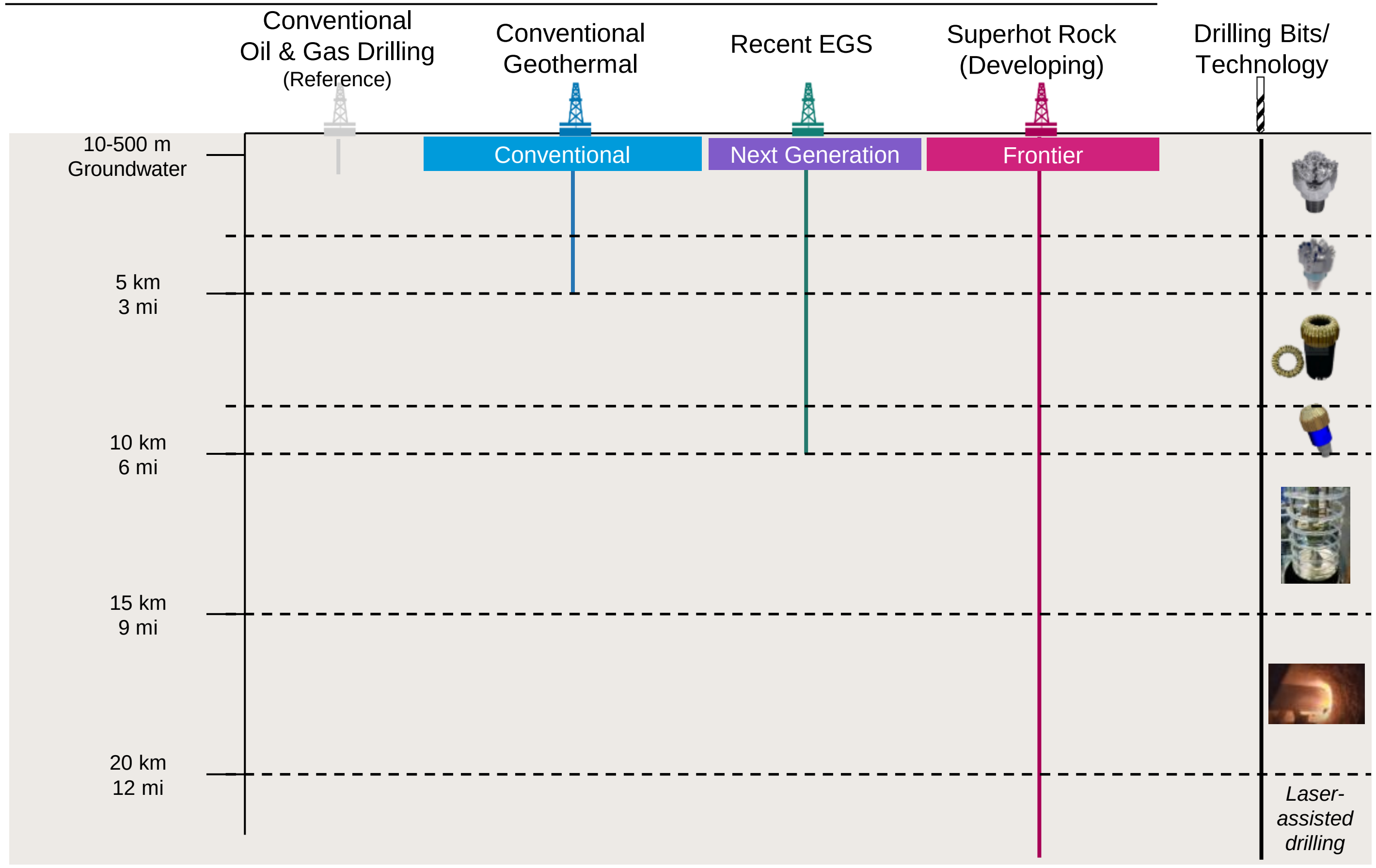
- Pilot results showed **repeatable charge-discharge cycles** with controlled pressure management.
- The 200-hour test confirmed potential for **multiday and resilience-focused applications**.
- Findings supported Sage's progression toward **commercial-scale deployment**.

Sources: Geomechanical Energy Storage (SGES) Overview (Sage Geosystems, n.d.); Sage Geosystems 200-hour pilot test results (PR Newswire, 2023); Sage Geosystems raises $17M for geothermal energy storage (Canary Media, 2023); Sage Geosystems: Next-Gen Geothermal Sources Driven by Earth's Pressure (Forbes, 2025); Sage's First 3-MW Geothermal Power and Energy Storage Project Will Feed ERCOT (Power Magazine, 2024).

Credit: Heather Hartel, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Innovations in drilling technologies are key to accessing higher thermal potential

Comparison of drilling technologies *(non-exhaustive)*



	Conventional	Next Generation	Frontier
Description	Baseline method for moderate depths, well-known in oil & gas, adapted to geothermal	Enhanced drilling with high-temp tools, directional drilling for reservoir targeting, or EGS creation	Millimeter-wave drilling, plasma/ hybrid thermal drilling
Drilling bits	• Tricone roller-cone **0-3 km** • Polycrystalline diamond compact (PDC) **3-5 km**	• Thermally stable PDC (TSP) **5-8 km** • Diamond-impregnated bits **6-10 km**	• Millimeter-wave (gyrotron) **10-15 km** • Plasma or thermal spallation **15-20 km** • Laser-assisted drilling **20+ km**
Opportunities	Mature and reliable	Reaches harder rock (basalt, granite, etc.)	Potential to unlock superhot rock
Challenges	Slow, wear issues	Higher cost, stress on materials and wellbore stability	Cost and uncertainty risk

Sources: Superhot Rock Energy (CATF, 2022).

Credit: Pia Doris Morrow, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," 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

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.

QUAISE ENERGY

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.

Canopus

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.

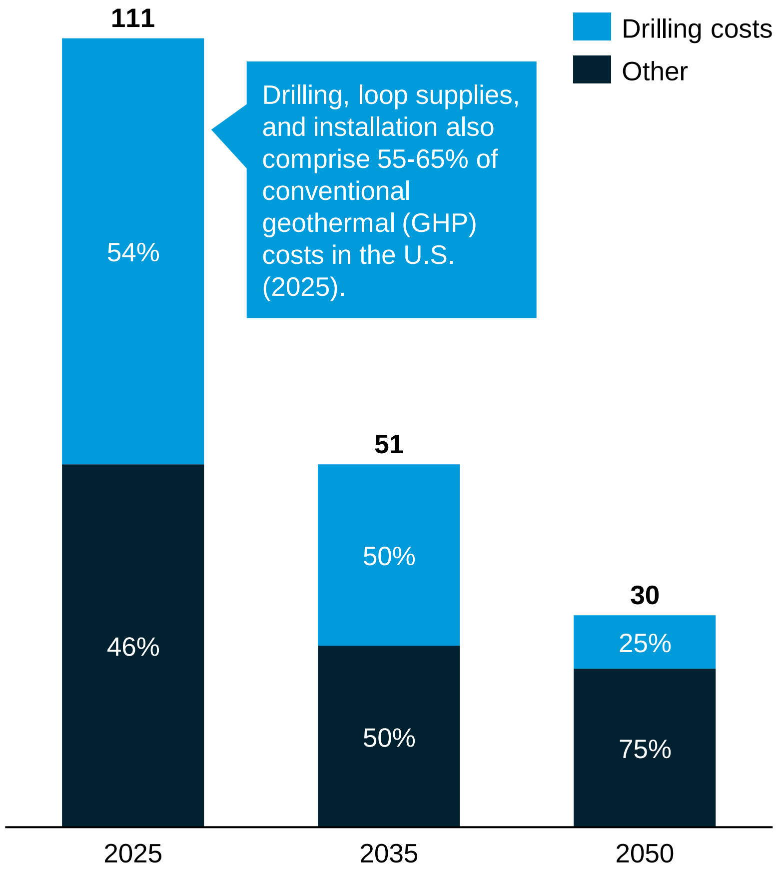
High-Pressure Water Jet-Assisted Drilling

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

ORCHYD

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.

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



Drilling, loop supplies, and installation also comprise 55-65% of conventional geothermal (GHP) costs in the U.S. (2025).

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 Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Companies at the frontier of drilling technology innovation show successes in pilots and field testing

Overview of first-mover companies *(non-exhaustive)*

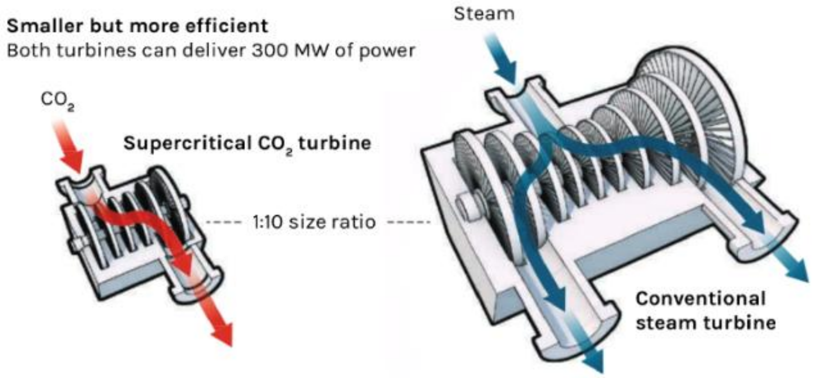
		FERVO ENERGY	SAGE GEOSYSTEMS	ALTAROCK	XGS ENERGY	GA Drilling	QUAISE
	Tech Approach	EGS/horizontal drilling	Geopressured	Laser-assisted drilling	Conductive heat transfer	Plasma drilling	Millimeter-wave (gyrotron)
Key Highlights	**Technology Readiness Level**	Commercial pilot ●	Commercial pilot ●	Pilot/demo ◕	Early pilot/demo ◑	Pilot/field test ◔	Pilot/field test ◔
	Target depth/ temperature	2-4 km 175-250° C	3-5 km 150-200°C	3-6 km High-temp rock	3-6 km >200° C (superhot)	5-10 km High-temp, hard rock	10-20 km >374°C (superhot)
	Valuation	$1.4B	~$150M	$3.8M-$4M	~$50M	~$140M	$95M-$105M
	Geographic focus	U.S. (Nevada, Utah)	U.S. (Texas, Gulf Coast)	U.S. (California, Oregon)	U.S. (Texas)	Slovakia, U.S.	U.S./global through MIT link
	Major projects	Project Red (Nevada EGS)	Pilot plant in Christine, Texas	Early EGS tests, laser enhanced drilling R&D	Pilot with DOE support	Field trials with oilfield partners	MIT test rigs, demo planned approx. 2028
	Key advantage	Proven horizontal EGS, scalable beyond volcanic zones	Hybrid approach allows energy storage and power generation	Novel stimulation and rock weakening with lasers	Closed-loop avoid fluid-loss and is scalable in many regions	Works in ultrahard formations, extended tool life	Ultra-deep, contactless drilling enables access to superhot rock

Sources: Superhot Rock Energy (CATF, 2022); Geothermal Energy Startups (Dealroom, 2025).

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

High-efficiency CO_2 turbines can accelerate geothermal commercialization

CO_2/sCO_2 turbines in superhot geothermal systems



Why CO_2?

- **CO_2 as a working fluid:** Provides non-explosive, non-flammable, non-toxic, and low-cost alternative to water.
- **Thermosiphon effect:** Large density change with temperature creates strong buoyancy forces, **reducing or eliminating pumping power** in geothermal wells.
- **High thermal efficiency:** Achieved through **low compression work** and **extensive heat recovery** from turbine exhaust.
- **Compact, efficient design:** In its supercritical state, CO_2 is **nearly twice as dense as steam**, allowing for **smaller turbines and pumps**, a **reduced plant footprint**, and **lower capital costs.**

✓ **Advantages**

- Higher efficiency (especially at high temperatures) vs. steam cycles
- More compact turbine/less bulky equipment (higher power density)
- Lower parasitic losses (reduced compression work) and strong heat recovery potential

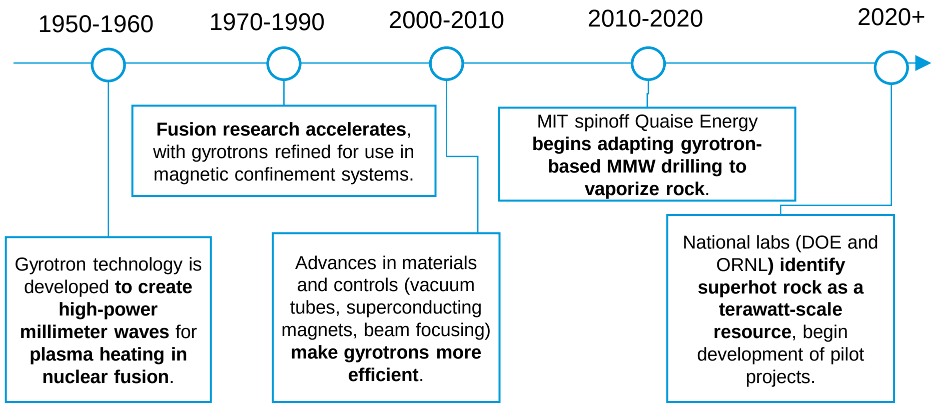
☒ **Key Challenges**

- Materials and durability under high temperature, performance, corrosion
- Heat exchanger design and integration
- Turbomachinery sealing, leakage, and fluid purity
- Control complexity (nonideal gas behavior)
- Matching geothermal temperature and heat delivery to turbine design

Sources: Superhot Rock Thermal (Chen, 2024).
Credit: Pia Doris Morrow, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Millimeter-wave drilling, pioneered for nuclear fusion, is being adapted to unlock terawatt-scale geothermal potential

MMW from nuclear innovation to geothermal application



1950-1960

Gyrotron technology is developed **to create high-power millimeter waves** for **plasma heating in nuclear fusion**.

1970-1990

Fusion research accelerates, with gyrotrons refined for use in magnetic confinement systems.

2000-2010

Advances in materials and controls (vacuum tubes, superconducting magnets, beam focusing) **make gyrotrons more efficient**.

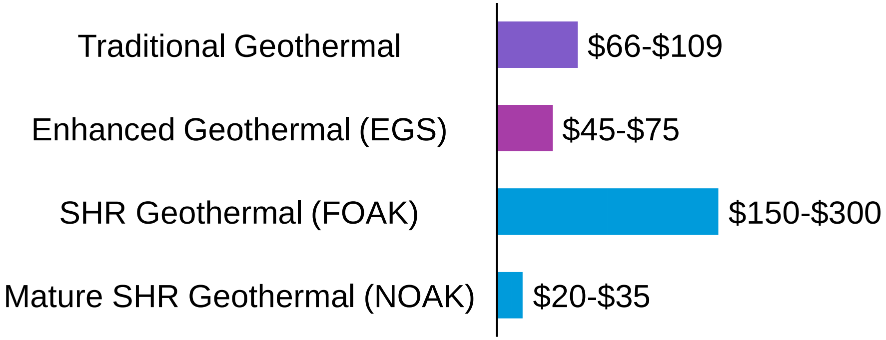
2010-2020

MIT spinoff Quaise Energy **begins adapting gyrotron-based MMW drilling to vaporize rock**.

2020+

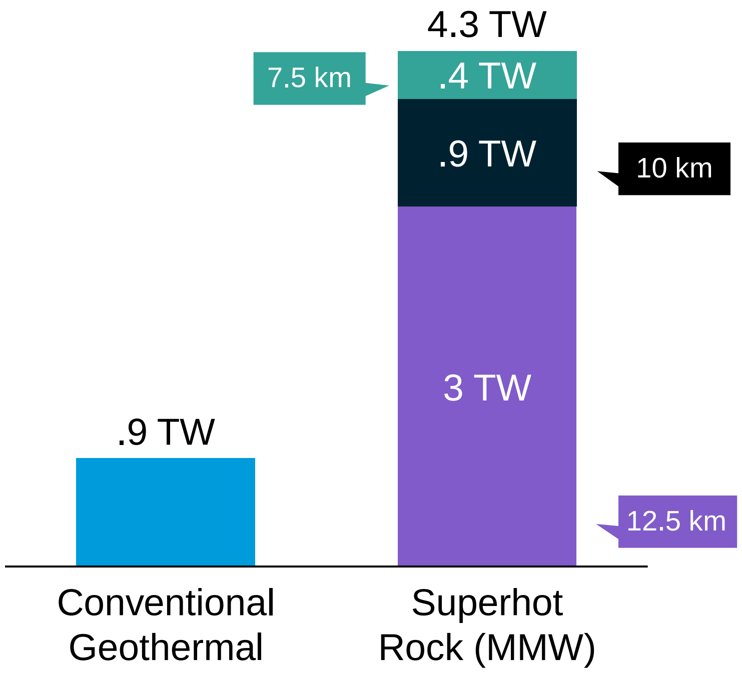
National labs (DOE and ORNL) **identify superhot rock as a terawatt-scale resource**, begin development of pilot projects.

LCOE for traditional, EGS, and SHR geothermal power



Superhot rock could unlock TW of firm power

Estimated U.S. energy potential from conventional vs. SHR geothermal



Observations

- **Technology:** MMW drilling originated from nuclear fusion research in the mid 20th century and has recently been leveraged for geothermal applications.
- **Power potential:** Accessing superhot rock at greater depths (10-20km) by using MMW drilling technology could unlock terawatts of power in the U.S.
- **Cost trajectory:** As MMW drilling matures and learning curves accelerate, LCOE is projected to fall from early pilot levels (~$150/MWh) to ~$20-$35/MWh, reaching parity with solar and wind.
- **Challenge:** Conventional drilling struggles with extreme temperature and pressure at superhot depths, which MMW aims to overcome by minimizing mechanical contact and material wear.

Sources: A Preliminary Techno-Economic Model of Superhot Rock Energy (Clean Air Task Force, 2023); The Potential for Superhot Rock Energy in the United States (Clean Air Task Force, n.d.); Unlocking deep superhot rock resources through millimeter wave drilling technology (Oak Ridge National Laboratory, 2021); Fusion Tech Finds Geothermal Energy Application (IEEE Spectrum, 2024); Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock (Clean Air Task Force, n.d.).

Credit: Heather Hartel, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

AI can improve accuracy in geothermal exploration and reduce the costs and timelines of project development

Geosensing is the use of remote sensing such as drones, satellites, or sensors to detect geological characteristics.

With the use of AI, geothermal reservoirs will be more easily and accurately identified. AI-enabled geosensing will address the uncertainties and challenges of geothermal exploration including identifying sites, subsurface characteristics, and geological risks.

- Remote sensors collect geological data.
- AI/ML models process geological data.
- Data is translated into real-time and predictive models.

	AI Process Map	Application
1	**Data Collection** *Data collected through remote sensing (satellite thermal imaging, LiDAR), seismic surveys, magnetic/gravity data, or well logs.*	Satellite collects thermal imaging of geological area.
2	**Data Processing** *Utilize AI models (e.g., convolutional neural networks, random forests) to detect correlations and hidden patterns*.	AI models detect promising geological resources.
3	**Prediction & Mapping** *AI generates heat flow maps, reservoir probability zones, and drilling targets.*	Models are generated with reservoirs with a high probability of success.
4	**Feedback Loop** AI refines predictions as new drilling/seismic data is collected.	Models are consistently improved based on new and existing data

Sources: The Geothermal Artificial Intelligence for geothermal exploration (OSTI, 2022).
Credit: Stephanie Chen, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

AI is transforming geothermal deployment by enabling faster, more accurate subsurface characterization

Key characteristics across exploration and project development

Exploration

Temperature
Temperature range of 210-300℉/99-149℃

Minerals
Low mineral content

Seismic Activity
Limiting seismic activity

Permeability
Assess fluidity for traditional geothermal or EGS

Gaseous Emissions
Low gas content

Geochemistry
Assess composition for siting and drilling

Project Development

Transmission
Availability of transmission lines

Permitting & Regulatory
Timelines and regulatory standards

Finance
Assess project risk, returns, and financing

Siting & Design
Siting and design plant and wellbores

Drilling
Improved drilling performance

Operations
Continuous assessment of performance

AI will transform deployment across the geothermal value chain

	Traditional	AI-Enabled
Time	***Up to 10 years*** to commission a geothermal project	Decrease exploration and project development timeline
Costs	Exploration, preparation, and drilling accounts for ***more than 50% of LCOE***	Reduce costs across geothermal development, especially drilling, the most expensive cost.
Drilling Rate	Exploratory drilling has a ***success rate of only 25%***	Achieve higher success rate with increased accuracy and improved drilling performance
New Regions	Challenges to resource mapping due to complexities of geographical regions	Enables resource mapping in unexplored regions (Africa, SE Asia, Latin America) and improves accuracy
Sustainability	Exploratory drilling required for feasibility studies, with a success rate of 25%	Minimizes environmental footprint by reducing exploratory drilling.

Sources: The geothermal artificial intelligence for geothermal exploration (OSTI, 2022); Geothermal FAQs (DOE, 2025); Generative AI: Prospects and Applications in Geothermal Energy (Pangea Stanford, 2024); The Future of Geothermal Energy (IEA, 2024); Phases of Geothermal Development (ISOR, 2013); Advances in geothermal energy (Science Direct, 2023).
Credit: Stephanie Chen, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Columbia Business School
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Geothermal Power Global Policy

Key messages
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.

Drilling is the largest and most variable cost driver of both conventional and next-generation geothermal heating & 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 comparative costs of vertical versus horizontal borehole loops.

Synergies with the oil & gas industry can drive down geothermal power 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 oil & gas industry can help de-risk geothermal heating projects and drive down costs, as demonstrated by the Eavor-Lite^{TM} demonstration project in Alberta, Canada.
- Improved oil & gas drilling techniques (e.g., fracking) can drive down drill time and risk and improve drilling efficiency.
- Technical synergies between the geothermal and the oil & gas industries highlight strong workforce transferability, which can help streamline geothermal commercialization.

Four key policy priorities can help scale geothermal power 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

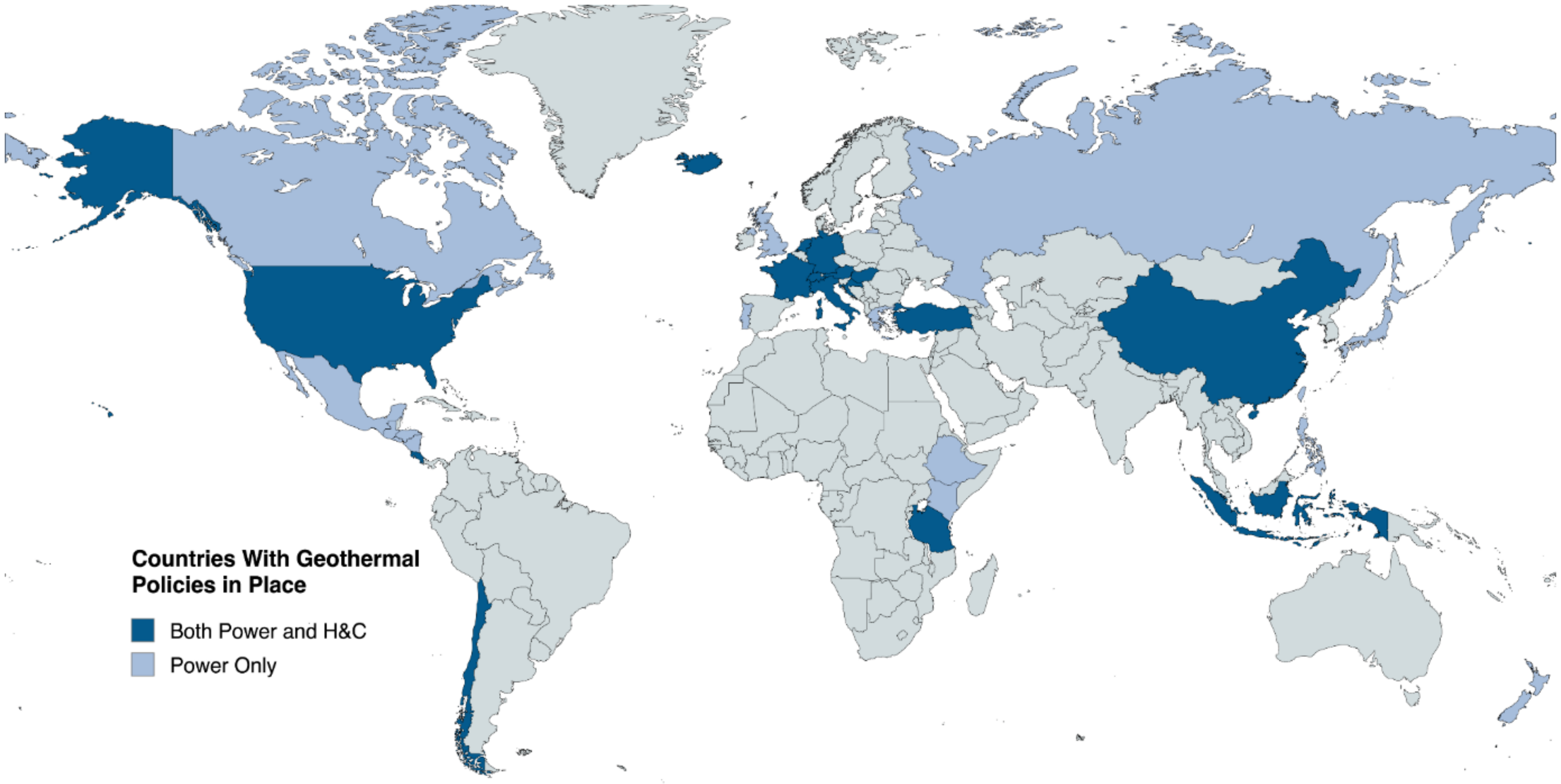
- Stronger implementation of policy goals could **boost new geothermal heat developments 50% by 2030** in the APS compared with the Stated Policies scenario.
- Strong policy can also help drive **next-generation geothermal cost reductions of up to 80%** by 2035.
- In the APS, expanding policy support and cost reductions would **scale GHP consumption to almost 3,000 PJ — 50% higher than in the Stated Policies 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.

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 Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Global leaders in deployment are developing policies not only for geothermal power but heating and cooling as well

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 Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

Scale	Power Generation	Heating & Cooling
Global	The **Global Geothermal Development Plan (GGDP)**, launched by ESMAP in 2013 to scale geothermal power, has **supported 13 countries and brought three projects online.**	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**.
Regional	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.	**Geothermica's €32.5 million** Joint Call 2021 aims to accelerate geothermal heating and cooling projects by 2030 through large-scale, commercially viable projects.
Bilateral	**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.	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.

Drivers of variable global collaboration on geothermal power versus heat

1. Power projects tend to be larger and have bigger returns compared to more localized heating projects.
2. There is a differential global emphasis on electricity access compared to heating access.
3. The development of EGS has spurred greater collaboration on geothermal power generation.
4. Scalability of power projects attracts greater private investment.

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 Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

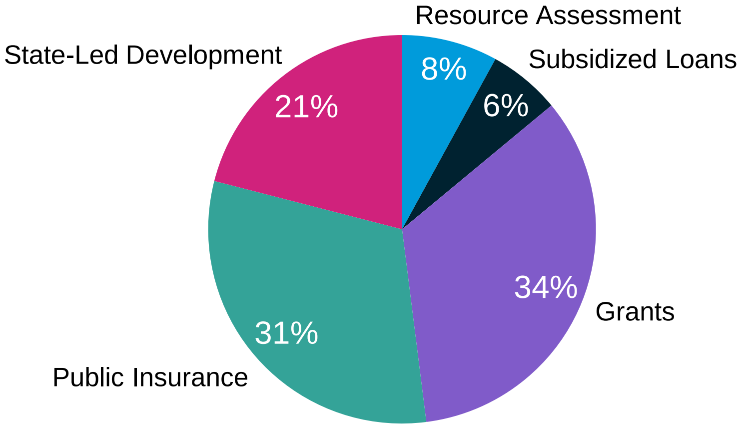
Successful geothermal risk mitigation policies target early-stage resource and exploration risks; grant schemes lead in nascent geothermal markets

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 Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

U.S. ranks No. 3 in superhot rock potential, has 12% of total global geothermal potential, and is set to scale with policy support

U.S. geothermal power policy timeline

1970

Geothermal Steam Act

- Landmark law grants federal authority over geothermal leasing on public lands (via BLM and U.S. Forest Service), enabling competitive leasing with royalties and rentals as part of a broader energy policy to address rising demand and foreign oil dependence.

2005

Energy Policy Act

- Energy Policy Act: Is overhauled, streamlining leasing and permitting and adjusting royalty structures.

2009-16

Obama Era

- DOE's Geothermal Tech program advances EGS demonstrations.

2017-21

Trump 1.0:

- Rollbacks in environmental policies broadly ease permitting; renewable incentives are de-emphasized.

2021-24

Biden: Bipartisan Infrastructure Law (2021) + IRA (2022)

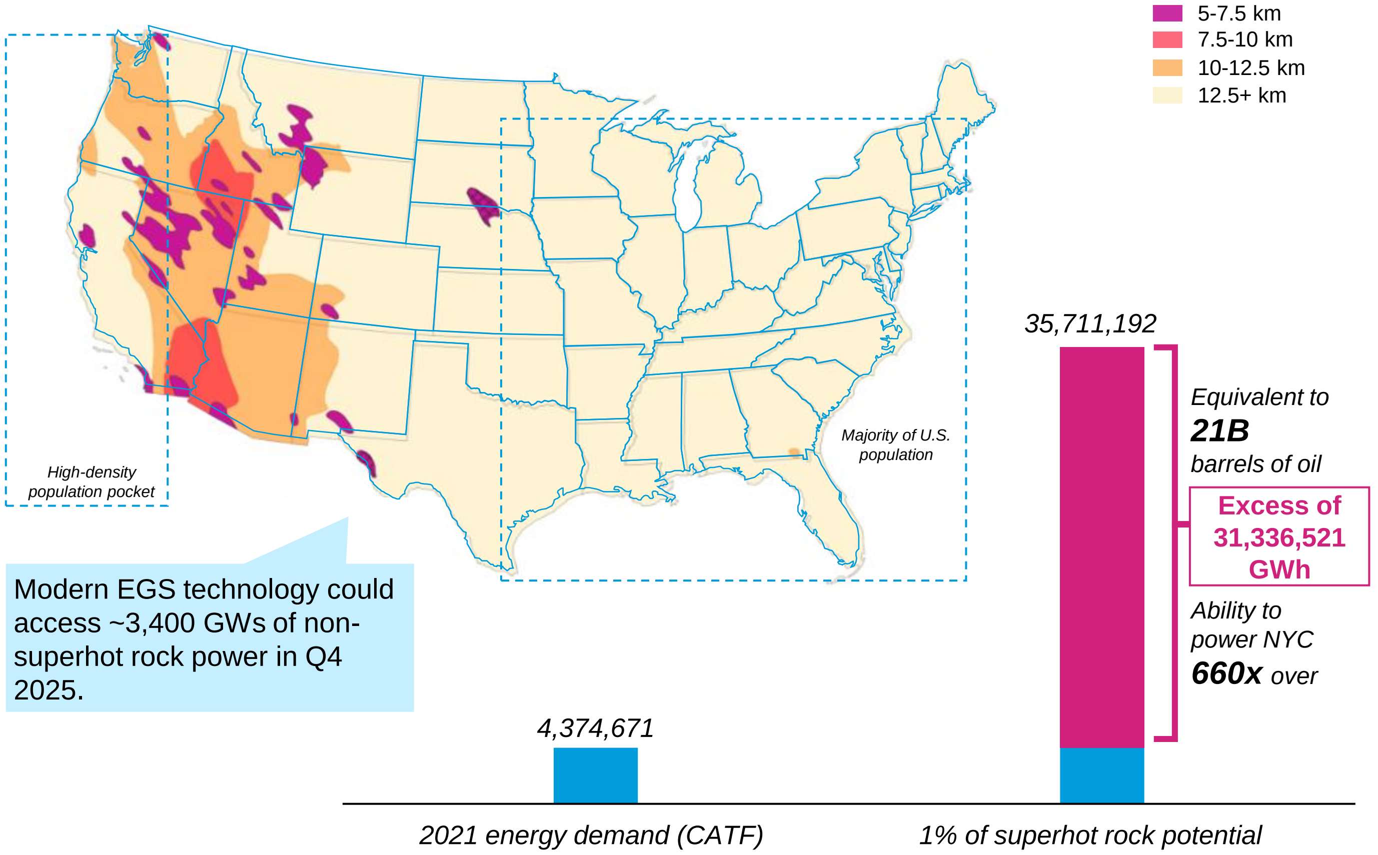
- Provides broad support of renewable energy development, support for DOE funding for EGS; geothermal included in net-zero planning.

2024-25

Trump 2.0: OBBA, Global Tariffs, Domestic Tech Giant Incentives

- IRA incentives repealed but geothermal spared — tax credits phase down after 2033. Global tariffs and U.S. support for tech reshoring boost emerging EGS startups (Fervo, Sage) supplying data centers with baseload power.

U.S. 2021 energy demand vs. 1% geothermal power potential, *GWh*



Modern EGS technology could access ~3,400 GWs of non-superhot rock power in Q4 2025.

Equivalent to ***21B*** *barrels of oil*

Excess of 31,336,521 GWh

Ability to power NYC ***660x*** *over*

Sources: Super hot Rock and the future of geothermal (CATF, 2025); Cumulative CO2 Emissions 2023 (Our World in Data, 2024); The U.S. Archipelago (Vivid Maps, 2020); U.S. Electricity Generation Mix (IEA, 2024), Project InnerSpace Analysis Shows Geothermal Can Cost-Effectively Scale to Power the AI Data Center Boom (Project InnerSpace, 2025).

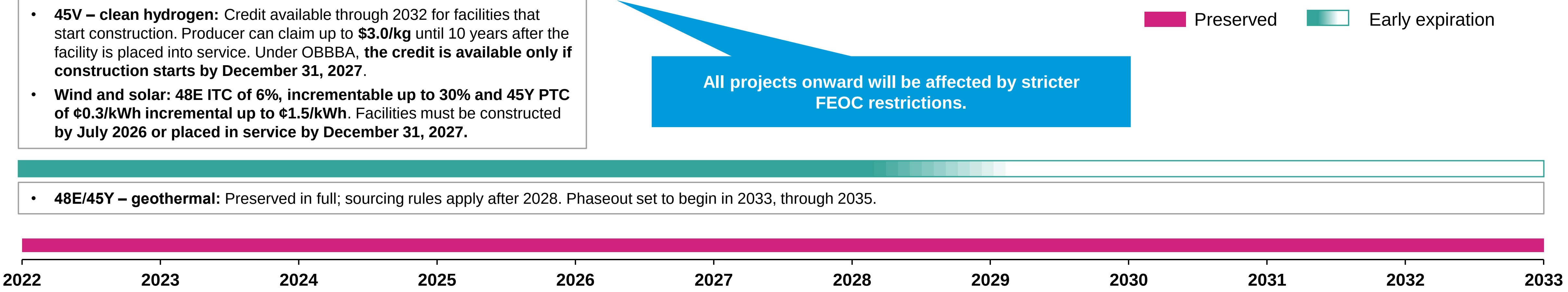
Credit: Zacharia Thurston, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

OBBBA keeps IRA 45Y and 48E incentives for geothermal power until 2035; foreign entity of concern (FEOC) rules apply after 2026

Inflation Reduction Act (IRA)	One Big Beautiful Bill Act (OBBBA)

- **45V – clean hydrogen:** Credit available through 2032 for facilities that start construction. Producer can claim up to **$3.0/kg** until 10 years after the facility is placed into service. Under OBBBA, **the credit is available only if construction starts by December 31, 2027**.
- **Wind and solar: 48E ITC of 6%, incrementable up to 30% and 45Y PTC of ¢0.3/kWh incremental up to ¢1.5/kWh**. Facilities must be constructed **by July 2026 or placed in service by December 31, 2027.**

All projects onward will be affected by stricter FEOC restrictions.



- **48E/45Y – geothermal:** Preserved in full; sourcing rules apply after 2028. Phaseout set to begin in 2033, through 2035.

Geothermal Power Under Trump Administration

Executive Order: Declaring a National Energy Emergency

- **Cites geothermal heat under** the definitions for the terms ***energy* or *energy resource***, 30 U.S.C. 1606 (a)(3).

Executive Order: Protecting American Energy from State Overreach

- States intention to **remove illegitimate impediments** for the discovery and production of geothermal power.

Secretarial Order: Unleash Golden Era of American Energy Dominance

- States intention to **focus time, resources, and technologies** of the DOE's R&D **toward the development of geothermal**.

DOE Office of Hydrocarbons and Geothermal

- Supports the **development of EGS and superhot technologies** through financing and R&D efforts.

The GTO's programs are building toward their strategic goal of **supplying 60 GW of EGS and hydrothermal resources deployment by 2050.**

Sources: Evaluating the OBBBA's Energy Provisions (American Action Forum, 2025); Declaring a National Energy Emergency (White House, 2025); Protecting American Energy from State Overreach (White House, 2025); Unleash Golden Era of American Energy Dominance (U.S. DOE, 2025); Multi-Year Program Plan (DOE, GTO, 2022); Geothermal Technologies Office (DOE, 2025).
Credit: Ariela Farchi, Brenda Rain, Clara Zibell, Quint Houwink, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

U.S. policy support for geothermal emphasizes national energy security and global leadership

	Rationale and significance for geothermal	Example actions
Resilience	• Extreme weather and volatile loads require power that is always available and not weather dependent, making firm power that is resilient and stable important. • Geothermal operates through storms and grid stress, with underground infrastructure that is inherently physically resilient.	• The U.S. Air Force, U.S. Army, and the Defense Innovation Unit launched geothermal pilot projects with the main goal of improving energy resilience at military bases. They tested the systems at Mountain Home Air Force Base in Idaho and Joint Base San Antonio in Texas to help ensure bases could keep reliable power even when the main electric grid went down.[1]
National security	• Domestic, fuel-independent power generation reduces geopolitical and import risks. • Geothermal requires no imported fuel, no complex supply chains, no mineral inputs, and no fuel transport, making it one of the most secure firm resources.	• Executive Order 14008, "Tackling the Climate Crisis at Home and Abroad" (2021), recognized climate change as a national security threat and directed the United States toward a carbon, pollution-free electricity sector by 2035.[2]
Energy dominance	• Access to firm clean energy technology enables countries to gain manufacturing advantage, export capability, and stable industrial power. • Next-gen geothermal (e.g., EGS, closed-loop) utilizes U.S. drilling prominence, offering a domain where the U.S. can become the global leader and have energy dominance in clean firm baseload technology.	• The Department of Energy's Utah FORGE site served as a dedicated EGS field laboratory in Milford, Utah, with R&D funding and project investment opportunities.[3] • Geothermal electricity plants qualified for the federal Investment Tax Credit, and the Inflation Reduction Act extended these clean energy credits, allowing eligible geothermal projects to claim a 30% credit.[4]

Sources: U.S. Air Force, U.S. Army, the Defense Innovation Unit, and Industry Advance DoD Installation Energy Resilience with Geothermal Energy Solutions (DIU, 2023); Executive Order on Tackling the Climate Crisis at Home and Abroad (2021); FORGE (n.d.); IRA Section 13102 Renewable Energy Investment Tax Credit (2025).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

With 8% of the world’s geothermal resources, China’s potential for geothermal power could fast-track its 2060 net-zero targets

Geothermal power lacks representation in Chinese energy policy

Renewable Energy Law

2005
- Provides broad support for renewable energy outbuild, with geothermal explicitly mentioned

13th Five Year Plan

2016-20
- Reach +1.1B meters of geothermal heating & cooling and increase power to 500-530 MW by 2020

Net-Zero 2060 Plan

2020
- Achieve carbon peak by 2030, reduce emissions rapidly by 2045, and reach deep decarbonization and neutrality by 2050

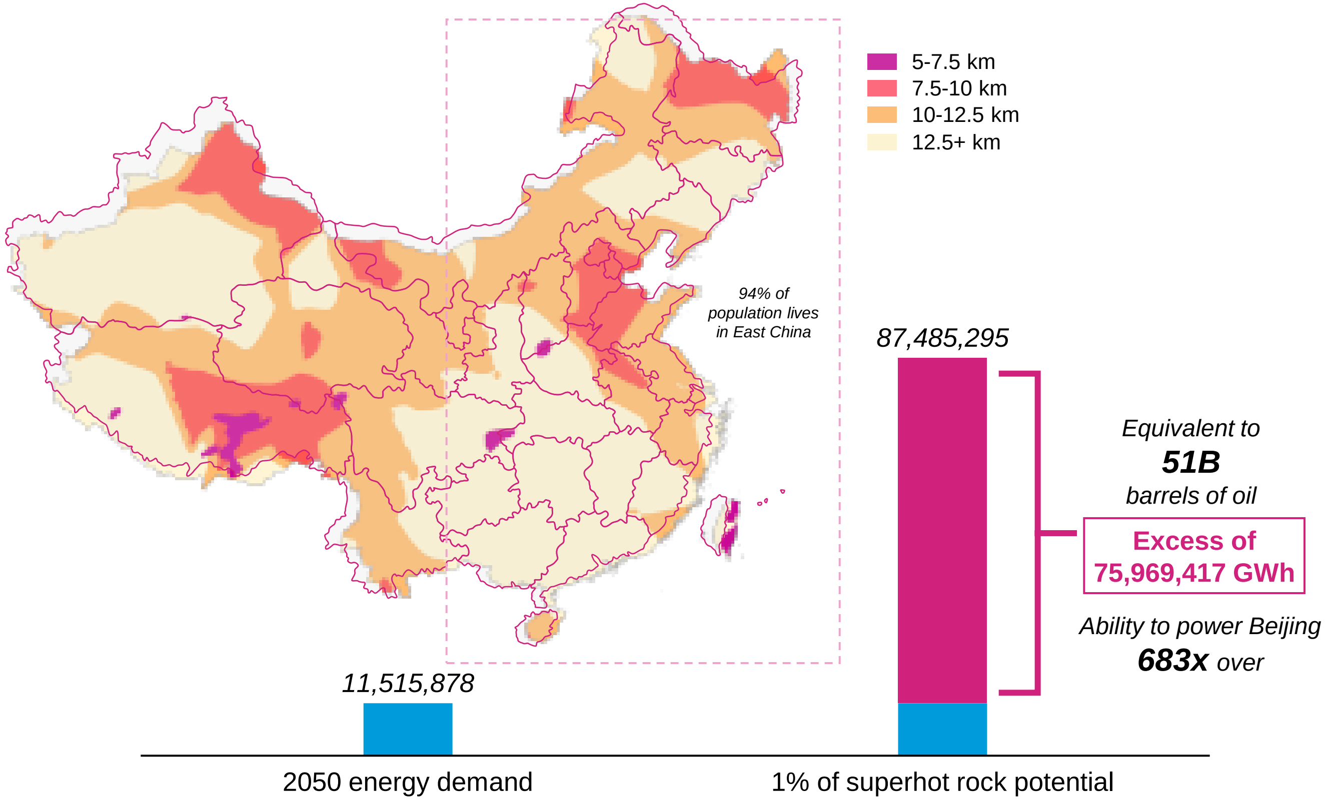
14th Five Year Plan

2021
- Promote deep geothermal heating & cooling and boost geothermal power generation

Geothermal Industry Standard and Beijing Declaration

2023
- Industry Standard focuses on heating & cooling; Beijing Declaration prioritizes geothermal development as one of the most popular energy sources of the future

China’s 2050 energy demand projections and 1% geothermal power potential in *GWh*

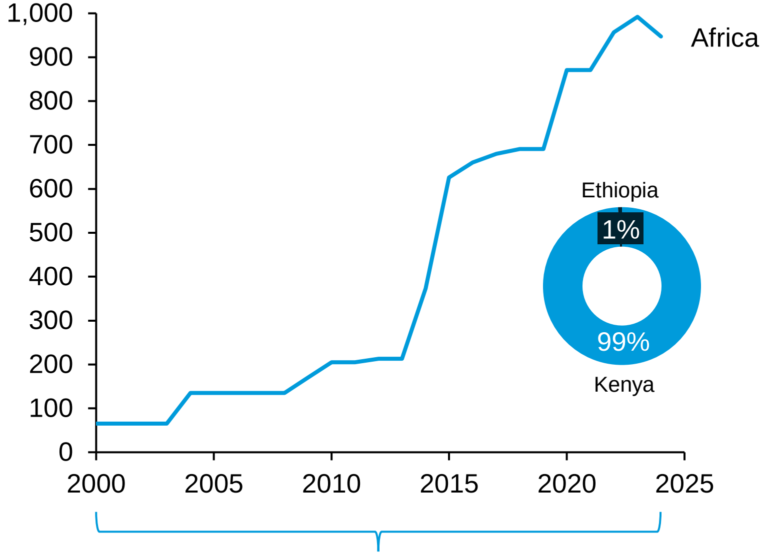


Sources: Superhot Rock and the future of geothermal (CATF, 2025); Chinas net-zero 2060 plan (S&P Global, 2021); China Energy Mix (IEA, 2024); Renewable Energy Law (Ministry of Commerce Peoples Republic of China, 2013); Beijing Declaration (PR Newswire, 2023); Carbon Neutrality in China (CNEUEN, n.d.); China’s population density (Visual Capitalist, 2024).
Credit: Zacharia Thurston, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

20% of global EGS potential is in Africa, providing opportunity for economic development and surpassing projected 2050 demand

Kenya holds the majority of the continent's installed conventional capacity

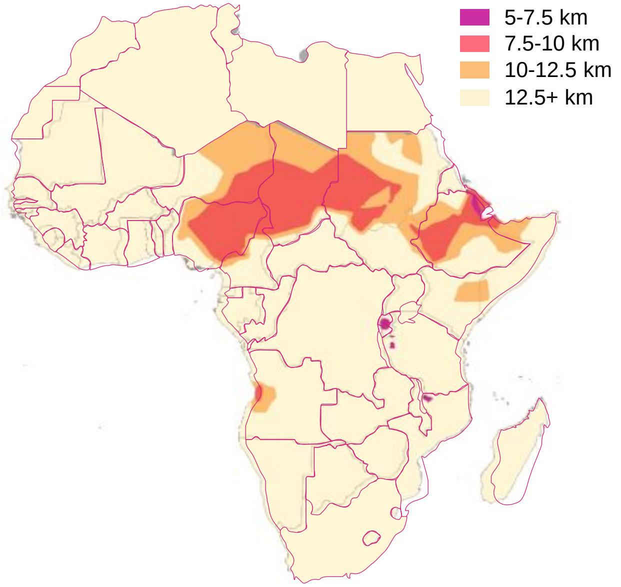
Cumulative installed capacity of geothermal power (*MW*)



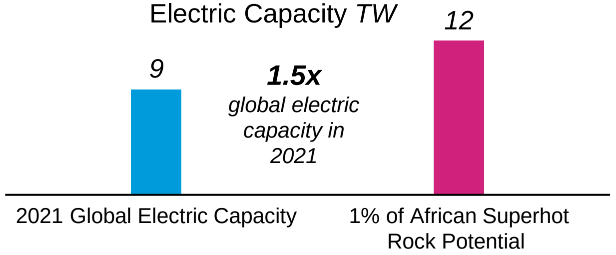
Africa approaches 1 GW of conventional geothermal power, with Kenya leading 99% of installed capacity. Ethiopia holds the remaining 1%.

Africa's population is expected to rise from 1.5B to 3B by 2070, requiring more energy and opportunities for socioeconomic development.

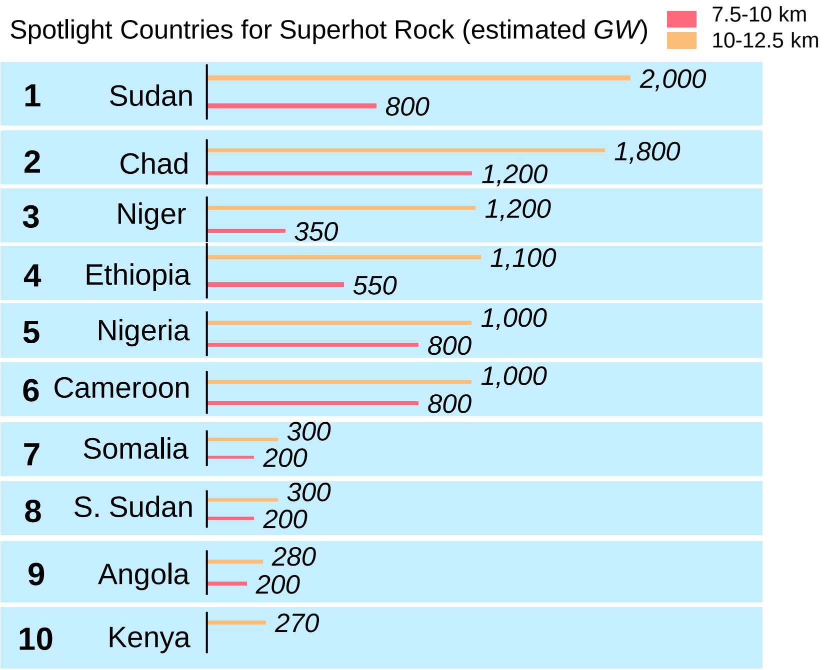
Next-generation geothermal development presents a significant opportunity to reliably meet Africa's growing energy needs and foster sustainable development



Electric Capacity *TW*



Spotlight Countries for Superhot Rock (estimated *GW*)



Sources: Superhot rock and the future of geothermal (CATF, 2025); The Future of Geothermal Energy (IEA, 2025); Africa's population (Our World in Data, 2024).

Credit: Zacharia Thurston, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

East Africa can deliver Africa’s ~13 GW geothermal potential by 2050; policy reform and regional coordination will determine the pace

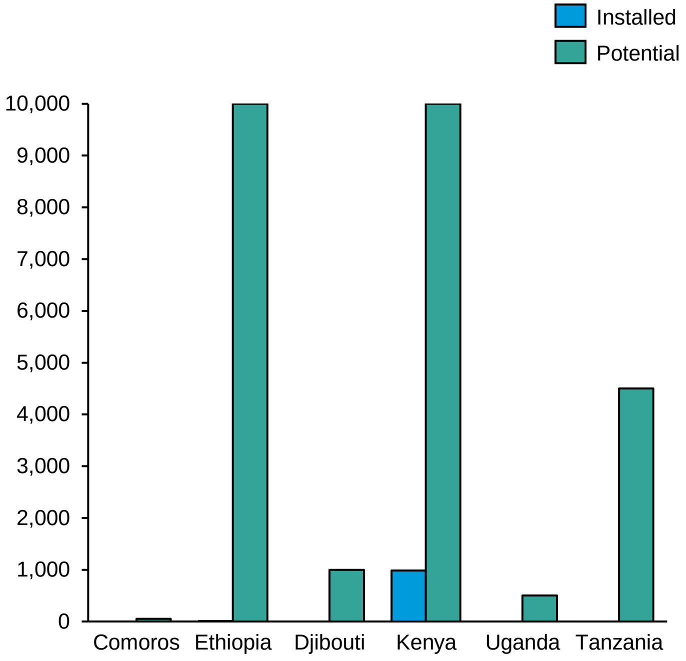
East Africa Potential

- Africa is on track to **surpass Europe** in geothermal capacity, scaling to **13 GW by 2050** versus Europe’s 5.5 GW.
- The **East African Rift**, one of the world's most active tectonic systems, contains more than 20 GW — roughly **70 to 80% of Africa's geothermal potential** — where continuous plate movement generates extraordinarily high heat flow.
- With **$35 billion in planned investment**, **Kenya** and **Ethiopia** are positioned to **deliver over 90% of Africa’s geothermal development by 2050**, anchoring the continent’s clean baseload expansion.
- **Unlocking this scale-up requires strong policy:** de-risking early drilling, harmonizing Rift Valley laws, and investing in cross-border grid integration to turn geology into bankable, scalable clean power.

From Barriers to Solutions: Policy Levers for Geothermal Growth in East Africa

Barriers	Emerging Solution Reform
High upfront costs: Drilling risk and CapEx-intensive exploration.	• Regional **Geothermal Risk Mitigation Facility** and blended finance with KfW, AfDB.
Institutional gaps: Weak regulatory clarity in early-stage markets (Tanzania, Uganda).	• **KenGen and GDC as regional training hubs** and harmonization of EAC geothermal policy.
Technical capacity: Lack of specialized workforce and site modeling data.	• **UNEP and IGA capacity programs** and Kenyan training of 200+ regional engineers.
Environmental and social consent: Local resistance near protected lands’ hot springs.	• Early-stage **community co-design** and geothermal tourism pilots (e.g., Menengai).

Geothermal Potential and Installed Capacity in East Africa Rift Valley Countries, *MW*



Kenya leads with 985 MW, while Ethiopia's current ~7.3 MW, backed by an expanding project pipeline, mirrors the Rift Valley's wider geothermal takeoff.

Sources: Africa to Overtake Europe in Geothermal Capacity (Rystad Energy, 2023); Geothermal is key to improving energy access in Africa (Project Syndicate, 2025); Geothermal Outlook in East Africa (UNEP, 2018); Inside East Africa’s Untapped Geothermal Goldmine (Africa Climate Insights, 2025); Geothermal Development in East Africa (IRENA, 2020); Geothermal Prospect for Decarbonization in East Africa (Energy Strategy Reviews, 2023).

Credit: Shubhangi Prasad, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal represents 43% of Kenya's 2024 electricity generation; unlocking superhot rock potential will dwarf existing capacity

Kenya's adoption of geothermal power and favorable policies revolutionized its national electricity mix

1977 United Nations permits Kenya Power (KenGen) to take charge of first integration amid 1970 oil crisis.

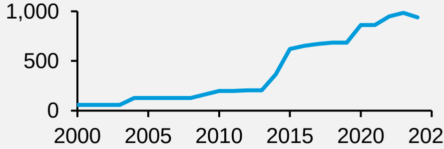
1982 Kenyan Parliament signs the Geothermal Reources Act, establishing a formal investing, siting, and licensing framework.

2009 **GEG** brings modular deployment to Africa's geothermal industry by winning the tender for **Kenya's first 5.5 MW modular geothermal wellhead** facility.

2018 At the Iceland Geothermal Conference, KenGen presents a case study and validates the **wellhead concept as a national fast-track strategy for early revenue production and clean firm power**.

2024-25 Kenya Vision 2030: Government plans rapid industrialization to become middle income by 2030, where the country expects to double geothermal power integration to 1,600 MW.

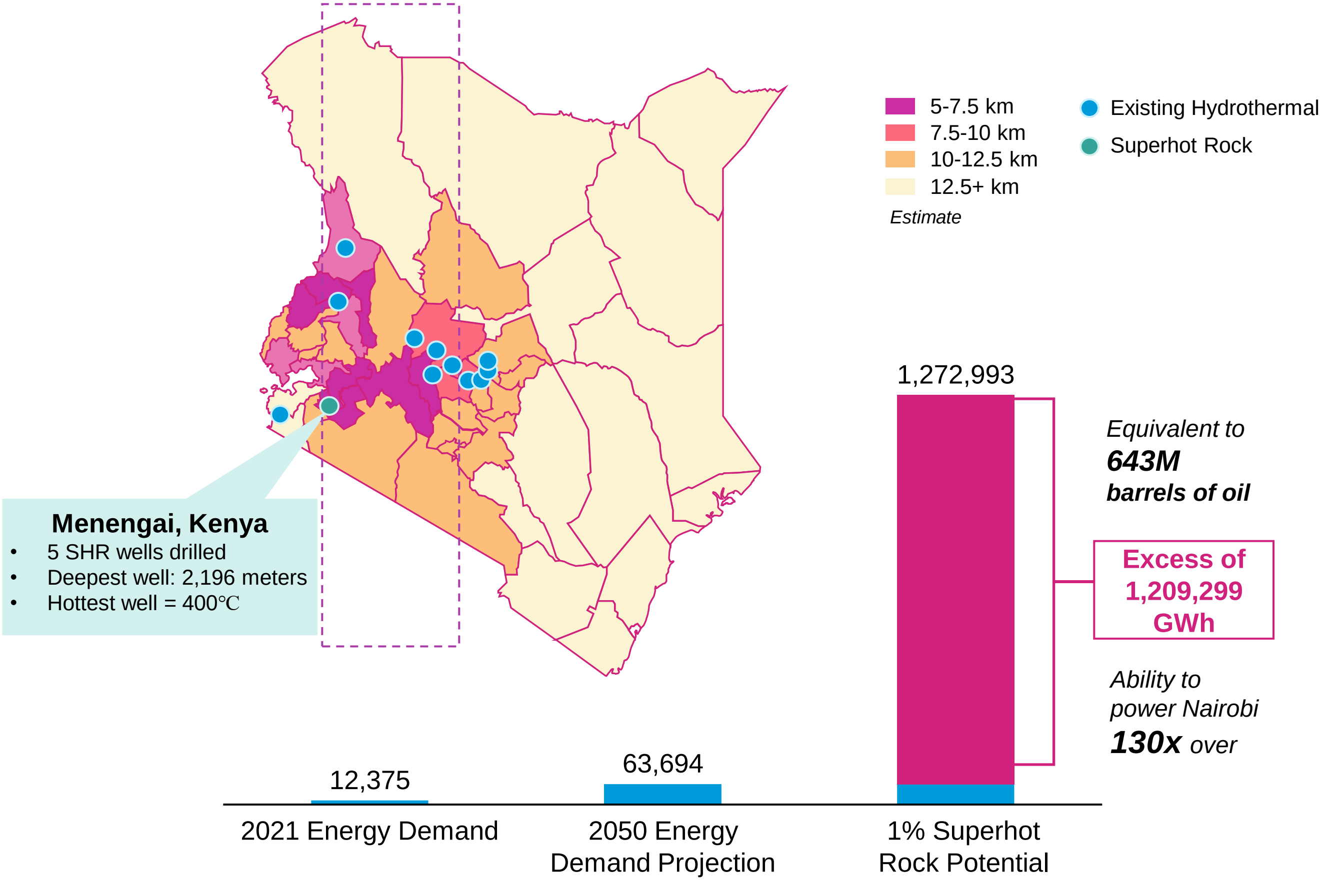
Kenya's current national electricity mix



939.73 MWh

*Geothermal comprises **43%** of total Kenyan electricity generation, 2024.*

Tapping into Kenya's superhot rock potential could produce 130x Nairobi's energy demand, far surpassing current hydrothermal capacity



Menengai, Kenya
- 5 SHR wells drilled
- Deepest well: 2,196 meters
- Hottest well = 400℃

*Equivalent to **643M** barrels of oil*

Excess of 1,209,299 GWh

*Ability to power Nairobi **130x** over*

Sources: Kenya geothermal energy (Reasons to Be Cheerful, 2022); 10 years in Kenya – the geothermal success story of GEG (ThinkGeoEnergy, 2021); The Role of Geothermal in Energy Mix: Kenya's Case Study (Xavier Shioya Musonye, 2022); An overview of geothermal energy in Kenya (University of Nairobi, 2009).

Credit: Zacharia Thurston, Shubhangi Prasad, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Türkiye’s 1.7 GW of geothermal capacity equals 11% of global installed capacity but meets only 1.5% of its own power demand

High geothermal potential and a revised FiT fueled Türkiye’s 2011-2016 geothermal boom

2005 — Renewable Energy Law No. 5346

First national renewable framework establishes feed-in tariffs. Policy introduces guaranteed offtake for renewables, attracting first private developers for geothermal exploration.

2007 — Geothermal Resources and Natural Mineral Waters Law No. 5686

Defines resource ownership by the state, licensing (exploration and operation), reinjection rules, and environmental obligations. It transfers authority to provincial administrations, which accelerate exploration.

2011 — Law No. 6094 (Amendment to 5346)

Revises feed-in-tariff scheme (geothermal tariff US10.5¢/kWh for 10 years), triggering surge of private financing and foreign interest (2011-2016 boom). Enables bankable PPAs under YEKDEM. Growth continues with the World Bank-Türkiye Development Project in 2016.

2019 — National Energy Efficiency and Renewable Strategy 2019-2023

Recognizes geothermal as a baseload renewable resource supporting grid stability, resulting in prioritization of geothermal in planning.

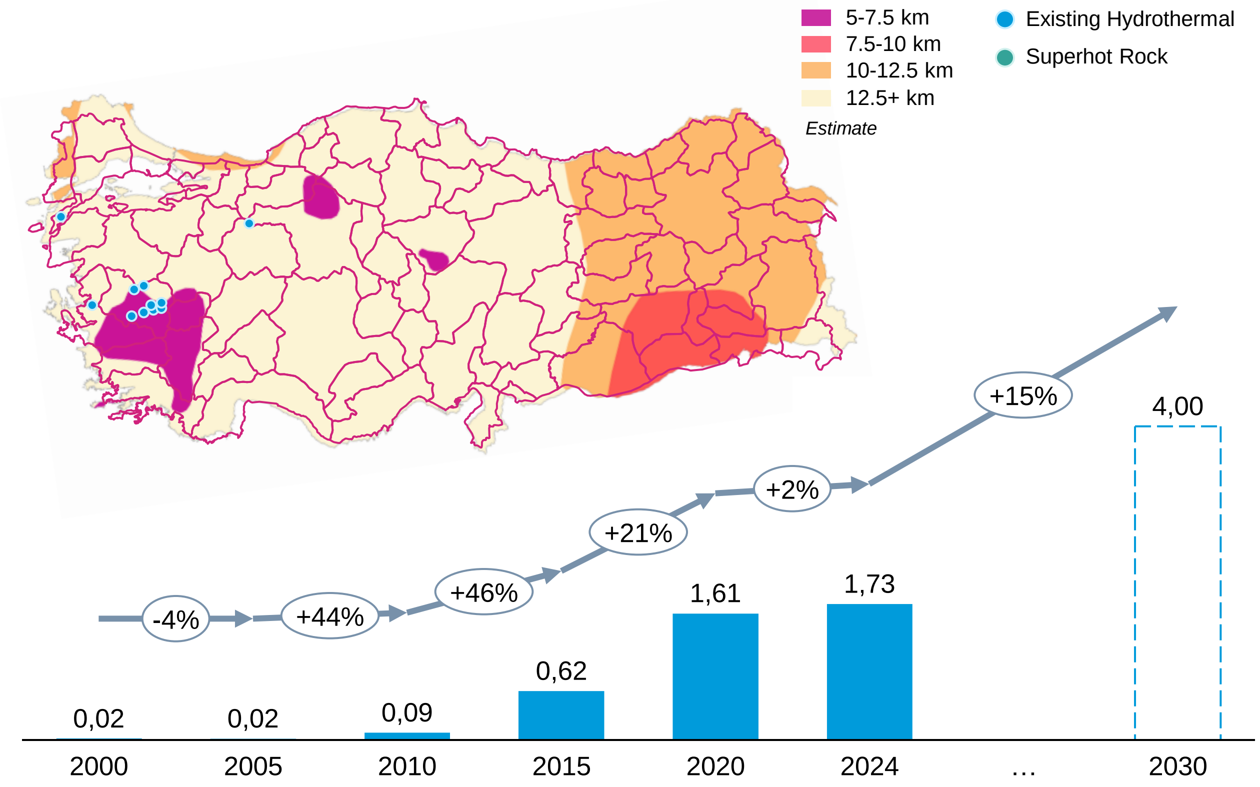
2021-2024 — Presidential Decree No. 3453

Converts FITs from USD to TRY due to TRY devaluation. That limits new investments but keeps the industry stable. Between 2022 and 2025, continues RSM and concessional funding with no new FIT scheme beyond 2025. Industry is focused on efficiency upgrades and binary cycle retrofits.

2025+ — Potential YEKDEM Extension and Carbon Market Integration

Industry proposes to link FITs to carbon pricing and baseload guarantees. Policy could restore long-term investor confidence and enable new deep-well exploration in Central and East Anatolia. Country aims for 4 GW geothermal power by 2030.

Installed geothermal capacity over time, *GW 2000-24*



Sources: Law No. 5346, Renewable Energy Law (2005); Amendment to 5346 (2010); Türkiye – Geothermal Development Project, World Bank (World Bank, 2016); Presidential Decree No. 3453, (2021); The ‘YEKDEM 2040’ demand in the geothermal sector (Energy and Environment, 2025).

Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Italy can achieve second ramp-up in geothermal power with FER2 support

Gap between FER1 and FER2 decrees resulted in stagnant installed capacity

1999
Bersani Decree
Liberalizes electricity generation and supply, opening both to competition.

2010
Legislative Decree 22/2010
Updates rules for exploration and exploitation of geothermal energy, which includes classifying resources by temperature, clarifying licensing procedures, and opening the market to new developers.

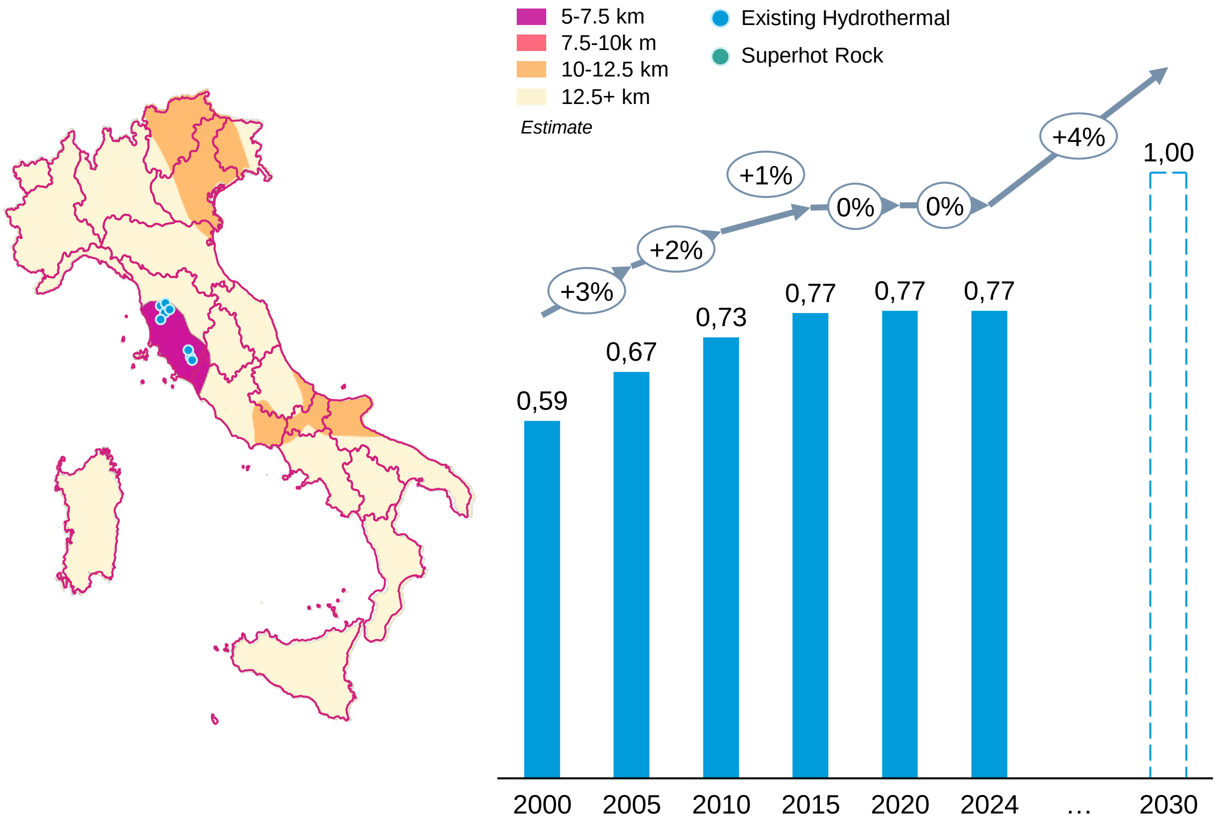
2011
Legislative Decree 28/2011
Implements EU RES rules and Autorizzazione Unica streamlined permitting.

2016
RES-E excl. PV Decree
Creates core incentives, including bonuses for low-impact/fully reinjected geothermal.

2019
FER1 (RES1) Decree
To boost renewable adoption, provides incentives to specific technologies (PV, onshore wind, hydro, and residual gas) with a total budget of about €5.8B. Criticized for excluding geothermal, which stalled new developments until the FER2 scheme was introduced.

2024-2025
FER2 (RES2) Decree
Provides for innovative, high-cost RES with a €35.3B budget, enabling restart of geothermal pipeline.

Installed geothermal capacity over time, *GW 2000-24*



Sources: Italy looks to end decade-long drought of new geothermal power stations (ThinkGeoEnergy, 2024); Decreto FER1 (EC, 2019).
Credit: Sevgi Helin Tilkicioglu, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

World’s No. 2 geothermal market, Indonesia is using policy reforms, private-sector investment to unlock hydrothermal capacity

Indonesia has integrated geothermal energy in its industrial policy and long-term decarbonization goals

Presidential Decree No. 22 (1981) and No. 45 (1991)

1981-91

Declare geothermal energy a national resource and provide preliminary guidelines for its exploration and development.

Geothermal Law No. 21/2014

2014

Eliminates restrictions on "mining" designation, establishes auction-based working regions, and allows for private and international participation.

Indonesia Just Energy Transition Partnership (JETP)

2022

Raises over $20 billion to boost investments in sustainable energy, with geothermal being a crucial baseload technology.

Electricity Supply Business Plan (RUPTL 2024-2034)

2024

Raises targets for renewable energy shares to over 35% by 2034, indicating greater policy support for the growth of geothermal energy.

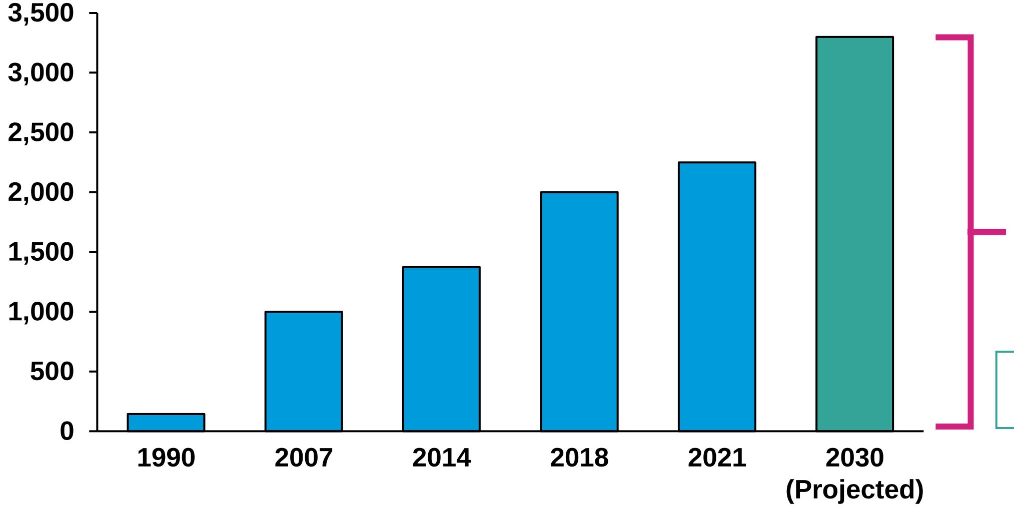
National Net-Zero Commitment

2060

Commits to achieving carbon neutrality for the entire economy by 2060, establishing geothermal as a deployable, low-emission power source for long-term security.

Situated on the Pacific Ring of Fire, Indonesia has 356 geothermal sites, 127 active volcanoes, and one of the world’s largest geothermal reserves

Indonesia Geothermal Installed Capacity, *MW*



2,342.63 MW installed *— twice as much as in 2009 (1,187 MW) and an additional 904 MW since 2015 (1,438 MW).*

Total Potential = ***23.36 GW***

Sources: The Future of Geothermal Energy (IEA, 2024); Harnessing Geothermal Energy to Power Indonesia’s Renewable Future (ABB News, 2025); Indonesia Issues New Regulation to Entice Investments (ThinkGeoEnergy, 2022); Geothermal Energy Outlook in Indonesia (Stanford, 2023); Indonesia’s Untapped Geothermal Potential (Energy Tracker Asia, 2024).

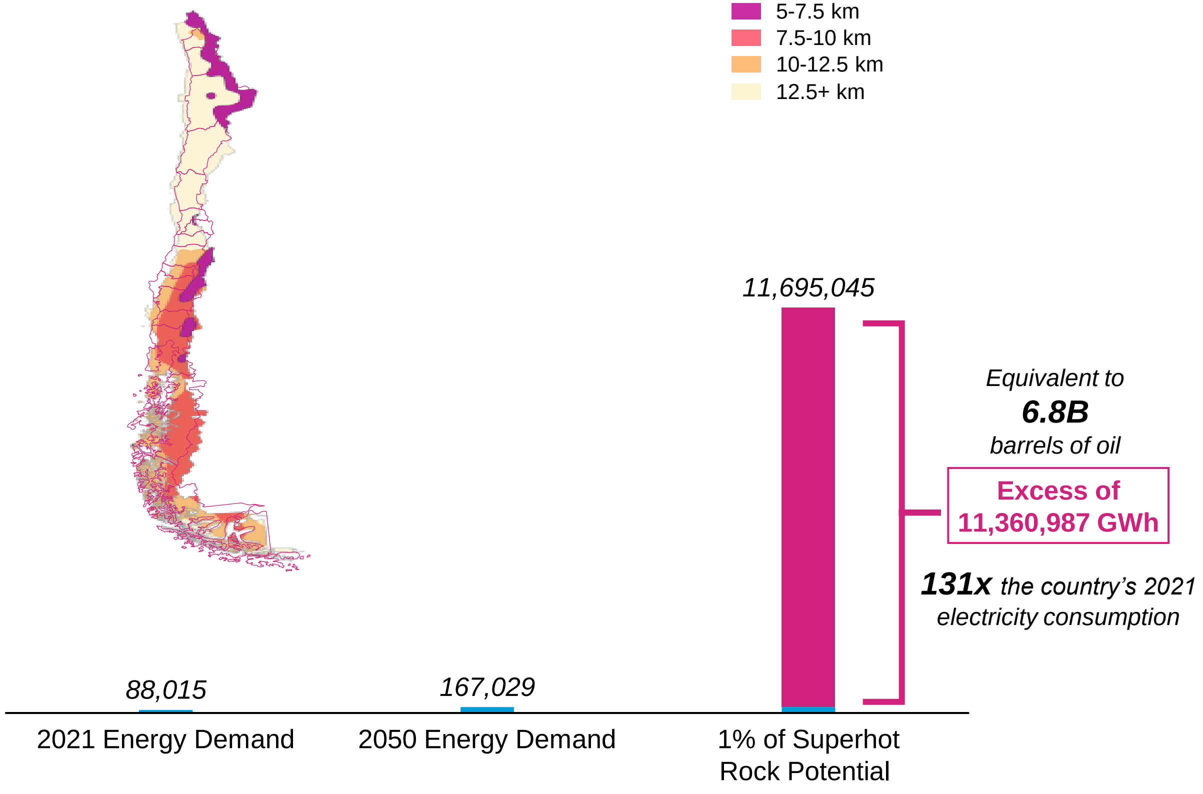
Credit: Shubhangi Prasad, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

With 12 GW potential, Chilean policy is now steering geothermal from resource mapping to real, scalable power generation

Chile’s geothermal policy evolved from concessions to market incentives, risk finance, and innovation

- 2000 — Introduces Geothermal Concessions Law, the first law for geothermal exploration rights and exploitation concessions.
- 2008 — Introduces mandatory renewable quotas for power providers under the NCRE Mandate (10% by 2024), creating demand and compliance pressure for non-conventional renewables like geothermal.
- 2013 — 20/25 Renewable Law improves long-term PPA structures and market access for geothermal as firm baseload generation, increases the clean energy objective to 20% by 2025, and modifies power supply tenders.
- 2014-15 — MiRiG – Geothermal Risk Mitigation Program (IDB + CTF) injects concessional public finance, guarantees, and loans convertible to grants to de-risk high-cost exploratory drilling.
- 2015 — Electricity tender reforms and structured PPAs produce transparent, technology-neutral contracts, improve auction regulations, and make it possible for geothermal developers to obtain 15- to 20-year PPAs.
- 2017 — Inaugurates South America’s first geothermal power plant (48 MW) at 4,500 meters in the Atacama Desert, by Enel and ENAP.
- 2025 — Issues two new geothermal exploration licenses to Transmark in the Andes, expanding its concession portfolio and signaling continued policy support for scaling geothermal as a firm, decarbonizing energy source.

Chile 2021 vs. 2050 energy demand and 1% geothermal power potential in GWh



Equivalent to ***6.8B*** *barrels of oil*

Excess of 11,360,987 GWh

131x *the country’s 2021 electricity consumption*

Sources: Superhot rock and the future of geothermal (CATF, 2025); Transmark issued 2 geothermal exploration licenses in Chile (ThinkGeoEnergy, 2025); Geothermal Energy in South America: A Case Study for Northern Chile (Scilight, 2025), Licenses and Tenders (CNE, 2025); The Future of Geothermal Energy (IEA, 2024).

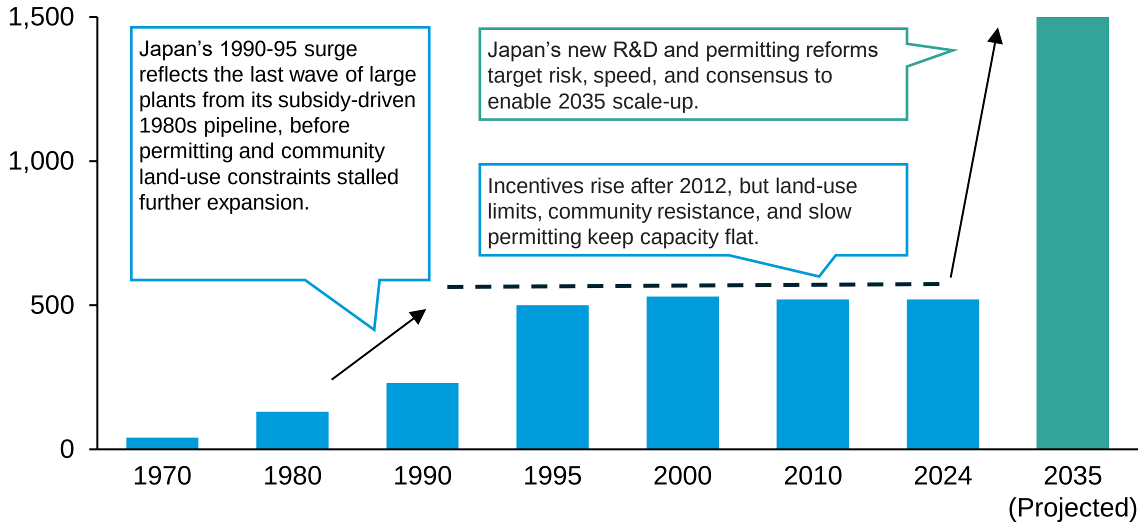
Credit: Shubhangi Prasad, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Japan’s 23 GW potential remained untapped for decades, but policy reform and local co-creation are driving a cautious revival

Japan is using FiTs, R&D programs focused on closed-loop and superhot potential for its geothermal strategy

1966	Matsukawa plant, Japan's first commercial geothermal facility, starts operations in 1966.
1960-1990	Government leads research and exploration under the New Energy and Industrial Technology Development Organization (NEDO); policy support is concentrated on geological surveys.
1997-2000s	National Parks Law and Hot Spring Act increase environmental regulations; social acceptance and environmental limits become core barriers.
2012-15	The 2012 Feed-in Tariff (FiT) and regulatory relaxation for under 7.5 MW projects, along with relaxed national park permitting reforms (2015), open new sites and create the first clear legal path for small-scale and binary geothermal plants.
2021	The 6th Strategic Energy Plan reaffirms geothermal as a key firm renewable alongside nuclear and hydrogen. Sets a 2030 target of ~1.5 GW (1.1% of power) and empowers JOGMEC with subsidies, equity, and loan guarantees, making geothermal officially part of national energy planning.
2025-35	New R&D programs for closed-loop and superhot geothermal pair with policies focused on risk reduction, faster permits, and community consensus to scale by 2035.

Japan Geothermal Installed Capacity, *MW*



Japan’s 1990-95 surge reflects the last wave of large plants from its subsidy-driven 1980s pipeline, before permitting and community land-use constraints stalled further expansion.

Japan’s new R&D and permitting reforms target risk, speed, and consensus to enable 2035 scale-up.

Incentives rise after 2012, but land-use limits, community resistance, and slow permitting keep capacity flat.

Observations

- Approximately 80% of Japan's geothermal reserves are in national parks and onsen regions, necessitating multi-ministry permissions and extensive coordination, which makes development difficult and slow.
- Japan uses only ~2%, or ~520 MW, of its 23 GW potential due to decades of policy, permitting, and community barriers; however, recent reforms and a new target of ~1.5 GW by 2030 signal a slow revival in the sector.

Sources: Geothermal Japan Country Report (IEA, 2024); Japan to develop geothermal power under net zero plan (Argus Media, 2025); Unlocking geothermal potential in Japan through small-scale generation (IRENA, 2009); The Future of Geothermal Energy (IEA, 2024).

Credit: Shubhangi Prasad, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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Geothermal Power Finance

Key messages

Finance

Energy Access, Development Needs, and Geothermal’s Role

- Developing countries face ongoing challenges in achieving **affordable, reliable, and sustainable energy**, limiting industrial growth and economic development. Expanding infrastructure, diversifying supply sources and transitioning to low-carbon systems are key priorities.
- Geothermal energy offers **24/7, low-cost, carbon-free baseload power**, but deployment is constrained by **high upfront costs**, **geological uncertainty**, and **limited technical capacity**.

Technological Cost Reductions in Binary and Flash Geothermal

- Both binary and flash geothermal technologies are achieving major cost declines through **faster drilling, material efficiency, and plant scaling**. Advanced binary systems can reduce CapEx by up to **30%**, while flash systems — with **monobore wells**, **4x faster drilling**, and **100 MW plants** — cut per-MW costs and timelines dramatically. Such innovations expand geothermal’s geographic reach and competitiveness in emerging economies.

Risk Mitigation, Policy Support, and Financing Models

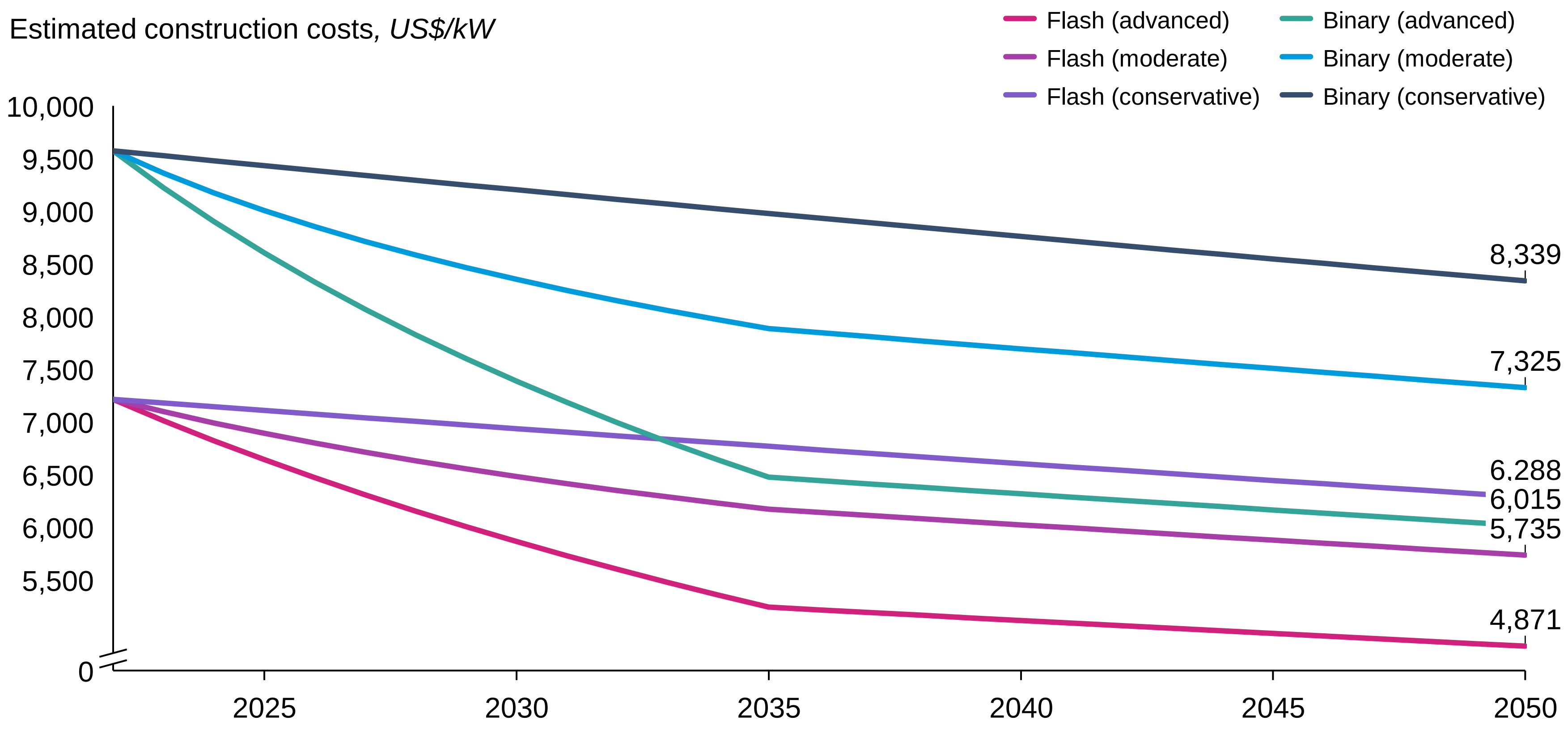
- Early-stage uncertainty remains the key investment barrier. Global programs like **World Bank’s ESMAP** show that **government-led exploration**, **cost-shared drilling**, and **fiscal incentives** attract private capital. De-risking tools such as **GRIF, insurance, and grants**, combined with **oil & gas expertise** in drilling and modular design, could reduce next-gen geothermal costs by up to **80%**, achieving **~$40/MWh**, competitive with nuclear and PV + storage.

Competitiveness and Industry Spillovers

- Geothermal’s **LCOEs ($61-$102/MWh)** are cheaper than coal and gas and about half the cost of nuclear, with **oil & gas technology spillovers** accelerating commercialization.
- **Fervo Energy** leverages **horizontal drilling** and **rapid well completion** to attract major **equity and debt financing**, including a **$300 million Series E** ahead of a planned IPO, advancing geothermal toward **commercial bankability** and a **trillion-dollar clean energy market**.

Conventional geothermal construction costs projected to continue to decline, driven by tech improvements and efficiency gains

Cost of construction for both flash and binary geothermal are expected to decline from 2022 to 2050 under conservative to advanced scenarios



Observations

Binary geothermal sees **cost reductions through both subsurface and surface improvements**.

- Conservative: Learning is incremental with limited drilling gains.
- Moderate: Introduces faster drilling, reduced material use, and moderate plant scaling (to 40 MW), supported by a 13% learning rate.
- Advanced: Accelerates progress with major drilling breakthroughs, larger plants, and advanced surface system efficiency, resulting in up to 30% learning-driven CapEx reduction. As a result, binary systems become increasingly viable across a wider range of geographies.

Flash geothermal sees cost reductions **driven by drilling efficiency and plant scale**.

- Conservative: Only modest gains are expected, with minor improvements in drilling speed and bit durability.
- Moderate: Assumes faster drilling, fewer casing stages, and streamlined permitting, leading to more meaningful CapEx savings.
- Advanced: Transformational gains, such as 4x faster drilling, monobore well designs, and deployment of 100 MW plants unlock significant cost reductions by cutting timelines, material use, and per-MW development cost.

Sources: Annual Technology Baseline (NREL, 2024).
Credit: Faradisa Anintya, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Next-gen tech is riskier and more equity-heavy, while proven technologies attract more debt through traditional project finance

Frontier tech, higher risk *Proven tech, lower risk*

	Fervo, U.S.	Rift Valley, Kenya	Sarulla, Indonesia
Technology	**Next-gen** geothermal (EGS, advanced drilling, and fiber optics)	**Conventional** geothermal (mixture of flash and binary)	**Conventional** geothermal (flash steam)
Risk profile	**Moderate technology risk:** While EGS has been de-risked by field pilots like Project Red (TRL 9 in 2024), scaling commercial deployment still carries subsurface and reservoir uncertainty. **Medium resource risk:** EGS creates its own reservoir, which avoids natural resource uncertainty but introduces engineered subsurface complexity.	**Low technology risk:** Uses proven conventional technology. **High resource risk:** In early phases, especially in unexplored or underexplored zones, but borne by the public sector through Kenya's state-owned GDC, which validates the resource before handing it off to private IPPs.	**Low technology risk:** Uses proven conventional technology. **Low resource risk:** Located in a well-characterized field with extensive drilling and historical data.
Revenue model	Long-term PPAs with utilities or corporate, pilot to commercial-scale model.	Utility offtake with donor-backed pricing.	IPP model with 30-year PPA under feed-in tariff, backed by political risk guarantees.
Financing instrument and stakeholder	**More equity:** Early-stage EGS projects are equity-heavy, backed by VC/PE (e.g., Breakthrough Energy, Capricorn). **Transitioning toward project finance** as risk perception declines.	**More debt:** GDC-led exploration allows donor-backed debt instruments (e.g., AfDB, AFD, World Bank); equity participation from KenGen and private IPP.	**More debt:** Classic project finance with concessional and commercial debt (ADB, JBIC, CTF); equity from Medco, Itochu, Kyushu Electric, INPEX.

Sources: Sarulla Case Study (World Bank, 2018); Renewable Energy Auctions in Kenya (IRENA, 2021); Geothermal Handbook (ESMAP, 2012); Cape Station Project Financing (TechCrunch, 2025).
Credit: Faradisa Anintya, Heather Hartel, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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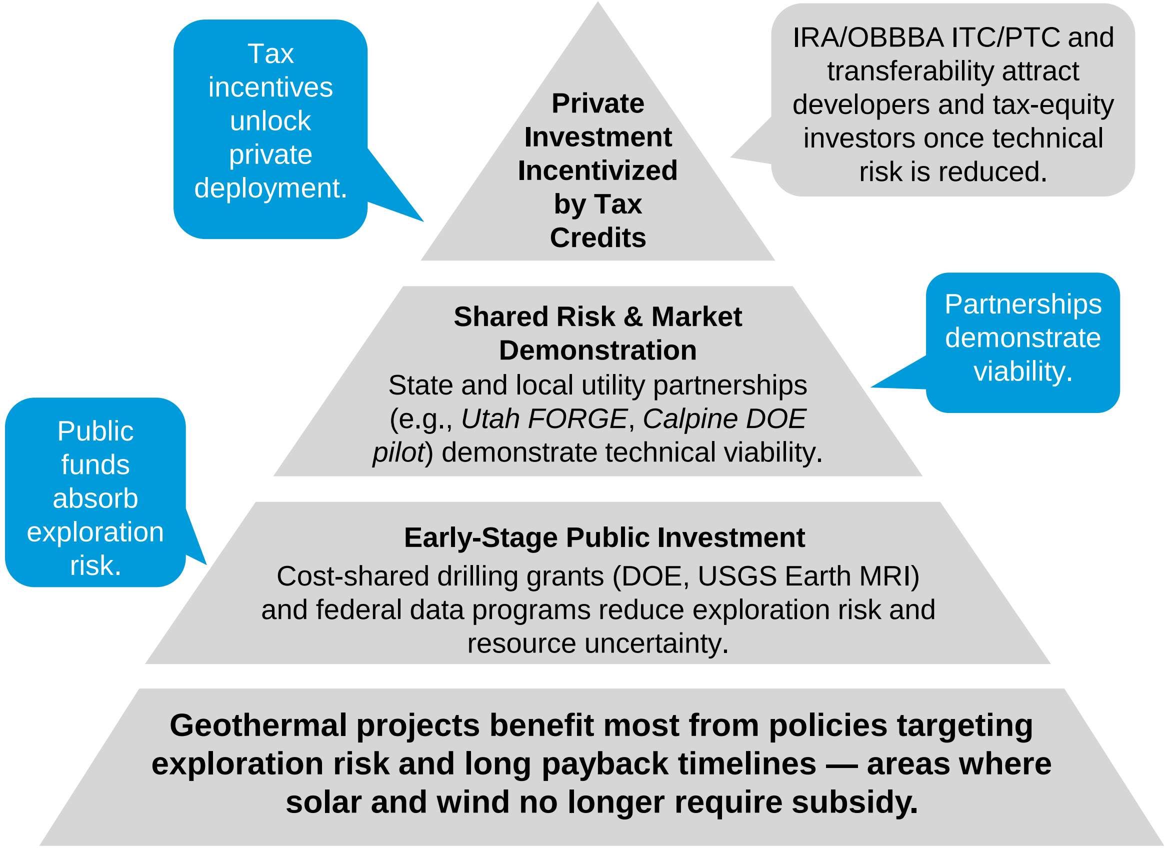
Domestic policy support that aims to de-risk geothermal development in the United States is preserved under the Trump administration

IRA, BIL, and OBBBA enhance bankability through tax credits, direct pay, and federal loan support

Policy	Type of Support	Key Provisions for Geothermal	Impact/Intent
Inflation Reduction Act (IRA) (2022)	Tax credits that improve project economics	30% **ITC** or **PTC** eligibility; **direct pay** (for tax-exempt entities); **transferability** of credits; **adders** (+10% energy communities; +10% domestic content, where met)	First-time **inclusion of geothermal**; enables **monetization of credits and broader investor participation**.
Bipartisan Infrastructure Law (BIL) (2022)	Federal R&D, grants, and data to reduce early-stage risk	DOE Geothermal Technologies Office funding; **EGS pilot demonstrations**; USGS Earth MRI mapping/data; authority for DOE to run field pilots	Focused on **early-stage risk reduction**: funding exploration, subsurface data, and demonstration wells; supports **cost-shared projects** to crowd-in private capital
One Big Beautiful Bill Act (OBBBA) (2025)	Credit design plus phase-out policy and domestic supply guardrails	Tightens **FEOC rules**; strengthens/clarifies domestic content; **retains geothermal ITC/PTC runway through 2033** with gradual phaseout; **accelerates phaseouts for mature tech** (solar/wind)	Protects geothermal's **long credit runway** while phasing out mature renewables; encourages **domestic supply-chain alignment**

Emerging risk-sharing programs and public-private partnerships lower risk and crowd in private capital



Tax incentives unlock private deployment.

Private Investment Incentivized by Tax Credits

IRA/OBBBA ITC/PTC and transferability attract developers and tax-equity investors once technical risk is reduced.

Shared Risk & Market Demonstration
State and local utility partnerships (e.g., *Utah FORGE*, *Calpine DOE pilot*) demonstrate technical viability.

Partnerships demonstrate viability.

Public funds absorb exploration risk.

Early-Stage Public Investment
Cost-shared drilling grants (DOE, USGS Earth MRI) and federal data programs reduce exploration risk and resource uncertainty.

Geothermal projects benefit most from policies targeting exploration risk and long payback timelines — areas where solar and wind no longer require subsidy.

Sources: Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); DOE Launches $84 Million Program to Demonstrate Enhanced Geothermal Energy Systems (DOE, 2022); How the One Big Beautiful Bill Changes Green Energy Tax Credits (Tax Foundation, 2025).

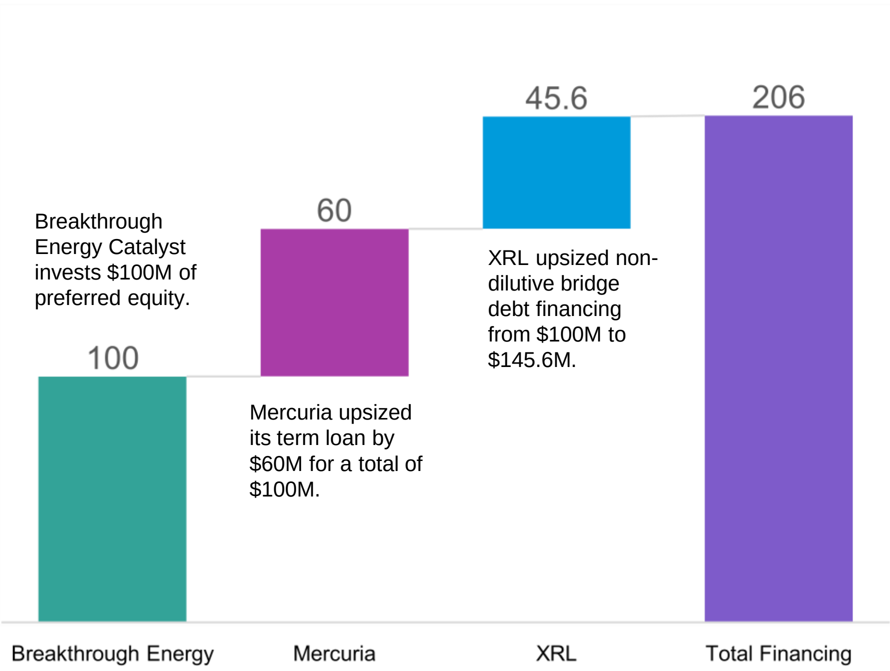
Credit: Heather Hartel, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Investors double down on Fervo with equity and debt funding to commercially deploy EGS; total $1.69B raised to date

As Fervo achieved scale-up milestones, the company consistently attracted capital

- **2017 – Grant:** Undisclosed, from Stanford TomKat program
- **2019 – Series A:** $11M, led by Breakthrough Energy
- **2021 – Series B:** $28M, led by Capricorn Investment Group
- **2023 – Series C:** $138M, led by DCVC
- **2024 – Series D:** $244M, led by Devon Energy
- **2024 – Debt:** $220M, term loan, letters of credit, project bridge loan
- **2024 – Series D extension:** $135M, corporate equity
- **2025 – Project finance:** $206M, preferred equity, bridge and term loan
- **2025 – Series E:** $460M, led by B Capital Group
- **January 2026 – Announced IPO**

Fervo lands $206 million in project financing in 2025 *(US$M)*



Breakthrough Energy Catalyst invests $100M of preferred equity.

Mercuria upsized its term loan by $60M for a total of $100M.

XRL upsized non-dilutive bridge debt financing from $100M to $145.6M.

Observations

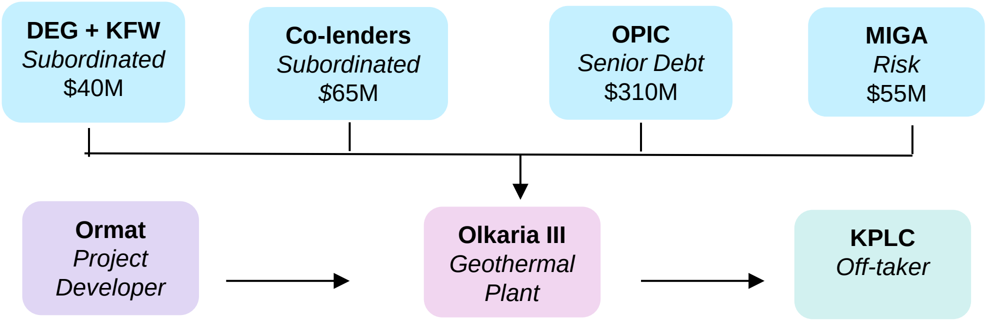
- Fervo **confidentially filed to go public on January 22, 2026**. It would be the first EGS startup to IPO in the United States.
- Breakthrough Energy Ventures is a longtime investor that has consistently invested in new rounds, demonstrating conviction in Fervo's technology.
- With technological breakthroughs like horizontal drilling and record-breaking drilling times, Fervo has consistently raised larger rounds and accessed debt financing.
- Fervo's ability **to attract project financing** is a critical hurdle for a hard tech investment and key to unlocking widespread commercial deployment.

Sources: Fervo Energy Secures $206M (Fervo Energy, 2025); Fervo Energy Secures $255M (2024); Bridging the Valley of Death (Consulate General of Denmark, 2021); Fervo Energy Raises $138M (Business Wire, 2022); Fervo Energy Raises $28 Million (Fervo Energy, 2021); Fervo Energy Raises $244 (Fervo Energy, 2024); Scoop: Fervo Energy raising $300M (Axios, 2025); Fervo Energy (Pitchbook, 2025).

Credit: Stephanie Chen, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Private and public sector financing was essential for Kenya’s Olkaria III geothermal project, leading to a 16% equity IRR

Olkaria III Project Stakeholders



Stakeholder	Details
Olkaria III	110 MW geothermal project in Kenya
Ormat	**Experienced project developer** and key equity, was a stakeholder at the beginning of the project.
Kenya Power and Lighting Company (KPLC)	***Signed 20-year PPA*** *in 1998, at the start of the project.*
DFI Banks: DEG and KFW, co-lenders	DEG and KFW Development Bank refinanced Ormat’s equity and provided **low-cost, long-term debt**.
OPIC	Provided a **19-year senior loan in three tranches**. The long-term debt was essential and was OPIC’s first geothermal investment.
MIGA	Multilateral Investment Guarantee Agency (MIGA) **provided political risk insurance** for equity stakeholder Ormat (2% premium).

Project Timeline

- **1996 – Pre-project:** Tender for geothermal
- **1998 – Ormat:** $40M equity financing
- **2006 – Ormat:** $150M equity financing
- **2009 – DEG & KFW:** Refinanced equity for $105M loan
- **2012 – OPIC:** Senior loan of $310M
- **2013 – Olkaria III:** Full plant commissioned at 84 MW
- **2014 – Olkaria III:** Full plant commissioned at 110 MW
- **2016 – Olkaria III:** Ormat expansion to 134 MW

Observations

- **First privately financed** geothermal project in Africa from field to operations and maintenance

Project returns:
  - **Equity IRR: 16%**
  - IRR without DFI support:10%

Factors that led to a 16% IRR:
  - Low-cost and long-term debt from DFI
  - Donation of wells from KenGen, Kenyan public electric company, saved Ormat $24M, leading to Ormat’s equity IRR increasing from 13% to 16%.
  - Refinancing of Ormat equity supported IRR, but delays prevented the project from achieving higher returns.

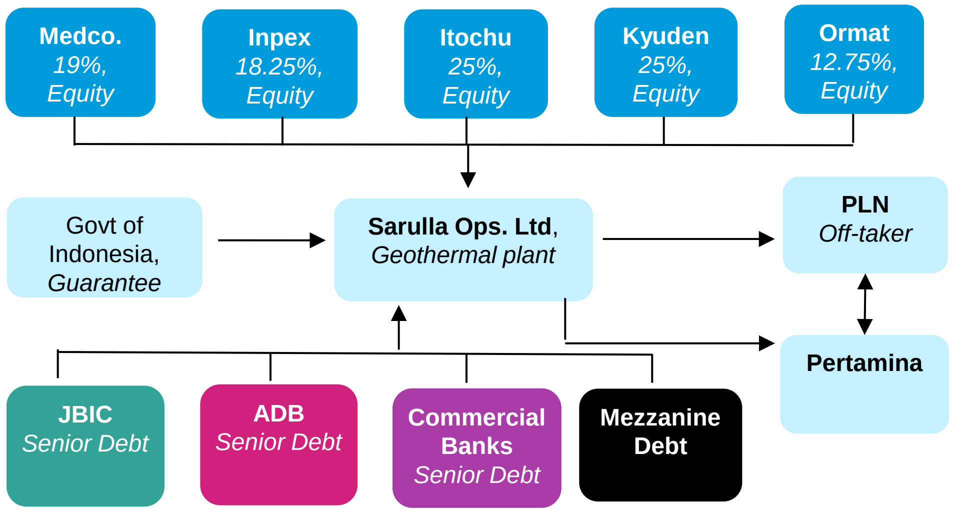
Project outcomes:
  - Estimated 13% lower LCOE and 31% decrease in costs for each geothermal plant
  - Reduced Kenya’s emissions by an estimated 2 to 4%

Sources: Using Public Finance to Attract Investment in Geothermal (Climate Policy Initiative, 2015); Kenya: EIB and Agence Française de Développement agree crucial financing (EIB, 2010).

Credit: Stephanie Chen, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Indonesia's Sarulla project's financing success proves bankability of conventional geothermal technology

Case Study: Sarulla Indonesia



Medco. *19%, Equity*

Inpex *18.25%, Equity*

Itochu *25%, Equity*

Kyuden *25%, Equity*

Ormat *12.75%, Equity*

Govt of Indonesia, *Guarantee*

Sarulla Ops. Ltd, *Geothermal plant*

PLN *Off-taker*

Pertamina

JBIC *Senior Debt*

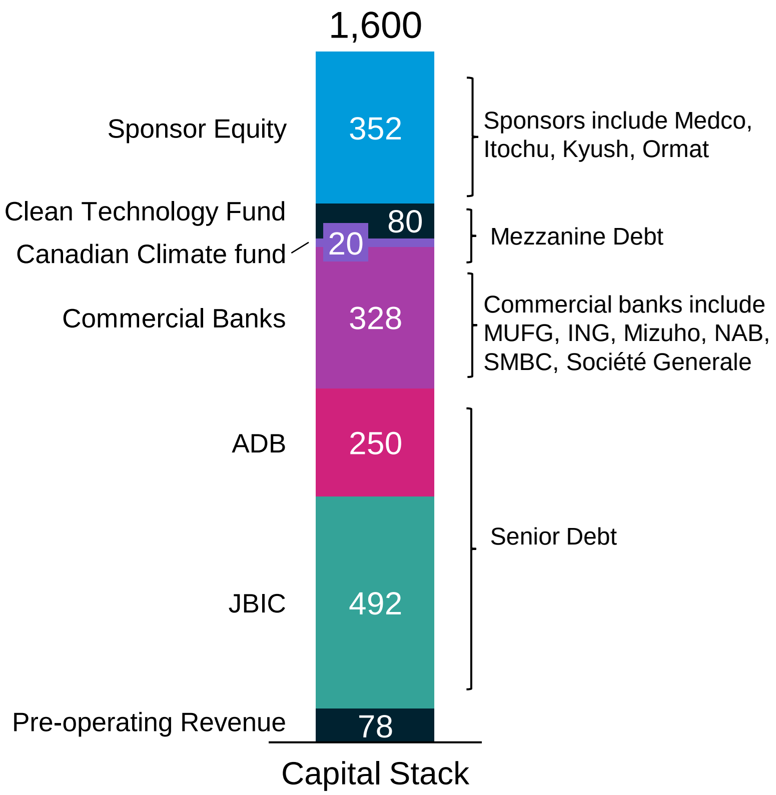
ADB *Senior Debt*

Commercial Banks *Senior Debt*

Mezzanine Debt

- **Location:** North Sumatra, Indonesia
- **Details:** A conventional geothermal project, built out in three phases across three 110 MW plants for a total of 330 MW.
- **Construction:** Started in 2014 with target completion in February 2018. The third plant was completed a few months after the target date in May 2018.
- **Offtake Agreement:** Signed an energy sales contract with PT Perusahaan Listrik, a state-owned utility, for 30 years of electricity offtake.

Sarulla Project Capital Stack



Observations

- Sarulla is one of the largest conventional geothermal projects in the world, financed for $1.6B with a combination of senior debt, mezzanine debt, and sponsor equity.
- Mezz lenders paid *pari-passu* in the event of default due to termination fee of the energy sales contract equaling the senior and mezz debt.
- **Guarantees:** To de-risk the project, the Indonesian government offered a guarantee on the project. JBIC also agreed to a political risk guarantee for the commercial banks if the government did not follow through.

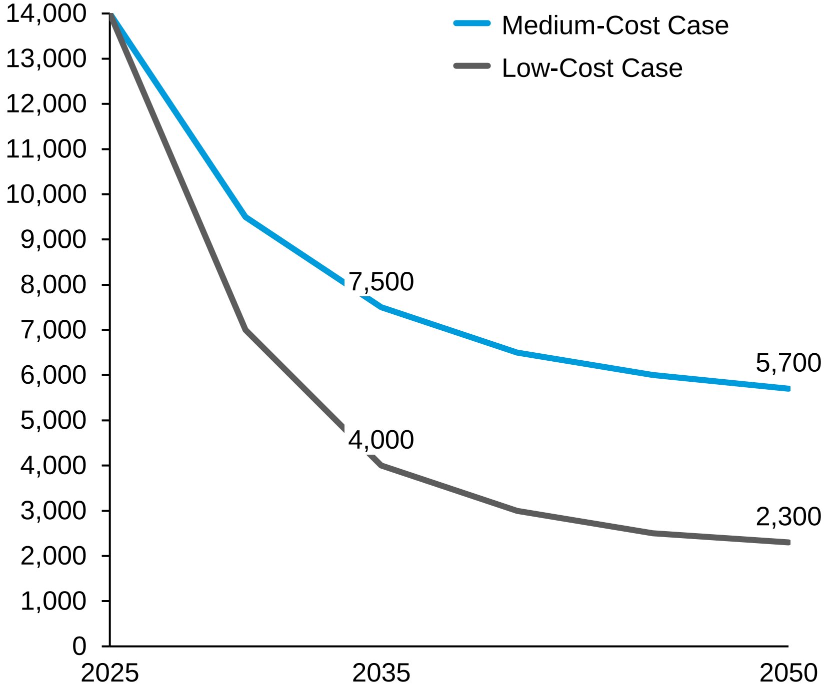
Sources: Sarulla Geothermal, Indonesia (IJ Global, 2014); Project Financing and Political Risk Guarantee (JBIC, 2014); Press release: Sarulla Geothermal (Ormat, 2017); Mizuho Overview of Project Finance (World Bank, 2018).

Credit: Stephanie Chen, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Oil & gas expertise transfer can significantly reduce subsurface drilling costs, the largest component of geothermal construction

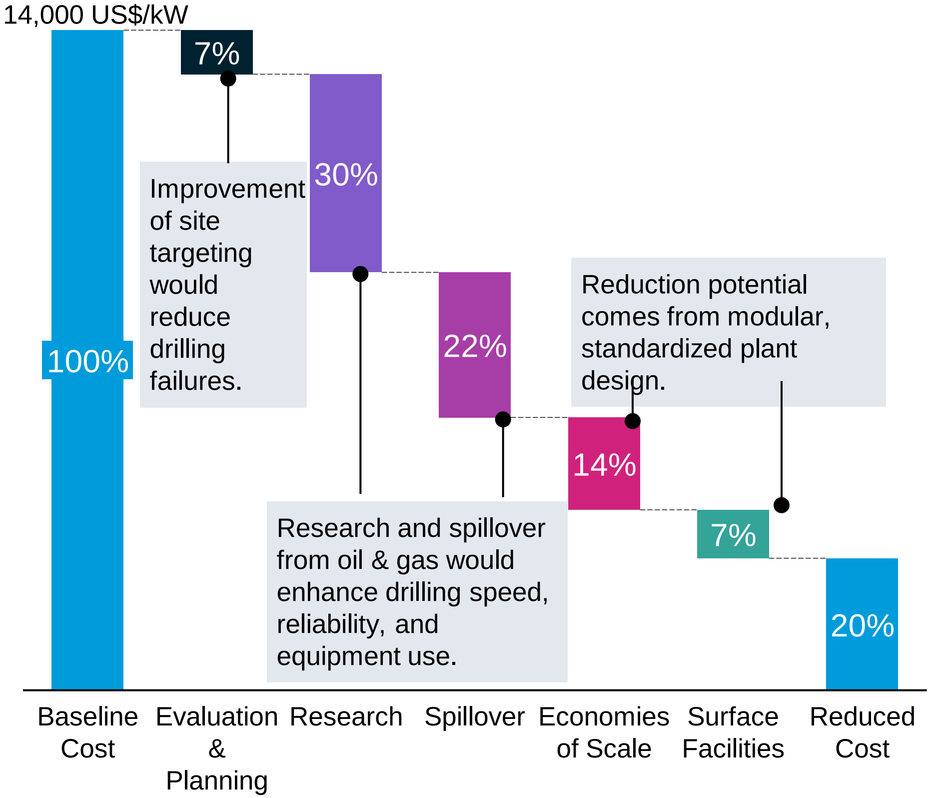
Next-gen geothermal construction costs are projected to drop ~60-80% by 2050 …

Next-gen geothermal construction costs, *US$/kW*



… driven by oil & gas expertise transfer; in the U.S., this can reduce costs by up to 80% of current baseline

Breakdown of geothermal construction potential cost reduction, *%*



Improvement of site targeting would reduce drilling failures.

Research and spillover from oil & gas would enhance drilling speed, reliability, and equipment use.

Reduction potential comes from modular, standardized plant design.

Observations

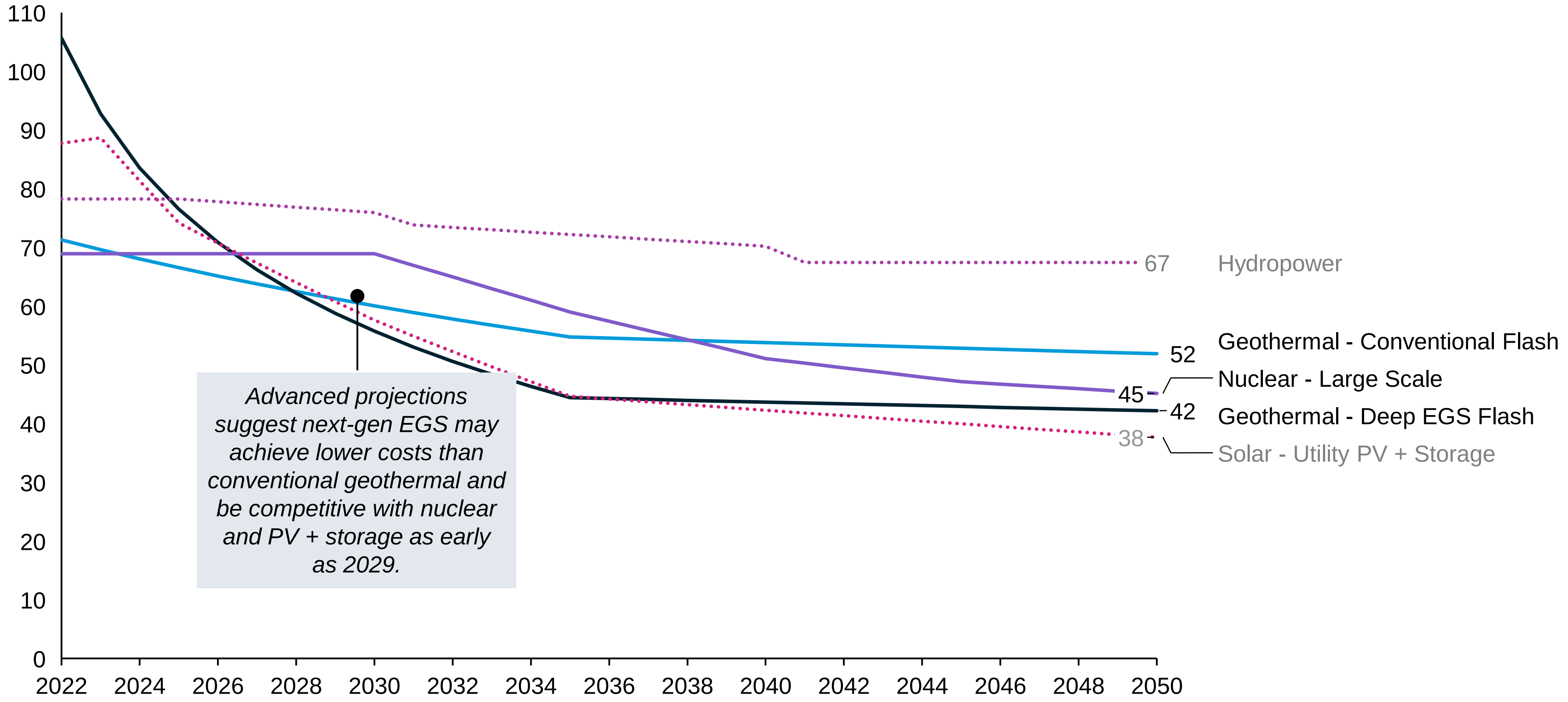
- Next-gen geothermal faces high upfront costs, with **subsurface drilling accounting for 60 to 80% of total expenses**.
- **Oil & gas expertise** in drilling, supply chains, and modular plant design **is key to reducing costs**, driven by improved site planning, technology spillovers, economies of scale, and surface facility optimization, all areas where O&G capabilities directly apply.
- In a low-cost scenario, **effective O&G knowledge transfer could cut costs by up to 80%**; the medium-cost case assumes more gradual progress and implementation barriers.

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

Credit: Faradisa Anintya, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal LCOE is on track to compete with hydro, nuclear, and solar PV + storage, through O&G transfer and policy-led de-risking

Estimated LCOE (levelized cost of energy) under NREL Advanced scenario, *US$/MWh*



Advanced projections suggest next-gen EGS may achieve lower costs than conventional geothermal and be competitive with nuclear and PV + storage as early as 2029.

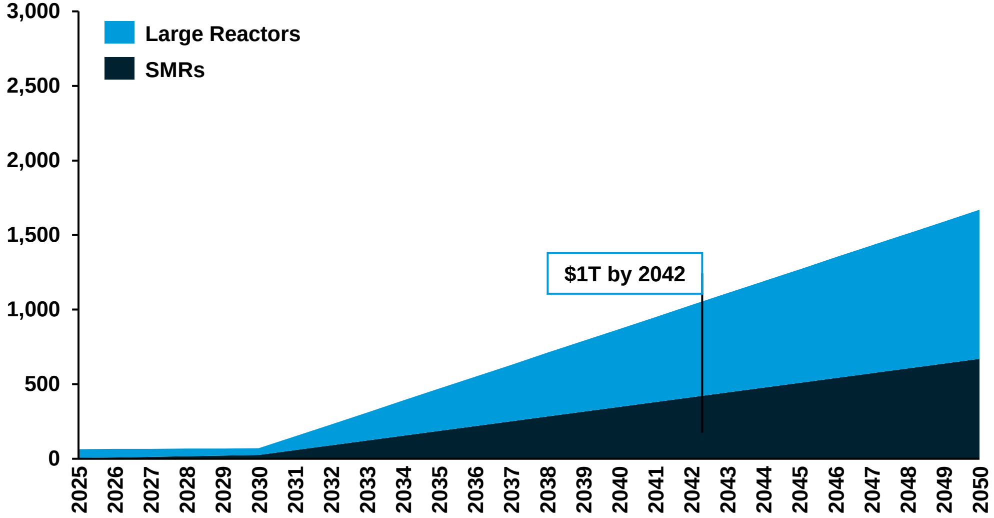
Observations

- Next-gen geothermal costs could drop significantly, **enabling power generation at ~US$40/MWh.** Both conventional and next-gen geothermal LCOE are on par with nuclear and PV + storage.
- Oil & gas expertise in advanced drilling, subsurface exploration, and modular plant design is accelerating cost declines. Solar PV, batteries, and EVs saw similar cost declines through industry spillover and rapid deployment.
- **Policy support and de-risking tools** (e.g., GRIF, insurance, grants) reduce early-stage risk, improve bankability, and crowd in private capital through blended finance and PPPs.

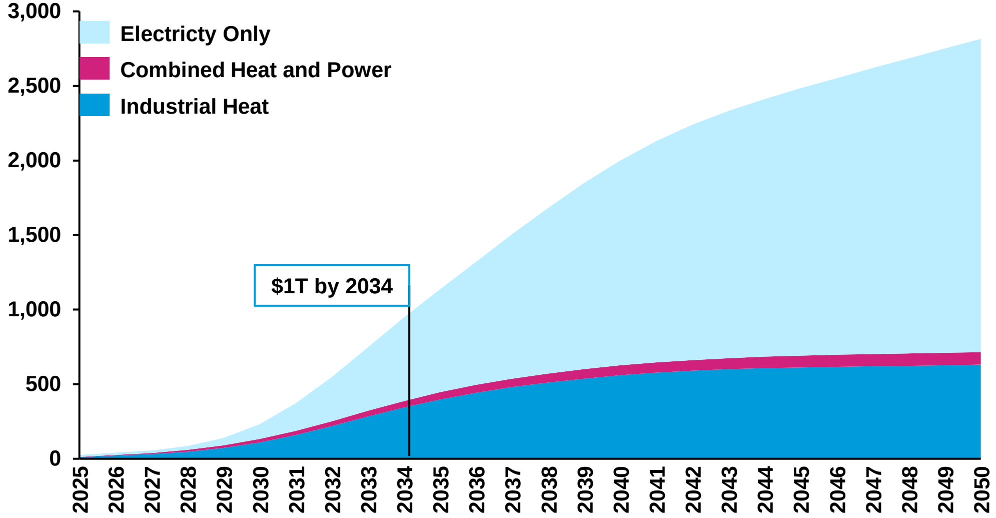
Sources: Annual Technology Baseline Cost and Performance Data for Electricity Generation (Open Energy Data Initiative, 2024).
Credit: Faradisa Anintya, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Modern cumulative investment in geothermal expected to reach $1 trillion a decade before nuclear fission technology

Cumulative Investment Estimate of Nuclear Fission Energy by Application (US$B)



Cumulative Investment Estimate of Geothermal Energy by Application (US$B)



Nuclear innovations pushing investor growth, but industry still facing setbacks

Potential reasons stunting projections

1. Still facing regulatory and safety concerns from the public
2. Low skill transferability from other energy technologies
3. Applications limited to power generation
4. Subject to price shocks of mineral fuels like uranium
5. More expensive to operate
6. No known alternative options for revenue generation
7. SMRs remain early in development
8. Relatively established technology

Geothermal is emerging and avoids contentious drawbacks of nuclear power

Potential reasons favoring growth

1. Viewed as a safer baseload power alternative than nuclear
2. Oil and gas engagement certifies large reserve of workforce with applicable knowledge
3. Applicable to heating and cooling plus electricity
4. Immune to price shocks of commodities like uranium
5. Less expensive to operate
6. Potential for critical mineral extraction, providing alternate revenue stream
7. Technology block generally limited to drilling
8. Emerging technology

Sources: Cumulative Investment for Next Generation Geothermal 2025-2050 (IEA, 2024); Global Geothermal Energy Market (Market.us, 2024); Outlook for Nuclear Investment (IEA, n.d.); Nuclear Renaissance Gains Momentum (Morgan Stanley, 2025)

Credit: Zacharia Thurston and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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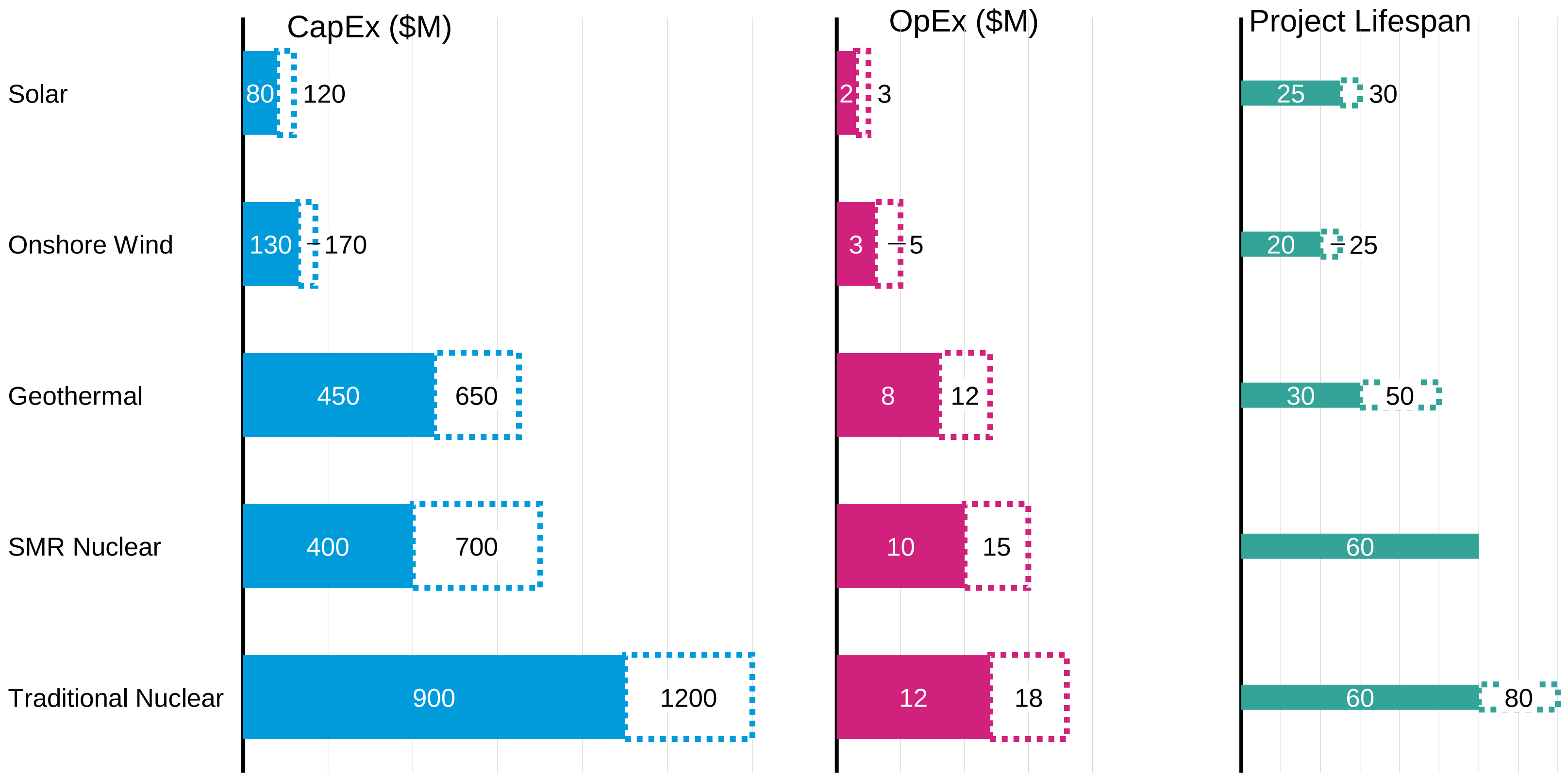
Geothermal requires large upfront investment but delivers stable returns and low O&M costs over a 30- to 50-year project life

CapEx, OpEx, and project life ranges for a 100 MW power plant



Observations

- **Capital Intensity:** Geothermal requires the largest upfront investment, with drilling and resource confirmation consuming 60-70% of total CapEx before revenue. Solar and wind projects front-load only ~30%.
- **Timeline:** Development and payback extend across 7-10 years before COD, compared with 2-3 years for solar and wind, 5-7 years for SMRs, and 10-15 years for traditional nuclear.
- **Returns:** Once operational, geothermal delivers steady baseload output for 30-50 years with capacity factors near 85%, far exceeding solar's and wind's 20-25 year lifetime and 30-45% capacity factors.
- **Financing Implications:** Longer horizons demand blended finance and government risk sharing, but geothermal's stable post-COD cash flows make it attractive to infrastructure and pension investors seeking duration.

Sources: Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); Renewables (IEA, 2025); Levelized Cost of Energy+ (Lazard, 2025); Geothermal (IRENA, 2024); The Future of Geothermal Energy (IEA, 2024); Renewable Power Generation Costs (IRENA, 2024); Annual Technology Baseline (NREL, 2024); GeoVision (DOE, 2019); Future of Nuclear Power (MIT, 2018); Vogtle (DOE, 2023)

Credit: Heaher Hartel, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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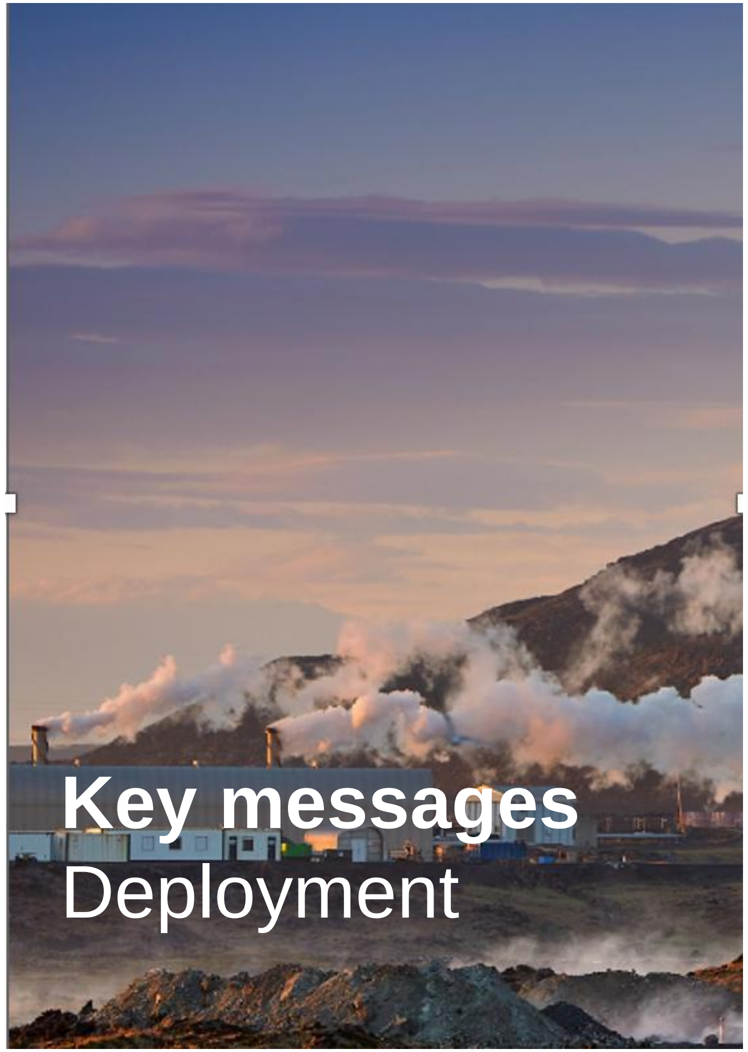
Geothermal Power Deployment



Key messages
Deployment

Geothermal to Meet Growing Energy Demand

- U.S. data centers could add **35 to 65 GW** by 2030, far exceeding incremental nuclear (~4 GW) and grid-connected geothermal (6 to 8 GW). **Behind-the-meter geothermal (~15 GW)** can supply data centers directly, bypassing grid and permitting constraints.
- Deployment depends on **drilling and permitting innovation** and applying conventional geothermal, O&G, and geospatial techniques to reduce **LCOE**.

Industrial and Corporate Drivers

- Tech giants (**Microsoft, Google, Meta, Amazon**) are accelerating deployment through PPAs and site development.
- **Fervo Energy** leverages **horizontal drilling, advanced data analytics, and O&G expertise** to speed deployment and increase resource efficiency, with corporate demand and energy security driving growth.

Workforce and Cross-Sector Capabilities

- Expanding the geothermal workforce via **reskilling, O&G talent transfer, and digital automation** is critical.
- Global geothermal employment grew from **96,000 to 196,000 (2021)** but remains small compared with **12.4 million in O&G (2023)**; the U.S. and EU must expand training to stay competitive with China.

Industrial Decarbonization Potential

- Co-locating geothermal with **Indonesia’s nickel reserves** (40% of global geothermal, 61% of EV nickel) can provide clean heat for refining, cutting upstream emissions and lowering **EV lifecycle carbon intensity**.
- Pilot regions like **Sulawesi, Sumatra, and Java** can combine industrial decarbonization with **local economic and labor development**.

Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal offers reliable, low-footprint baseload energy, though costs and longer timelines may constrain scale-up

🟩 *More desirable* 🟨 *Moderate* 🟥 *More challenging*

	Geothermal	Hydro	Nuclear	Wind	Solar
Resource availability & scalability	🟨 **Scalable in select locations,** high upfront costs, deep drilling needed	🟨 **Limited** scalability due to size *(smaller hydro projects more feasible vs. larger dams)*	🟥 **Limited** scalability due to high investments and long construction times *(SMR easier to scale as modular alternative)*	🟩 **Highly scalable anywhere** due to modular deployment	🟩 **Highly scalable anywhere**, due to modular deployment
Costs (LCOE)	🟨 \$66-\$109/MWh	🟨 \$47/MWh	🟥 \$141-\$228/MWh (new plants)	🟩 \$37-\$86/MWh (onshore), \$70-\$157/MWh (offshore)	🟩 \$38-\$78/MWh (utility scale)
Capacity factor	🟩 70-90%	🟨 Variable (global avg. is around 44%)	🟩 ~90%	🟨 38-47% for onshore, 41-50% for offshore	🟥 25-33% for standalone systems
Reliability	🟩 **Reliable baseload** resources	🟨 **Baseload resource only** with reservoir storage	🟩 **Reliable baseload** resources	🟥 **Intermittent**, variable output	🟥 **Intermittent**, energy storage required
Setup time	🟨 **Moderate timeline**, typically 3-5 years	🟥 **Long timeline**, often 5-10 years or more	🟥 **Longest timeline**, often 10+ years due to regulatory & construction complexities	🟩 **Relatively quick to deploy**, often within 1-2 years	🟩 **Relatively quick to deploy,** often within 1-2 years
Technology readiness	🟨 **Established** but room for significant advancements (e.g., EGS)	🟩 **Mature**, limited room for improvement	🟨 **Established** but challenges in cost reduction & public accept.	🟩 **Mature**, ongoing innovations improving efficiency & reducing costs	🟩 **Mature**, ongoing innovations improving efficiency & reducing costs
Land-use footprint efficiency (km^2/TWh/year)	🟩 7.5	🟥 54.0	🟩 2.4	🟥 72.1	🟥 36.9

Despite its higher LCOE and longer development timeline — especially compared to wind and solar — **geothermal remains a highly competitive energy source in regions with significant geological activity,** offering high reliability and efficient land use.

Sources: LCOE report (Lazard, 2025); U.S. Energy Information Administration Annual Energy Outlook (DOE, 2022); Geothermal Basics (DOE, 2025); Beyond Levelized Cost (SLB, 2025).

Credit: Faradisa Anintya, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Nuclear and geothermal both offer firm, low-carbon power but face distinct financing, technical, and deployment challenges

Non-exhaustive overview of opportunities and challenges

<table>
<tr><th></th><th>Nuclear</th><th>Geothermal</th></tr>
<tr><td rowspan="5">Opportunities</td><td colspan="2">Provide firm, dispatchable, low-carbon baseload power</td></tr>
<tr><td colspan="2">Long asset lifetimes (with upgrades)</td></tr>
<tr><td colspan="2">Potential for distributed/behind-the-meter deployment near load centers</td></tr>
<tr><td>SMRs with shorter construction timelines</td><td>EGSs expand resource base</td></tr>
<tr><td>Integration with hydrogen/ammonia production</td><td>Co-benefits: heating, desalination, minerals</td></tr>
<tr><td rowspan="6">Challenges</td><td colspan="2">High upfront CapEx, financing hurdles (risk for investors)</td></tr>
<tr><td colspan="2">Long permitting and siting processes compared to solar and wind</td></tr>
<tr><td>NRC approval cycles drive 10- to 15-year timelines</td><td>7- to 10-year development cycle</td></tr>
<tr><td>Public resistance around safety, accidents, waste</td><td>Resource risk and drilling uncertainty</td></tr>
<tr><td>Limited viable siting options (cooling water)</td><td>Seismicity concerns from EGS</td></tr>
<tr><td>Waste management and decommissioning costs</td><td>Smaller project scale, bankability concerns</td></tr>
</table>

Sources: Pathways to Commercial Liftoff: Advanced Nuclear (DOE, 2024); Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); The Potential for Geothermal Energy to Meet Growing Data Center Electricity Demand (Rhodium Group, 2025); The Future of Geothermal Energy (IEA, 2024); Net Zero Roadmap (IEA, 2023); Nuclear Power in the USA (World Nuclear Association, 2025); Geothermal Resources and Technologies (NREL, n.d.).

Credit: Heather Hartel, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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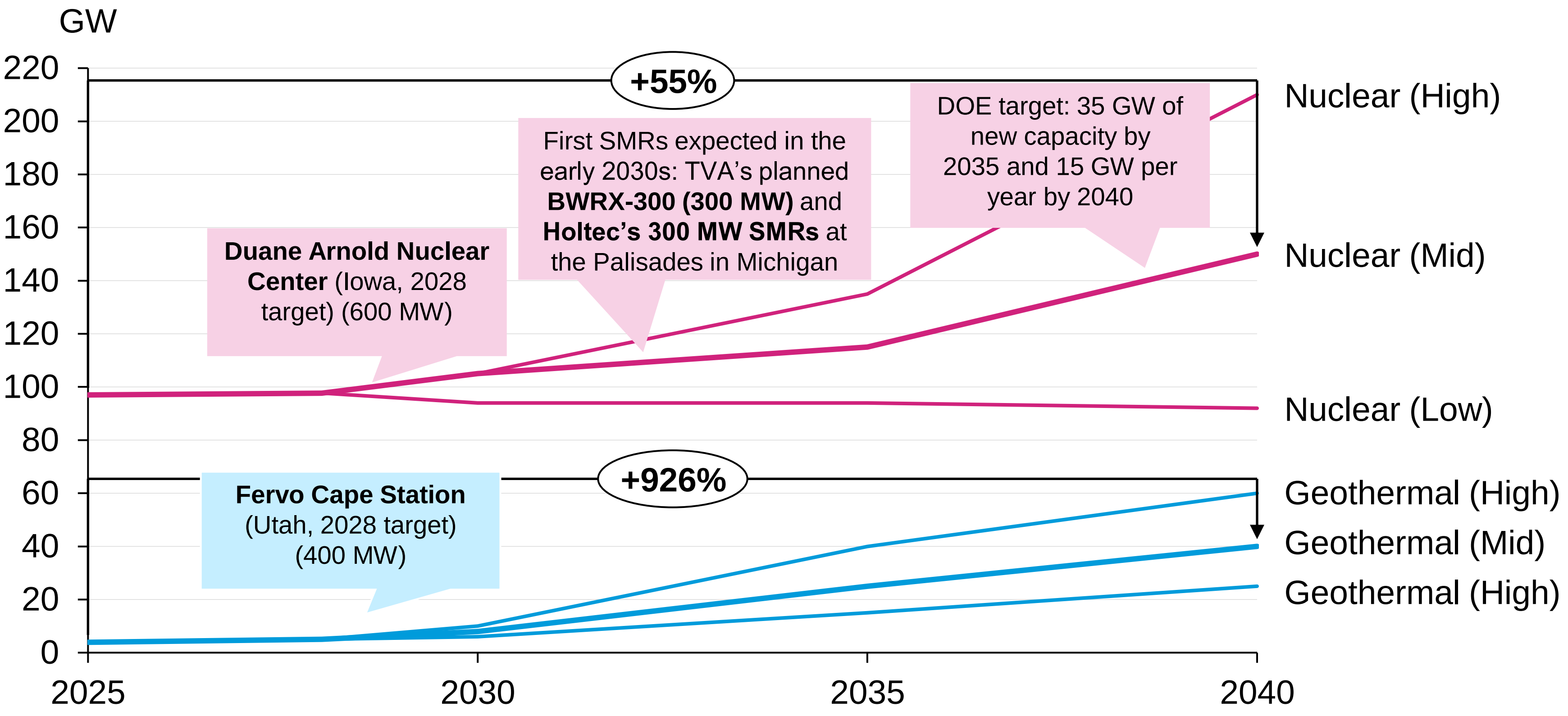
Geothermal power is bringing on new U.S. projects this decade while nuclear holds greater capacity, but the gap is narrowing

Installed capacity scenarios for traditional geothermal, next-gen geothermal, existing nuclear, and new nuclear builds in the United States, *GW*



Duane Arnold Nuclear Center (Iowa, 2028 target) (600 MW)

First SMRs expected in the early 2030s: TVA's planned **BWRX-300 (300 MW)** and **Holtec's 300 MW SMRs** at the Palisades in Michigan

DOE target: 35 GW of new capacity by 2035 and 15 GW per year by 2040

Fervo Cape Station (Utah, 2028 target) (400 MW)

Observations

Geothermal

- Today's U.S. geothermal fleet is small (~ 4 MW), but geothermal is **bringing new projects online this decade**, which drives faster near-term growth.
- Future scale depends on **technology progress, lower drilling costs, and access to project finance**.
- As next-generation geothermal expands, **the gap with nuclear capacity begins to narrow**.

Nuclear

- Nuclear holds **higher total capacity** because of its large legacy fleet.
- Near-term nuclear growth is limited, since **only one restart is expected before 2030**.
- New nuclear capacity depends on **long development cycles for SMRs and large reactors**.
- Nuclear's **long-term expansion occurs later in the 2030s**, once early SMR projects move into construction.

Sources: Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); Today in Energy: U.S. nuclear power plants (EIA, n.d.); NextEra Energy and Google Announce New Collaboration to Accelerate Nuclear Energy Deployment in the U.S. (NextEra Energy, 2025); Fervo Energy Breaks Ground on the World's Largest Next-Gen Geothermal Project (Fervo Energy, 2023); Is geothermal energy ready to make its mark in the US power mix? (McKinsey, 2025); Geothermal (NREL, n.d.); U.S. Sets Targets to Triple Nuclear Energy Capacity by 2050 (DOE, 2024); DOE Report Finds More Than 60 Gigawatts of New Nuclear Capacity Could Be Built at Existing Nuclear Power Plants (DOE, 2024).

Credit: Heather Hartel, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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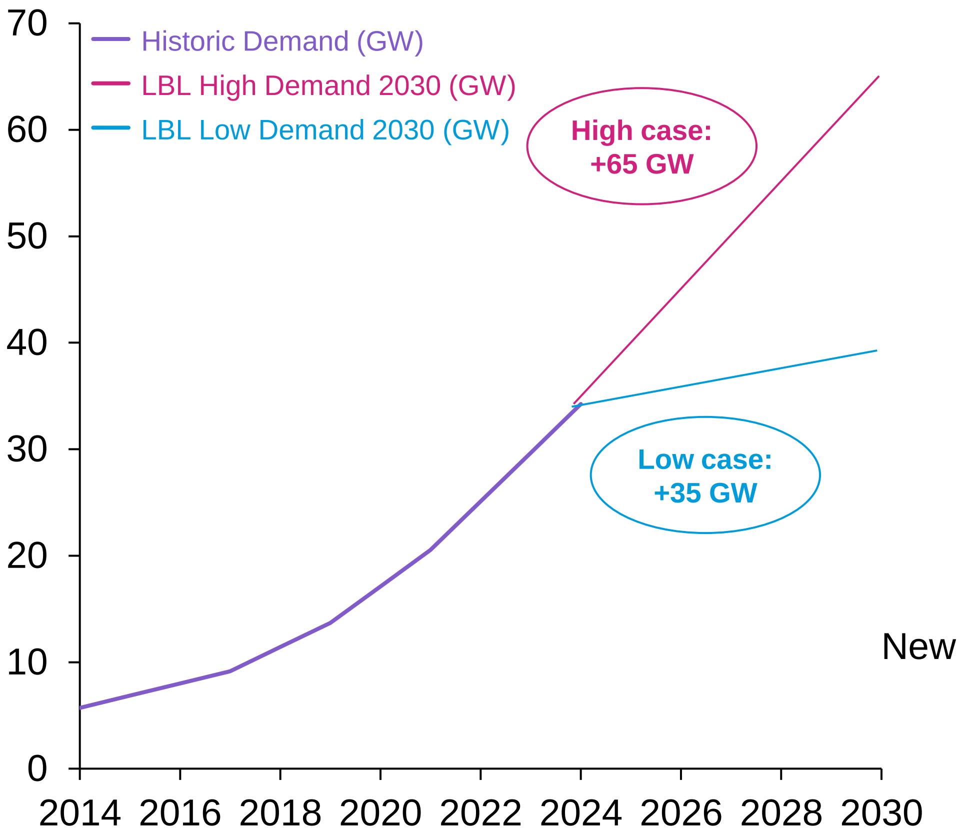
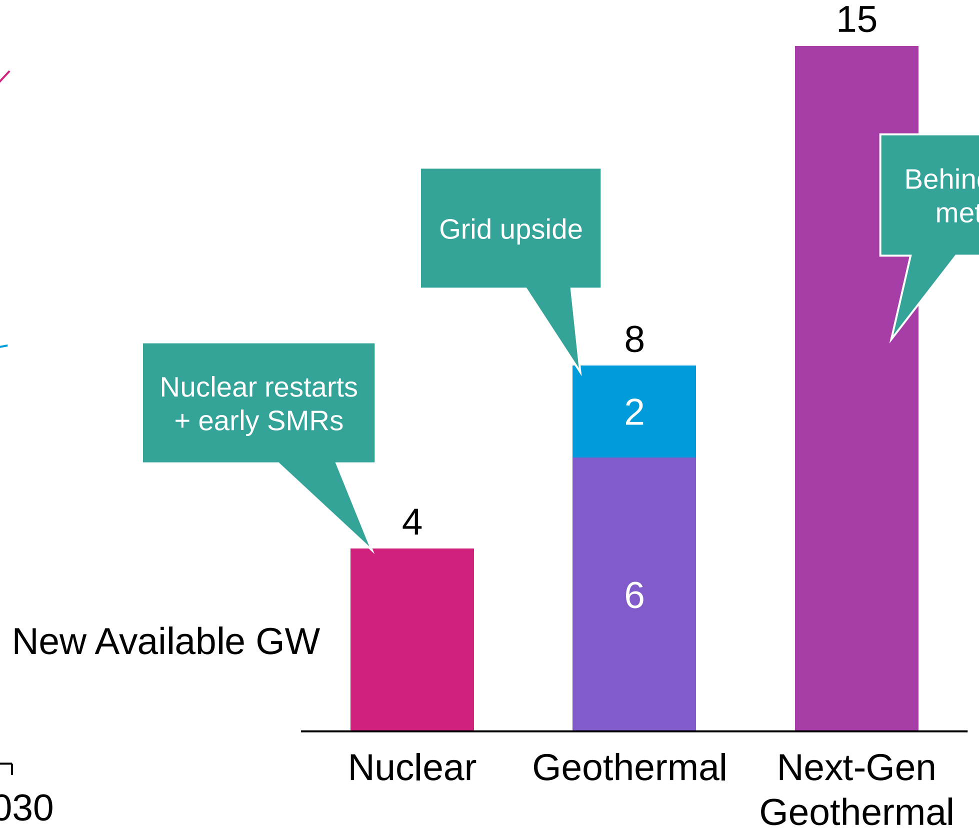
Increasing U.S. energy demand, largely driven by data centers, requires increased baseload supply of power

Projected growth in power demand from U.S. data centers



Incremental firm capacity by 2030



Observations

- Data centers could add more than **35 to 65 GW of firm power demand by 2030 in the U.S.**, equivalent to a large fraction of today's existing nuclear fleet.

  Nuclear restarts and SMRs provide only ~4 GW incremental capacity, which is meaningful but insufficient against projected demand growth.
- **Grid-connected geothermal adds 6 to 8 GW**, but that is also insufficient against projected demand.
- **Behind-the-meter geothermal (~15 GW)** could directly supply data centers, bypassing grid constraints and permitting bottlenecks.
- Innovation in drilling and permitting will determine **whether geothermal can scale fast enough** to complement nuclear in delivering zero-carbon baseload.

Sources: The Potential for Geothermal Energy to Meet Growing Data Center Electricity Demand (Rhodium Group, 2025); U.S. Data Center Energy Usage Report (Lawrence Berkeley Lab, 2024); Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); The Future of Geothermal Energy (IEA, 2024); Holtec Palisades Nuclear Plant Restart (U.S. Department of Energy Loan Programs Office, 2023); Microsoft signs 20-year PPA for Three Mile Island Nuclear Plant restart (Utility Dive, 2024); World Energy Outlook (IEA, 2024).

Credit: Heather Hartel, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Untapped geothermal potential is uniquely positioned to meet the growing demand for data center power

Reliable Baseload Power

- Geothermal offers 24/7 power that is ideal for baseload power and grid stability.
- Offers a high-capacity factor between 70 and 90%.
- Global estimated potential of 4,000 PWh/year if next-gen geothermal can unlock resources.

Declining LCOE for Next-Gen Geothermal

- $75 per MWh for EGS FOAK (unsubsidized) and $120-$150 MWh for ACL FOAK.
- McKinsey anticipates a decrease to $45-$75 per MWh for Nth of a kind next-gen geothermal.

Clean Energy

- Geothermal provides a **clean energy baseload resource**.
- Nuclear is far more capital-intensive and requires far more development time.
- Solar and wind are intermittent renewable resources that are not ideal for baseload power.

Potential for Build-to-Suit Data Center Solutions

- Behind the meter solution and decrease energy costs by avoiding transmission and grid interconnection costs.
- NREL and the DOE are exploring Cold Underground Thermal Energy Storage to support data center cooling. Geothermal can also support cooling water efficiencies..

Observations

- Geothermal provides reliable, the clean baseload power required for data centers.
- Existing technologies for conventional geothermal, oil and gas drilling, and mineral and geospatial exploration can be modified and improved to optimize geothermal development and decrease LCOE.
- Emerging and frontier geothermal technologies will find innovative, cost-effective ways to continue to reduce LCOE.
- Geothermal has other potential uses for cooling and water management for data centers.

Sources: Is geothermal energy ready (McKinsey, 2025); Reducing Data Center Peak Cooling (NREL, 2025); Harnessing the Heat (DOE, 2019); Geothermal Mythbusting: Water Use and Impacts (Fervo Energy, 2025); Global geothermal potential (IEA, 2024).

Credit: Stephanie Chen, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Microsoft, Google, and Meta lead geothermal power investment for data centers, while Amazon sticks to geothermal heating & cooling

Microsoft

Power

Microsoft's major capital investments, i.e., **$1 billion** project in Kenya with an initial capacity of 100 MW+, geothermal heating and cooling in its Redmond campus, **emphasizing large-scale generation in high-potential regions and operational energy efficiency.**

Microsoft & G42: $1B Digital Initiative in Kenya incl. Geothermal
May 2024 Microsoft

10-Year Agreement for Geothermal Power Station at Te Huka
May 2023 contact

Microsoft Opens Thermal Energy Center
March 2021 Microsoft

Google

Power

Google leverages geothermal energy through power purchase agreements and investments in enhanced geothermal systems, including 115 MW in Nevada and 10 MW in Taiwan, **focusing on baseload clean power, geographic expansion, and reducing regulatory barriers**.

Google Signs 10 MW Geothermal Energy Deal in Taiwan
April 2025 Google

Google Unlocks Geothermal with Fervo EGS systems
October 2024 TIME

Google Secures 115 MW Geothermal plant in Nevada
June 2024 Reuters

Meta

Power

Meta is developing a 150 MW geothermal plant in New Mexico using advanced geothermal methods to access non-traditional sites, with a **focus on scalable, always-on power for data centers and AI workloads**.

Meta Touts $1B Investment in Geothermal for Data Centers
June 2025 Source NM

Meta Signs Agreement with Sage Energy
April 2024 ESGDIVE

Amazon

Heating & Cooling

Amazon primarily employs geothermal heat pumps for heating and cooling in facilities, such as its fulfillment center in Japan, focusing on on-site energy efficiency and renewable energy matching rather than utility-scale power generation.

Amazon Unveils Geothermal, Solar-Powered Center in Japan
June 2025 ESG NEWS

Observations

- **Geothermal strategies vary:** Microsoft and Meta target **utility-scale, always-on geothermal** for data centers; Google combines PPAs with EGS investments; and Amazon focuses on **on-site efficiency** rather than baseload generation.
- **Location choices reflect resource and technology maturity:** Microsoft and Google invest in **established geothermal regions**, while Meta uses closed-loop players' methods to unlock **non-traditional sites**.

Sources: Our First Geothermal Energy Deal in Asia (Google, 2025); Google partners with Nevada Utility (Reuters, 2024); Tim Latimer (Time, 2024); Meta Inks geothermal deal (ESG Dive, 2024); Microsoft and G42 (Microsoft, 2024); Contact signs 10 year agreement (Contact Energy, 2023); Unusual machine in the woods (Microsoft, 2021); Amazon Unveils Geothermal (ESG News, 2025).

Credit: Zacharia Thurston, Thomas Smith, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Google signs first corporate geothermal agreement in Taiwan to power data centers and expand across the Asia-Pacific region

Google and Baseload Capital partner to develop 10 MW of geothermal in Taiwan

Baseload Capital is a global geothermal developer. Baseload Power Taiwan, a subsidiary, has explored geothermal resources since 2019.

Baseload Power Taiwan is the only geothermal developer in Taiwan. It actively partners with the government to implement regulatory frameworks for geothermal.

Google demonstrated its commitment to geothermal with an equity investment in Baseload Capital.

Google plans to accelerate geothermal across the Asia-Pacific region and utilize its learnings from the Taiwan project.

It partnered with the University of Newcastle to research geothermal energy potential in Australia.

Several tailwinds make Taiwan the ideal location for geothermal development

Net-Zero Commitment | Taiwan aims to be net zero by 2050

Taiwan’s 2023 energy mix was 35% coal, 34% oil, 24% natural gas, 4% nuclear, <2% other renewables, <2% other sources.

Proximity to Pacific Rim | Located near high-potential resources

Taiwan is located along the Pacific Rim, known for its volcanic activity. A 2016 study found that geothermal resources could be up to 160 GWe.

Geothermal Targets | Taiwan targets 6 GW of geothermal

Taiwan established incremental geothermal targets: 20 MW by 2025, 200 MW by 2030, 2 GW by 2040, and 6 GW of geothermal by 2050

Technology Hub | Taiwan as a center for AI Infrastructure

Taiwan announced its 10 Major AI Infrastructure Projects, which is expected to generate $520 billion-plus in economic value.

Sources: Our first geothermal energy deal in Asia (Google, 2025), Chinese Taipei (IEA, 2023); Taiwan’s Pathway to Net-Zero (Climate Change Administration Ministry of Environment, 2022); Taiwan plans AI projects (Reuters, 2025); The Geothermal Potential (Astrophysics Data System, 2016); Geothermal energy in Taiwan (Euroview, 2025); Unlocking Australia’s geothermal (Google, 2024).

Credit: Stephanie Chen, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

XGS signs its first commercial deal, partnering with Meta to develop 150 MW with zero operating water in New Mexico by 2029

Meta and XGS partner to develop a 150 MW geothermal plant to power data centers in New Mexico

XGS's proprietary solid-state, closed-loop system enables the production of geothermal energy with zero operating water use, which is significant in water-scarce regions such as New Mexico.

The project's first 5 MW are projected to be deployed around 2027, with the remaining by 2029.

Meta is seeking clean firm power to support the development of domestic data centers as AI technologies continue to scale.

Partnerships with clean energy innovators like XGS are key to securing energy supply for data center operations in the region. Meta also signed a purchase agreement for a Sage Geosystems planned 150 MW power plant in the Rocky Mountains in 2024.

New Mexico sets up to unlock next-generation geothermal potential

Geothermal potential | ~160 MW of potential for next-generation developers

New Mexico has the potential to tap into 160 MW of geothermal energy in the first 4 to 5 km of subsurface.

Skilled workforce | New Mexico has the second-largest U.S. oil and gas industry

The state is equipped with a vast workforce with significant transferrable skills that could help lower costs across all geothermal operations. It currently drills 1,000 wells per year.

Policy support | Financial incentives and 100% clean energy targets

Beyond mentioning geothermal energy in its constitution, New Mexico has a $15 million project development fund, a $0.15 tax credit, and regulations to help govern and grow the industry. The state also has strong renewable portfolio standards, targeting 80% clean energy by 2040 and 100% by 2045.

Sources: XGS Energy and Meta to partner (Business Wire, 2025); XGS Energy (XGS, 2025); New geothermal energy project (Meta, 2024); XGS Energy says its advanced geothermal tech is ready to scale (Canary Media, 2025); Geothermal in New Mexico (Project InnerSpace, 2025).

Credit: Ariela Farchi, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Fervo is leading EGS with advanced analytics to improve drilling and development with an emphasis on data center demand

May 2021
Fervo-Google Agreement

- **Fervo signs a landmark deal with Google** to deliver 5 MW of power through a first-of-a-kind geothermal project.
- Project to deliver power for Google's Cloud region in Nevada.
- In April 2021, Fervo raised a $28M Series B.

July 2023
Project Red Successful Well Tests

- Fervo completes well tests at its first-of-a-kind commercial pilot in Nevada.
- **Fervo becomes the first company to drill a horizontal well** for commercial geothermal.
- It achieves lateral length of 3,250 feet and 191℃.

September 2023
Cape Station Breaks Ground

- Cape Station targets 400 MW of power starting in 2026 and is fully operational by 2028.
- Expected to create 6,600 jobs and generate $437M in wages.

November 2023
Project Red Operational

- **Project Red begins delivering geothermal power to Google's data centers** just two years after their agreement.

February 2024
Cape Station Drilling Improvements

- Cape Station successfully drills 2100 ft. deeper than Project Red.
- Fervo demonstrates a **70% reduction in drilling time**.
- **Drilling costs decline significantly,** from $9.4M to $4.8M per well.

- Cape Station will deliver 100 MW by 2026 and 400 MW by 2028.
- Fervo targets first data center cluster in Utah.

June 2025
Sugarloaf Well Drilling at Cape Station

- Fervo drills to 15,765 feet and 520℉.
- Completes in 16 days of drilling, for a **79% reduction in drilling compared to DOE baseline**.
- An independent report identifies up to 5 GW of development in the Cape Station area.

Observations

- Fervo's advanced data analytics enables faster geothermal deployment, demonstrated by its record-breaking drilling and resource temperatures.
- The company's success is attributable to its horizontal drilling technology, from the oil and gas industry. It has also attracted oil and gas talent.
- Fervo utilizes real-time data and advanced analytics to assess subsurface characteristics to identify geothermal resources.
- Fervo has attracted significant funding traction. The company has gained community buy-in through economic and labor opportunities.

Sources: Google Taps Fervo (Canary Media, 2021); Fervo Energy Announces Technology (Fervo Energy, 2023); Fervo Energy Breaks Ground (Fervo, 2023), The Enhanced Geothermal Data Center Corridor (Fervo, 2025); A first of its kind geothermal project (Google, 2023); Fervo Energy Drilling results (Fervo, 2024); Fervo Energy Drills (Fervo, 2025).
Credit: Stephanie Chen, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

Temperature requirements and potential geothermal applications for key industrial processes

Temperature (ºC)	Industrial applications	Geothermal application
<100ºC	• Food & beverage processing • Textile processing • Paper processing	GHPs are most competitive for satisfying low-temperature industrial heat demand.
100-200ºC	• Paper & chemicals production • Auxiliary processes in cement production & food processing	Next-generation geothermal can provide midrange temperatures across a wide geography.
200-400ºC	• Petrochemical cracking • Cement & steel pre-processing • Aluminum smelting	Fuel combustion or direct electricity use will most likely remain necessary.

Geological conditions

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

Key industrial processes

- Paper & pulp mi
- Wood drying
- Dairy processin

Norske Skog

SEQUAL GIVE MORE

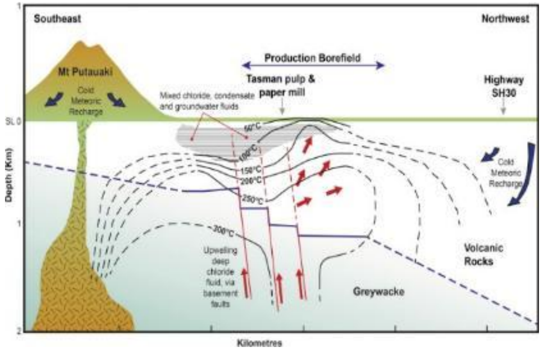
Oji Fibre Solutions

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 **170ºC**
- **~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); Kawerau Geothermal Field (New Zealand Geothermal Association, n.d.); Geothermal Operations.(Tūwharetoa Geothermal, n.d.).

Credit: Una Oljaca, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal power and geothermal heating & cooling show sectorial flexibility but remain rare in global deployment, despite savings potential

Emerging 🟥 🟨 🟩 Established

Opportunity Area	Integration Concept	Value Proposition	Locations
🟨 **District Energy Networks**	Supplying heating & cooling and power via geothermal-driven systems and distribution networks	Enables high total-energy efficiency in cities, on campuses, in communities	
🟥 **Industrial Clusters/ Eco-Industrial Parks**	Using geothermal heat/power for process heating, drying, and cooling in manufacturing or colocated industrial zones	Diversifies revenue, enhances resource utilization, creates industrial symbiosis	
🟨 **Tourism & Wellness**	Direct-use geothermal heat for spas, resorts, pools, wellness centers	Monetizes geothermal by-products, enhances public acceptance of geothermal energy	
🟥 **Agriculture & Aquaculture**	Geothermal-heated greenhouses, fish farms, food dehydration using geothermal heat	Enhances year-round productivity, reduces fossil fuel input, supports food systems	
🟨 **Building Energy Systems Data Centers**	Geothermal power supply and cooling (or heat reuse) for large thermal loads like data centers or buildings	Enables carbon-free baseload power, cooling efficiency, and waste-heat reuse	

Sources: Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); IEA (2023); GeoVision DOE (DOE, 2019); IPCC (2011); CKI analysis (2025).

Credit: Pia Doris Morrow, Faradisa Anintya, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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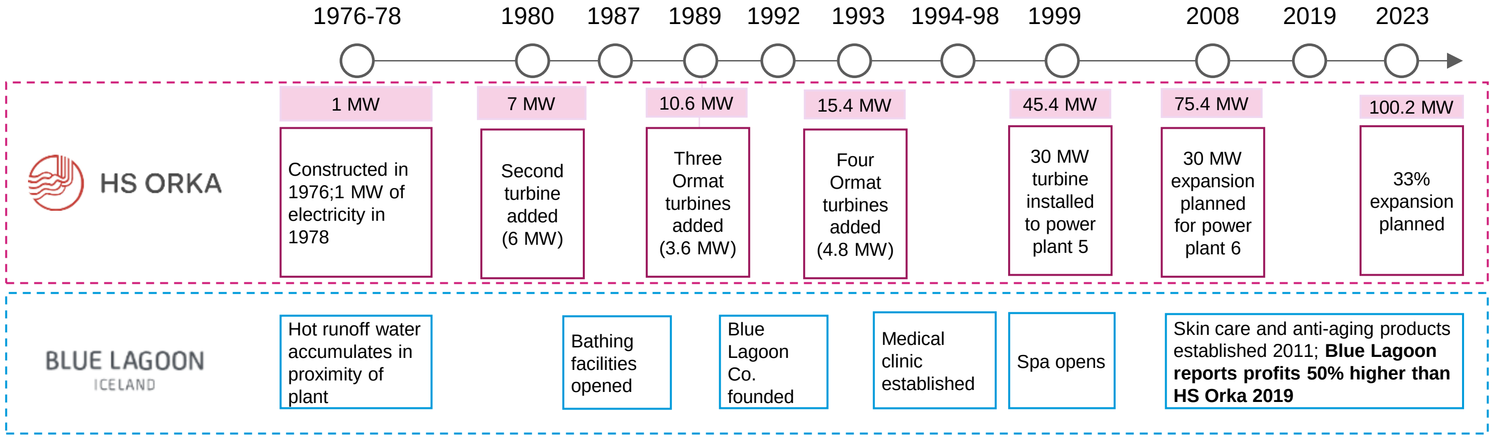
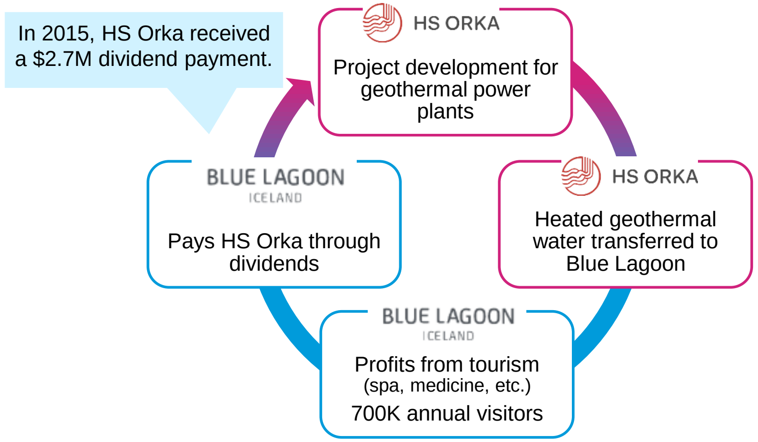
Iceland shows that leveraging heating and cooling provides greater financial security for geothermal power projects

Svartsengi Power Plant x Blue Lagoon enable national power and tourism dollars



	1976-78	1980	1987	1989	1992	1993	1994-98	1999	2008	2019	2023
HS ORKA	1 MW Constructed in 1976;1 MW of electricity in 1978	7 MW Second turbine added (6 MW)		10.6 MW Three Ormat turbines added (3.6 MW)		15.4 MW Four Ormat turbines added (4.8 MW)		45.4 MW 30 MW turbine installed to power plant 5	75.4 MW 30 MW expansion planned for power plant 6		100.2 MW 33% expansion planned
BLUE LAGOON ICELAND	Hot runoff water accumulates in proximity of plant		Bathing facilities opened		Blue Lagoon Co. founded		Medical clinic established	Spa opens		Skin care and anti-aging products established 2011; **Blue Lagoon reports profits 50% higher than HS Orka 2019**	

Co-ownership unlocks economic co-benefits



In 2015, HS Orka received a $2.7M dividend payment.

HS ORKA
Project development for geothermal power plants

HS ORKA
Heated geothermal water transferred to Blue Lagoon

BLUE LAGOON ICELAND
Profits from tourism
(spa, medicine, etc.)
700K annual visitors

BLUE LAGOON ICELAND
Pays HS Orka through dividends

Blue Lagoon co-ownership built a resilient, diversified business model

Power — Orka Financial Highlights (2015)

- EBITDA: $21M | Gross profit: $15M; FX-adjusted growth of +1% and +7%
- Revenue: $5.5M from staff transfer; retail sales +13% YoY.
- **Net income loss $1.9M driven by $24.7M non-cash derivative loss tied to aluminum prices**

H&C + Power — Blue Lagoon Impact

- **Dividend: $2.7M from spa operations**
- **Income from associates: +78% to $8.9M**
- One-time $2M gain from share issuance

Operational Strength

- **Loan repayments: $17.5M**
- Continued dividend payouts to shareholders

Sources: Svartsengi Power Plant (HS Orka, n.d.); Blue Lagoon (Blue Lagoon, n.d.); Iceland – Blue Lagoon (Business Insider, 2023); How spa operations lifts profits for Icelandic geothermal power company (ThinkGeoEnergy, 2016).

Credit: Zacharia Thurston, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

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

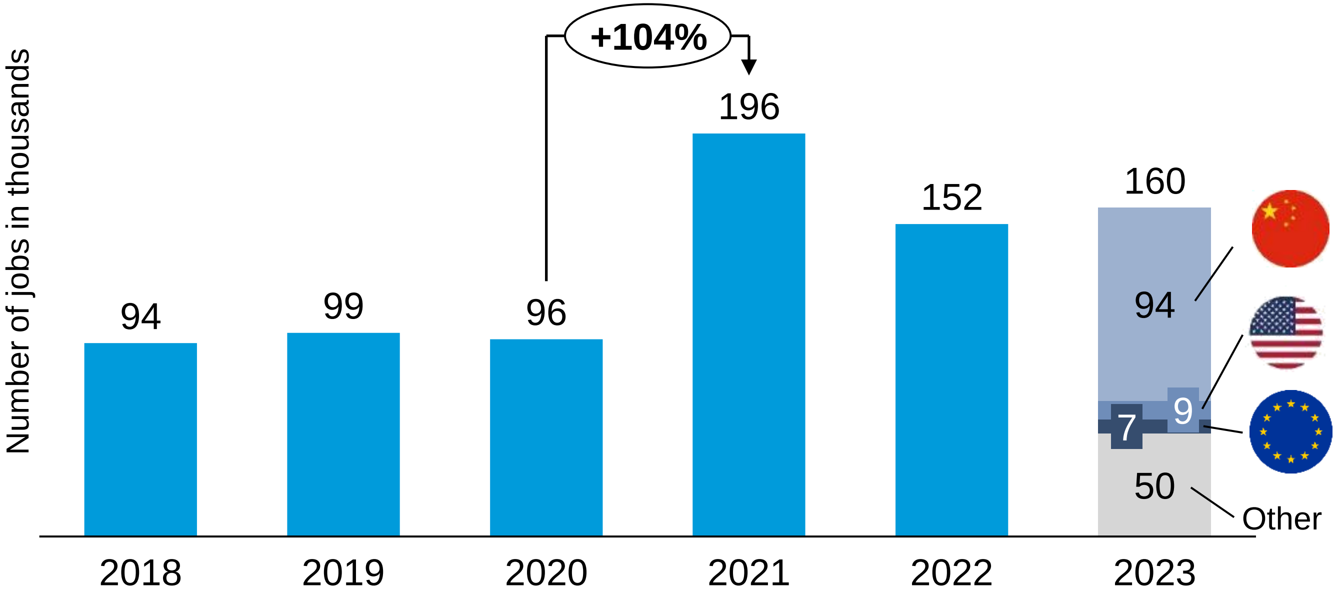
Problem	Current Challenge	Oil & Gas Synergy	Limitations	Case Example
Resource Identification ●●●●○	Accurate **geothermal resource identification and modeling** require multi-parameter surface data (seismic, geology, heat flow, permeability).	Oil & gas surface imaging and drilling data **reduce exploration risk and improve reservoir targeting**.	Legacy O&G datasets often **lack thermal gradient resolution or long-term heat recharge data**.	**Hungary** and **The Netherlands:** Open oil & 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 & 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, multi-stage stimulation) can be **directly transferred to EGS.**	Geothermal wells require **sustained reinjection and higher temperature tolerance** than oil & gas 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 Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Expanding the geothermal workforce through education, automation, and oil & gas talent transition is essential to compete

Global number of geothermal energy jobs (2018-2023)



- Global geothermal employment more than **doubled from 96,000 to 196,000 in 2021**. In contrast, oil & gas employed 12.4 million people in 2023 (a 5% annual increase).
- **China leads in geothermal jobs,** while the **U.S. and EU must expand technical training and re-skilling to stay competitive**.
- Next-generation geothermal growth will depend on **cross-sector training pipelines and digital automation**.

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).

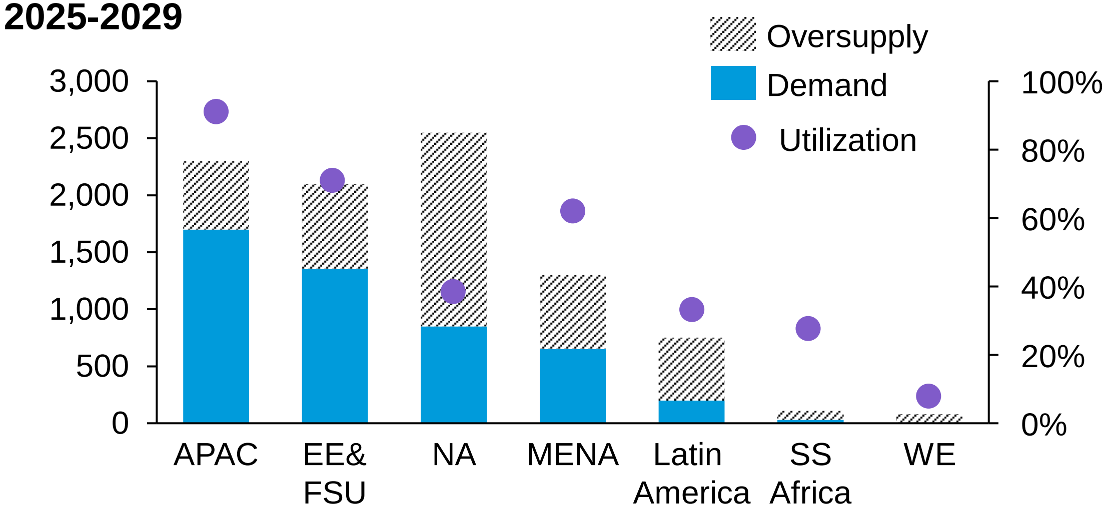
Credit: Pia Doris Morrow, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

While North American land rigs are underutilized, geothermal rigs equipped with over 2,000 horsepower are in short supply

Need for production shift from general land rigs to geothermal 2,000+ HP rigs

Global land rig supply vs. geothermal 2,000+ HP rigs

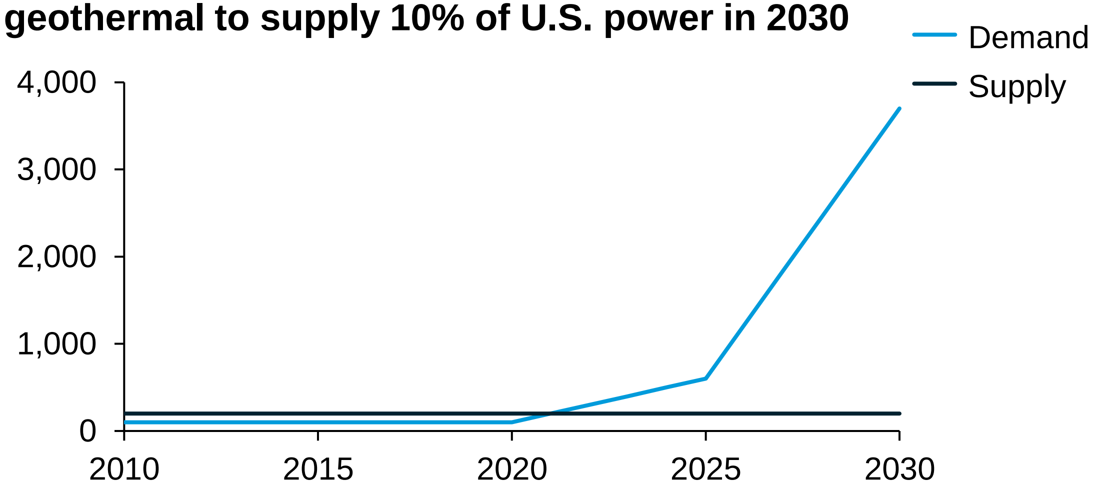
Average land rig supply, demand and utilization by region 2025-2029



Source: Westwood World Land Drilling Rig Market Forecast 2025-2029 (2025)

- Global rig demand is forecast to average **4,704 units between 2025 and 2029**, an 18% increase on historical averages, with Asia Pacific leading at 36% (China remains the largest market), followed by Eastern Europe (27%) and North America (17%).
- Although North America has the largest fleet, its rigs are **underutilized**, averaging only 33% utilization.
- However, these figures apply to all land rigs — geothermal rigs require **special prerequisites** to meet operational demands, such as horsepower.

Demand and supply forecast of 2,000+ HP rigs for geothermal to supply 10% of U.S. power in 2030



Source: GRC Transactions: Supply Chain Challenges (2012).

- Rigs for EGS need a minimum **of 2,000 HP** to reach the required depths of **2,000-10,000 meters for EGS drilling**.
- Only about **5% of the current rig supply** meets this horsepower specification.
- **Most rigs** with 2,000+ HP are already **used for oil & gas drilling**, leading to a constrained supply for EGS drilling that is unlikely to change without a significant shift in demand.

Sources: Westwood World Land Drilling Rig Market Forecast 2025-2029 (2025); Supply Chain Challenges (GRC Transactions, 2012).

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

Traditional oil and gas service companies provide consulting, drilling, and technology to the geothermal industry

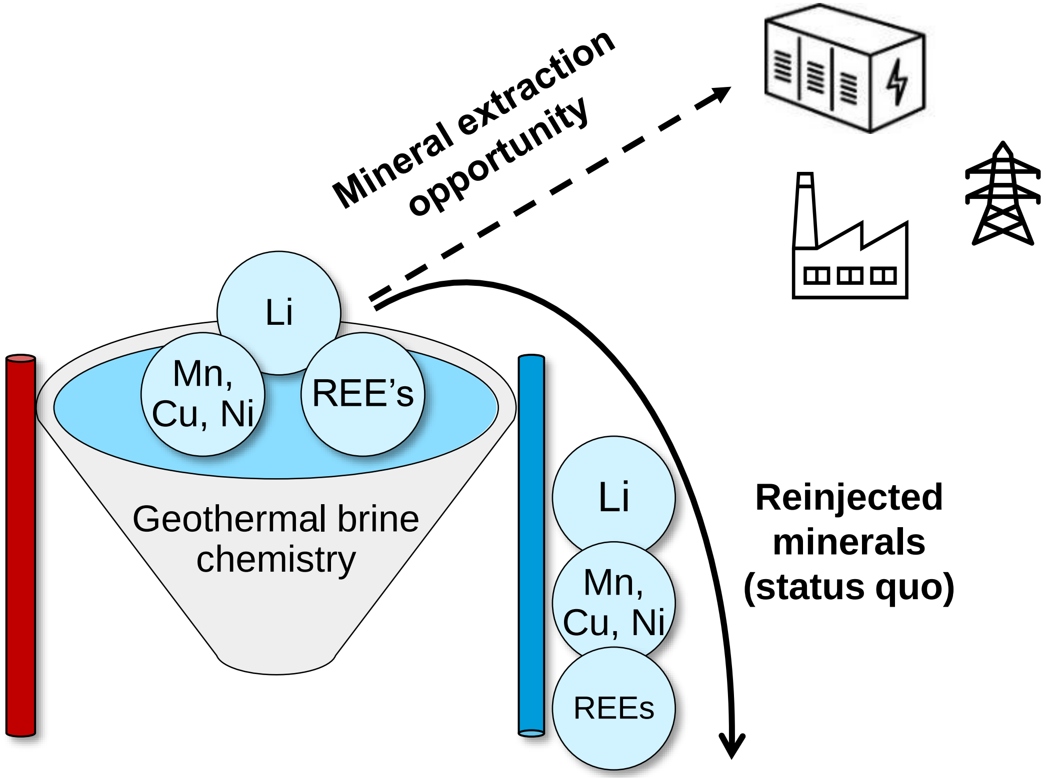
Scale	Schlumberger	Baker Hughes	Halliburton
Geothermal-Specific Capabilities	• GeothermEx, a Schlumberger subsidiary, involved in 80% of geothermal projects worldwide • Resource exploration, development, design, construction, operations, and technical support • Equipment: drill bits, fluid control systems, submersible pumps • Ground source heat pumps	• Geothermal turbines for both steam flashing applications and lower enthalpy Organic Rankine Cycle applications • Geothermal drilling solutions (drill bits, mud motors, wellpath controls, etc.) • Strategic investing partner in next-gen geothermal • Equipment, products, and services on over 1,800 geothermal wells across 25 countries	• 70 years of experience on global geothermal projects • Consulting, project management, and equipment • Subsurface intelligence, well construction and completion, production systems
Partnerships	ORMAT DEEP star energy geothermal	FERVO ENERGY CTR BASELOAD CAPITAL	Eavor™ GEOFRAME ENERGY CeraPhi energy FERVO ENERGY
Achievements and Recent Progress	• Selected by U.S. DOD to research geothermal electricity potential of U.S. military sites. Schlumberger will partner with Ormat to provide end-to-end geothermal power solutions. • Joint demonstration project in partnership with Ormat to fast-track EGS at existing Ormat site. • Mount Ida Geothermal Power Plant (Türkiye): Employed Schlumberger's electric submersible pump systems, which enabled well stimulation to increase expected output of 10 MW to actual output of 12 MW.	• BH's proprietary geothermal drilling components enabled drilling and operation of the deepest and hottest geothermal well ever drilled in Iceland (15,285 feet, max. temp 426℃). • Selected by Fervo to design and deliver equipment for five Organic Rankine Cycle power plants at Fervo's Cape Station power. • Collaborating with Controlled Thermal Resources on 500 MW Hell's Kitchen project in California.	• Engineering and project management support to CeraPhi as it builds it's first UK geothermal power project. • Planning and design of geothermal wells in East Texas for GeoFrame Energy. The geothermal electricity will power lithium extraction. • Custom drilling fluid solutions and cement at Fervo's Cape Station project

Sources: Schlumberger Geothermal (Schlumberger, n.d.); Schlumberger Geothermal (Star Energy (Indonesia) Partnership SLB, n.d.); Schlumberger Geothermal (SLB Ormat Partnership, n.d.); Schlumberger Geothermal (SLB Partnership Türkiye, n.d.); Baker Hughes (Baker Hughes Fervo Selection, n.d.); Baker Hughes (Iceland & Baker Hughes, n.d.); Baker Hughes (Baker Hughes Solutions, n.d.); Baker Hughes (CTR Baker Hughes, n.d.); Eavor (Halliburton Eavor, n.d.); Halliburton (Halliburton Fervo, n.d.); GeoFrame (Halliburton, n.d.); Halliburton (Halliburton, n.d.); Halliburton (Halliburton, n.d.).

Credit: Thomas Smith, Zacharia Thurston, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Mineral extraction from geothermal brines before reinjection offers an untapped domestic source for clean energy transition materials

Geothermal brines can be a significant source of critical minerals



Opportunity

01	Diversify project revenue by **co-producing lithium and rare earth elements**.
02	**Utilize existing brine reservoirs** with proven mineral content.
03	Deploy **emerging direct lithium extraction technologies** to monetize brines without disrupting power generation.

Challenges

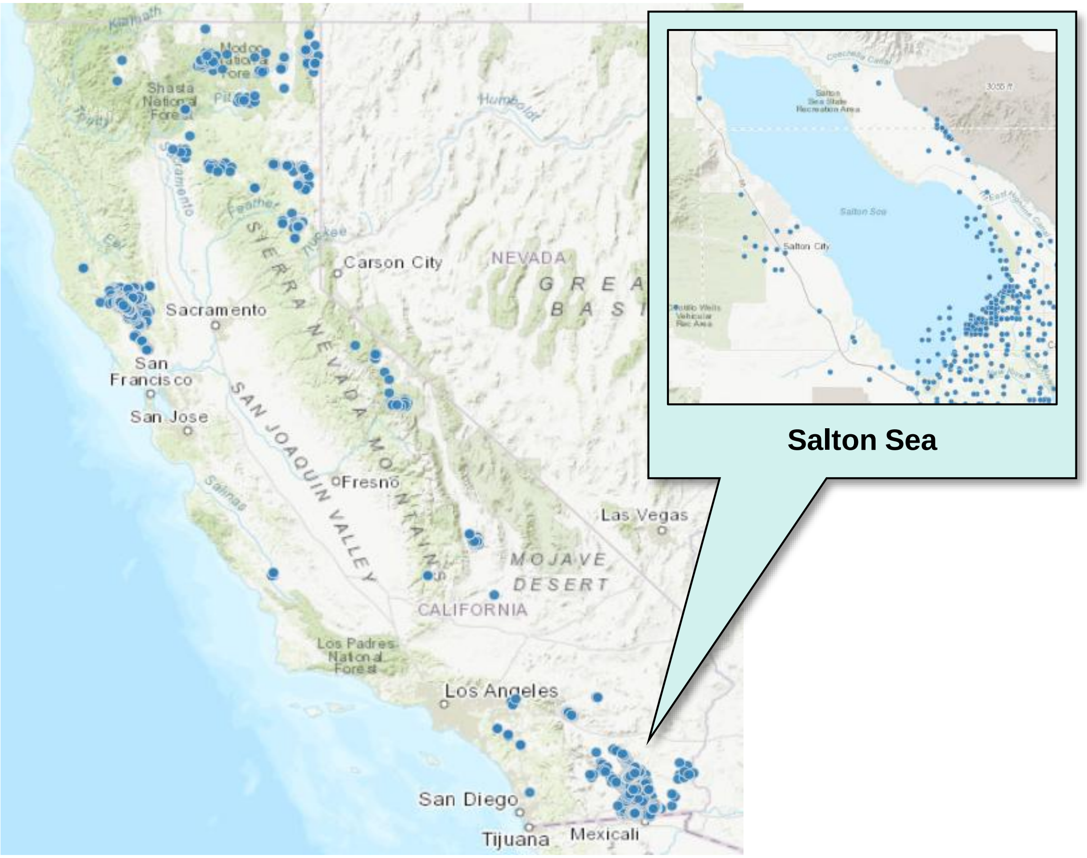
01	Technology **integration and compatibility** of DLE efficiency and brine chemistry vary across sites.
02	Mineral recovery may **disrupt flow rates, scaling, or reinjection balance**.
03	**High CapEx and unclear revenue streams** make prioritization difficult.

Sources: Geothermal Brine Composition in the Salton Sea (California Energy Commission, 2024).

Credit: Thomas Smith, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

California's Salton Sea has one of world's highest lithium brine concentrations, with commercial DLE projects underway

Geothermal-Li co-production at Salton Sea could anchor a domestic battery supply chain



Direct lithium extraction (DLE) potential in Salton Sea:

- Over **4 million tons** of lithium, enough to support **10,000 GWh** of battery capacity.
- Existing advantage: **Extensive geothermal infrastructure enables rapid DLE scale-up.**
- Could supply **~40% of global lithium demand** if fully developed.

Commercial DLE projects underway:

① **Hell's Kitchen:** Controlled Thermal Resources
  - Potential: 175,000 tons per annum
  - Technology: Koch proprietary DLE
  - Funding: $285M invested to date

② **Project ATLiS:** EnergySource Minerals (ESM)
  - Potential: 20,000 tons per annum
  - Technology: ESM proprietary DLE
  - Funding: Direct loan up to $1.36B from DOE

Sources: Salton Sea Reserve Estimate, Lawrence Berkley National Laboratory (2023); GIS Data and Map, California State Geoportal (2025).

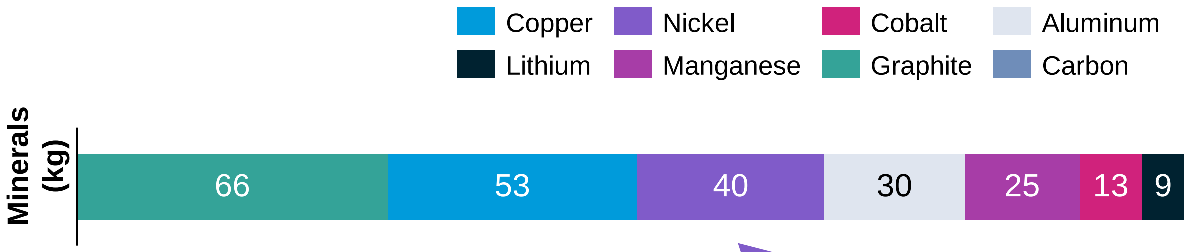
Credit: Thomas Smith, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Using geothermal energy to process Indonesia's nickel reserves can significantly reduce EV battery lifecycle GHG emissions

Indonesia

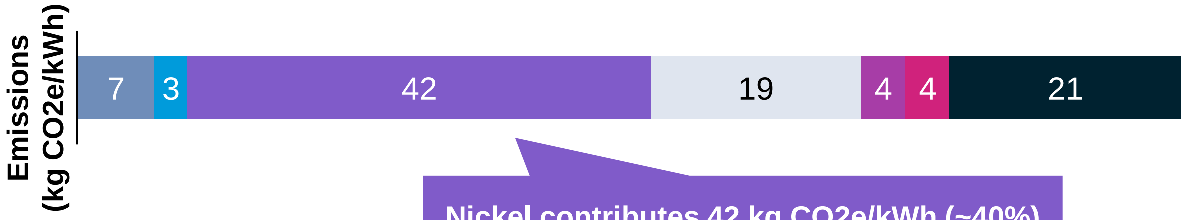
Challenge: High emissions from nickel-intensive EV battery

Minerals required for NMC EV battery, kg



~40 kg of nickel is required for an average electric vehicle.

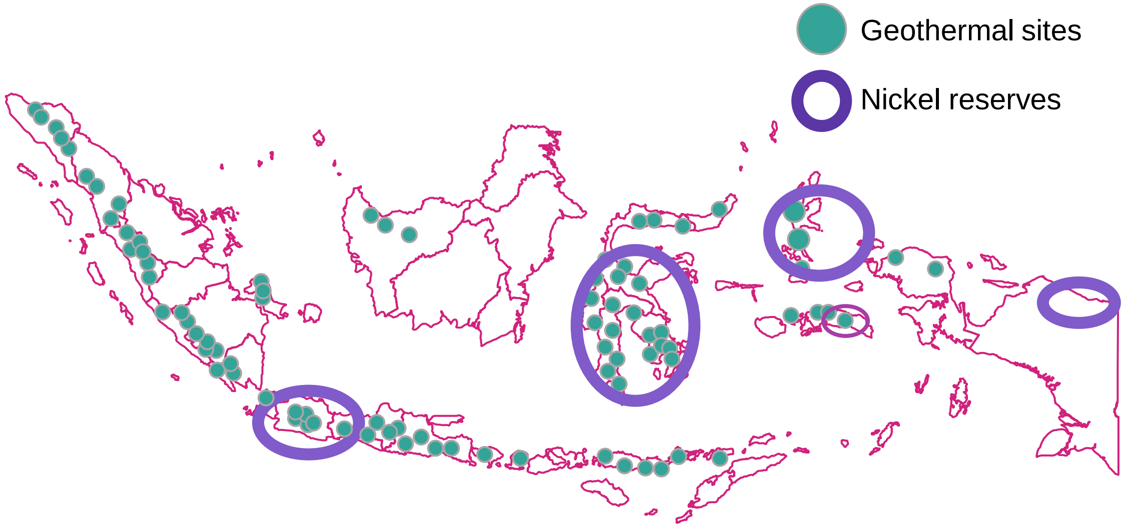
Emissions by raw material, kg CO_2e/kWh



Nickel contributes 42 kg CO2e/kWh (~40%) of EV battery raw material emissions.

Opportunity: Geothermal power to decarbonize nickel refining

- **61%** of all nickel used for EV batteries comes from Indonesia.
- **40%** of global geothermal reserves are also in Indonesia.
- Integrating geothermal energy into refining can **cut nickel processing emission based on modeled clean-heat substitution**.
- Potential pilot regions: Sulawesi, Sumatra, and Java, where nickel and geothermal collocate.



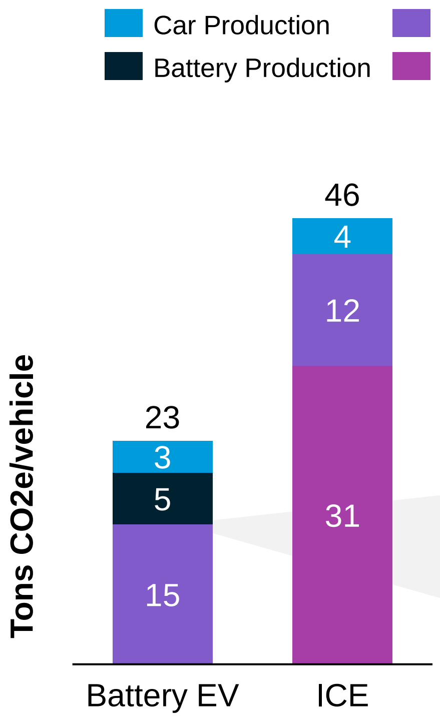
Sources: Indonesian Government Study (Geothermal Sites, 2024); International Energy Agency (IEA, 2022); International Energy Agency (IEA, 2021); Deloitte Study Indonesian Geothermal Reserves (Deloitte, 2025); S&P Global Indonesia - Mining by the Numbers (S&P, 2023); Toward security in sustainable battery raw material supply (McKinsey, 2024); Geographic Distribution of EV Supply Chain (IEA, 2025).

Credit: Thomas Smith, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal power can eliminate upstream nickel emissions and lower EV lifecycle carbon intensity

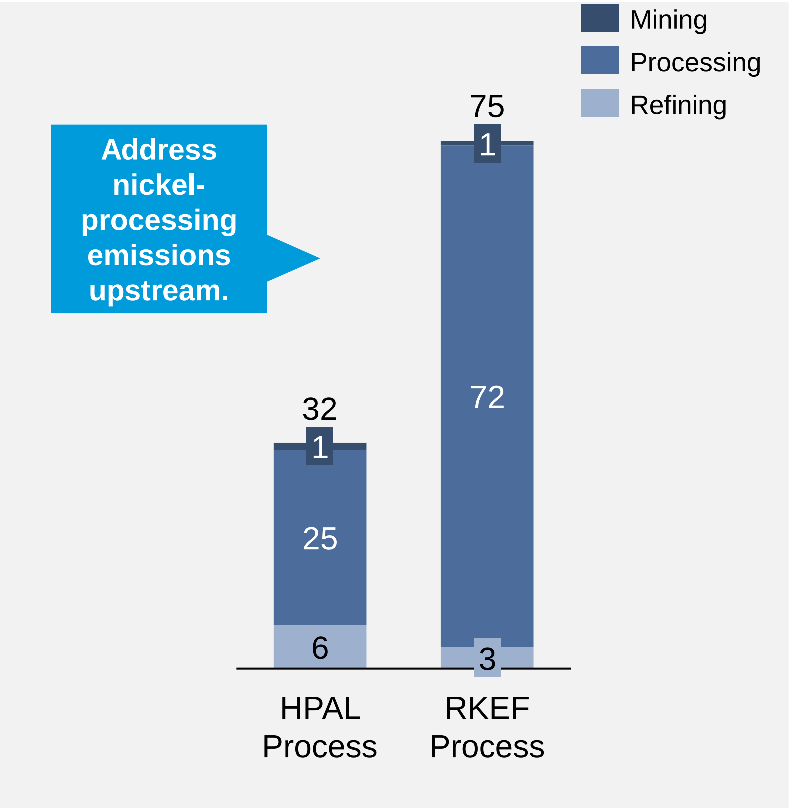
Battery production dominates EV lifecycle emissions

GHG emissions comparison between EV and ICE, tons CO_2e/vehicle



Processing and refining steps drive the majority of nickel carbon footprint

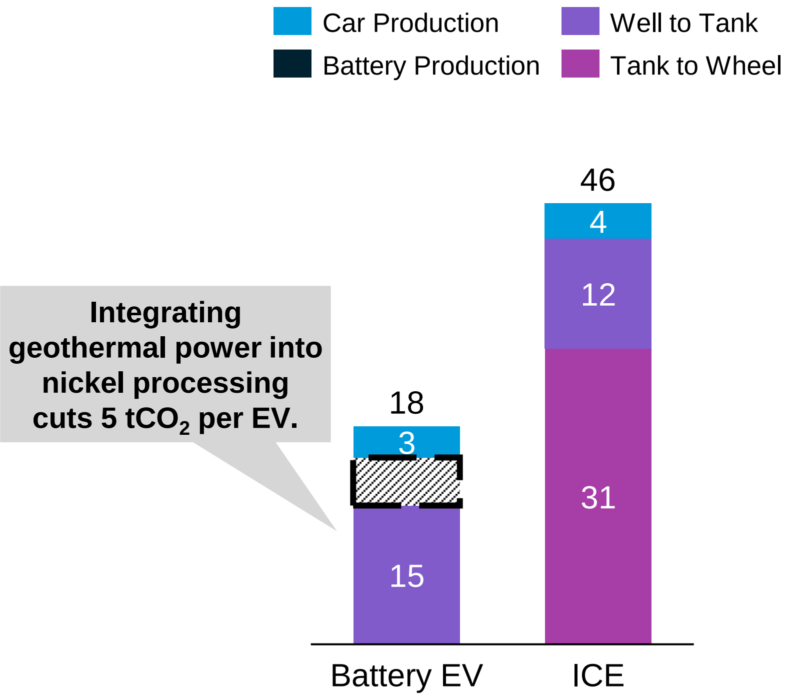
GHG emissions by nickel production step mtCO$_2$/ton of nickel



Address nickel-processing emissions upstream.

Replacing fossil energy with geothermal power can cut EV lifecycle emissions by ~25%

GHG emissions comparison between EV and ICE, tons CO_2e/vehicle



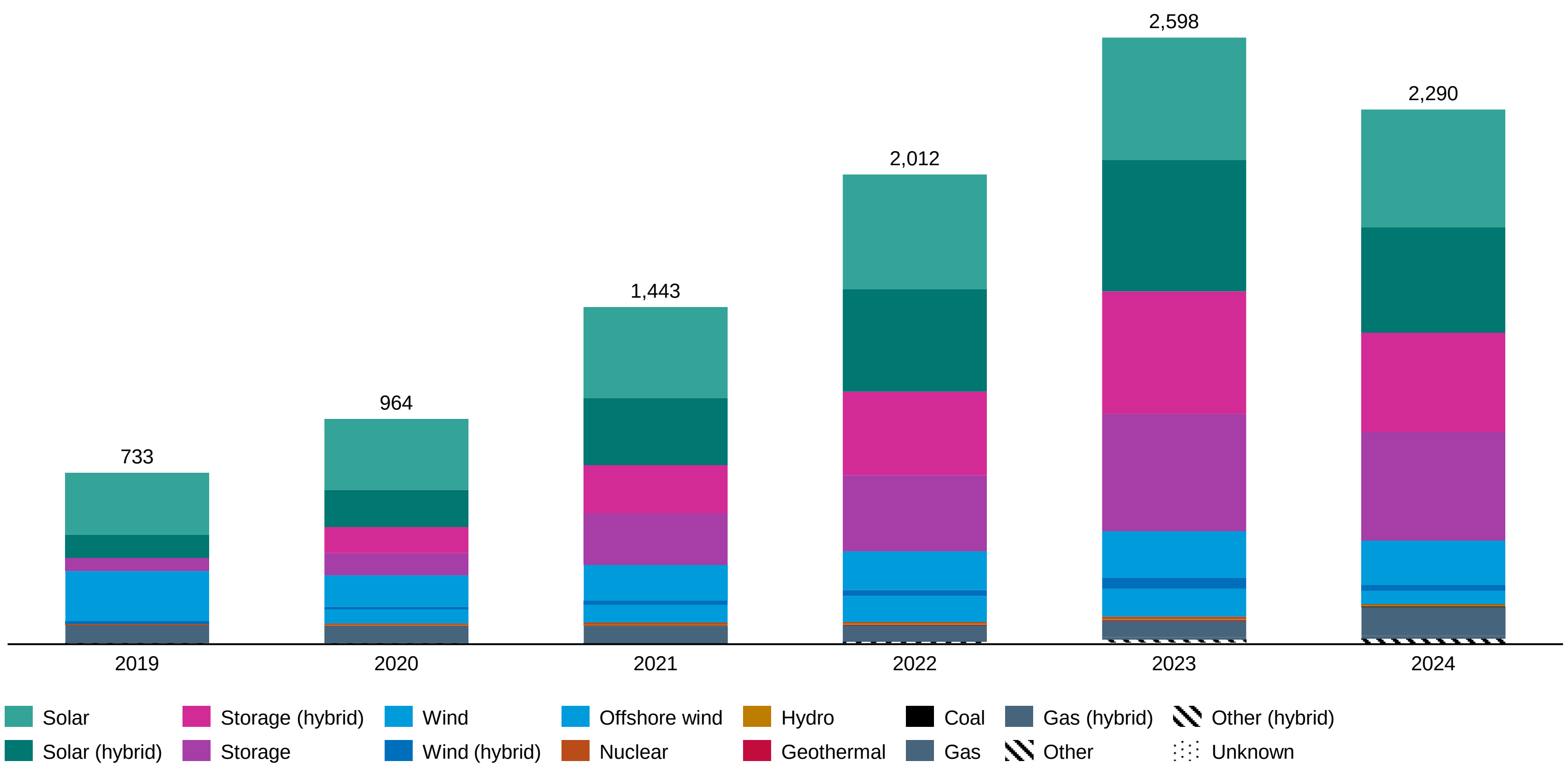
Integrating geothermal power into nickel processing cuts 5 tCO_2 per EV.

Sources: Toward security in sustainable battery raw material supply (McKinsey, 2024); IEA comparison of global average lifecycle emissions by powertrain (IEA, 2023).

Credit: Thomas Smith, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

Queue composition (95% variable renewables, <1% firm resources) highlights structural interconnection barriers to geothermal scalability

U.S. interconnection queue by energy sources, cumulative GW



Observations

- Data centers, electrification, and reshoring are pushing load growth 10 times faster than in the previous decade, but the grid has not expanded in parallel.
- LBNL finds 2.6 TW of queued capacity vs. 1.28 TW installed — driven overwhelmingly by solar, hybrids, and storage.
- Projects took <2 years in 2008, ~3 years in 2015, and nearly 5 years in 2023, with costs rising 44% in the past five years.
- Only 20% of projects (2000 to 2018) reached COD; >70% withdrew, often because transmission upgrades triggered by other projects caused cascading restudies.
- Outdated lines, limited hosting capacity, and project-by-project upgrade triggers create multiyear delays irrespective of technology.
- Recent BLM emergency permitting procedures have fast-tracked geothermal projects, helping offset the long delays created by the interconnection backlog

Sources: Grid connection barriers to renewable energy deployment in the United States (Berkeley Lab, 2024); Generation, Storage, and Hybrid Capacity in Interconnection Queues (Berkeley Lab, 2025); Emergency Permitting for Geothermal (Bureau of Land Management, 2025).
Credit: Shubhangi Prasad, and Gernot Wagner. Share with attribution: Wagner *et al.* "Geothermal Power," Columbia Business School Climate Knowledge Initiative (10 March 2026).

Geothermal faces structural barriers across permitting, transmission, and interconnection, but new pathways are beginning to unlock deployment

Structural barriers facing geothermal

01. Complex, multilayer permitting slows development, with dual federal-state reviews and sensitive-resource checks extending timelines far more than for wind and solar.

02. High upfront exploration costs increase financial risk, with $5-$10M for site characterization and up to $450M for full next-gen resource confirmation before PPAs are secured.

03. PPA uncertainty constrains bankability, since geothermal requires large sunk costs before revenue agreements are locked in.

04. Transmission distance and interconnection costs erode project economics, as remote resources face expensive upgrades and long IQ delays.

05. The interconnection queue structurally disadvantages long-lead clean firm resources, with 95% of queued capacity coming from solar, wind, and storage.

Emerging pathways that can improve geothermal deployment

01. Behind-the-meter deployment offers a near-term geothermal pathway, allowing industrial loads and data centers to bypass interconnection entirely.

02. BLM emergency permitting creates faster federal approval routes, with 14-day reviews for select geothermal activities.

03. Streamlined permitting practices, including tiering, MOUs, and integrated reviews, can materially reduce delays without weakening environmental rigor.

04. Next-generation geothermal (EGS, closed-loop) expands the viable subsurface resource base, reducing dependence on rare hydrothermal conditions.

05. Federal tax credits, DOE's Enhanced Geothermal Shot, plus a goal to reduce EGS costs 90% by 2035 improve project economics, supporting early commercial deployment.

Sources: Emergency Permitting for Geothermal (Bureau of Land Management, 2025); Is geothermal energy ready to make its way into the US energy mix (McKinsey, 2025); How the Interconnection Backlog Is Slowing Energy Growth (Uchicago, 2025); Clearing the Path for Renewable Geothermal Project Deployment (NREL, 2023); Issue Brief (Citizens for Responsible Energy Solutions, 2023).

Credit: Shubhangi Prasad, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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Climate Knowledge Initiative

Geothermal power maturity and deployment is in reach as tech investment and policy continue to co-work and de-risk projects

Current state of geothermal heating and cooling vs. electricity generation

Emerging 🟥 🟨 🟩 Established

		Heating, cooling, and thermal energy storage		Electricity generation	
Scale & Momentum	**Main stakeholders**	Governments, municipalities, real estate developers, industries, energy utilities		Energy utilities, governments, investors, technology firms, industrial users	
	Scalability	🟨🟨⬜	Moderate (local and regional impact)	🟩🟩🟩	High (grid-scale impact)
	Market momentum	🟩🟩🟩	In action (transitions happening now)	🟨🟨⬜	First movers
Deployment	**Speed of deployment**	🟨🟨⬜	Faster (months to a few years)	🟥⬜⬜	Slow (5-10+ years)
	ROI timeframe	🟨🟨⬜	Moderate (5-10 years)	🟥⬜⬜	Long (10-30 years)
Policy & Financing	**Industry & policy demand**	🟩🟩🟩	Strong	🟨🟨⬜	Emerging
	Funding availability	🟩🟩🟩	High (government incentives for urban decarbonization)	🟥⬜⬜	Limited (large-scale investments with long return periods)
	Risk & uncertainty	🟩🟩🟩	Low (proven technology, well-established market)	🟥⬜⬜	High (geological risks, high upfront costs)
Technology	**Technical & regulatory barriers**	🟩🟩🟩	Low (fewer permits, well-established technology)	🟥⬜⬜	High (complicated permits, deep drilling risks)
	Conversion efficiency	🟩🟩🟩	High (300-500% for heat pump COP)	🟥⬜⬜	Low (10-20% for binary plants, 10-15% for flash systems)
	Capacity factor	🟨🟨⬜	Seasonal, lower utilization in warm climates	🟩🟩🟩	High (70-90%), base-load capable
	Depth of drilling	🟩🟩🟩	Shallow (tens to hundreds of meters)	🟨🟨⬜	Deep drilling (1-5 km+), depending on resource

Sources: Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); IEA (2023), GeoVision DOE (2019); IPCC (2011), CKI analysis (2025).

Credit: Pia Doris Morrow, Faradisa Anintya, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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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

Sources: CKI analysis in accordance with IEA guidelines (2025).

Credit: Pia Doris Morrow, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

Sources: CKI analysis in accordance with IEA guidelines (2025).

Credit: Pia Doris Morrow, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Power,” Columbia Business School Climate Knowledge Initiative (10 March 2026).