Columbia Business School
Climate Knowledge Initiative

10 March 2026

Geothermal Power and Electricity

Executive Summary

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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).

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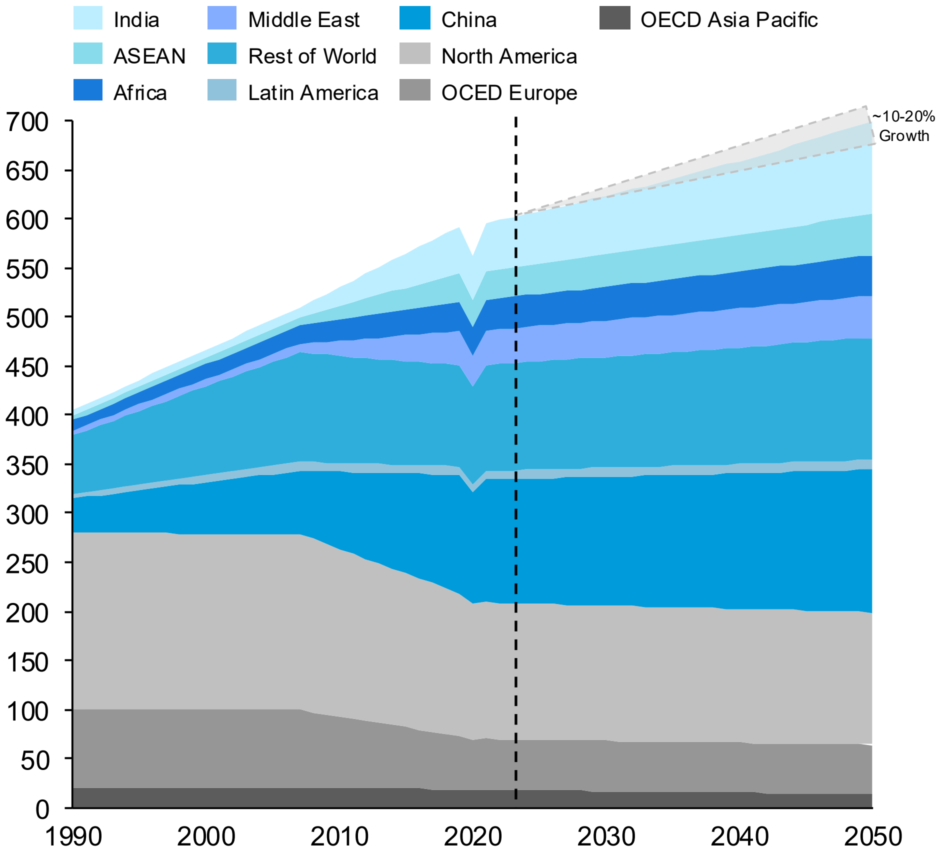
Global energy demand expected to grow ~10-20% by 2050, largely driven by emerging economies, electrification, and data centers

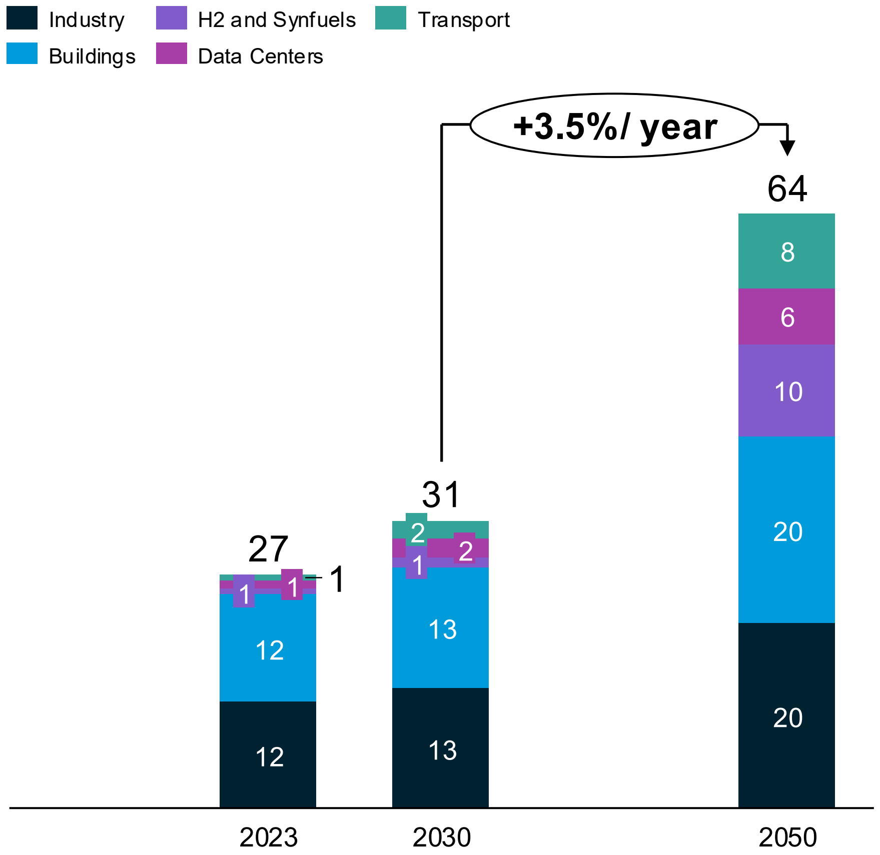
India, ASEAN*, Africa, and the Middle East will be responsible for ~65-95% demand growth

Global primary energy demand (million TJ)



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

Global power consumption by sector (thousands of TWh)



Observations

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

*Association of Southeast Asian Nations

Sources: Global Energy Perspective (McKinsey, 2024).

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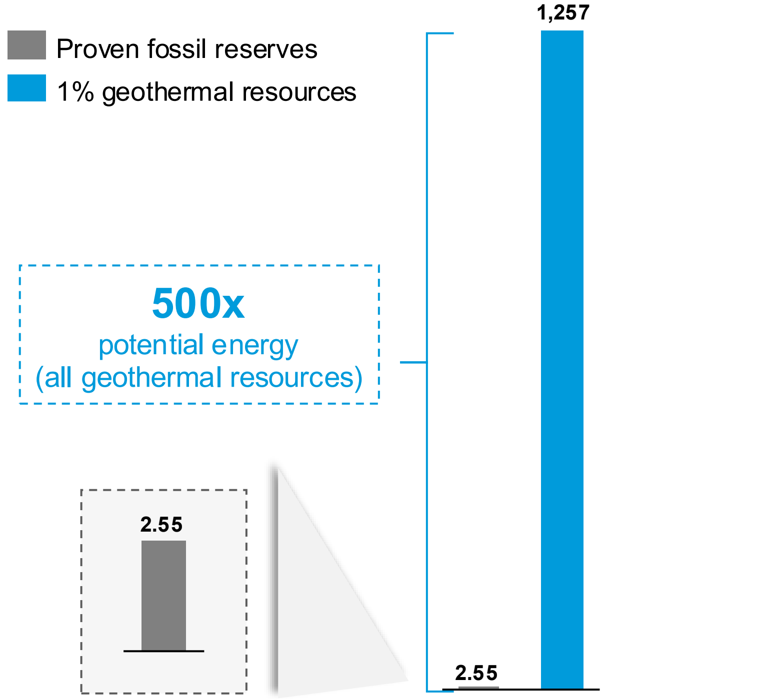
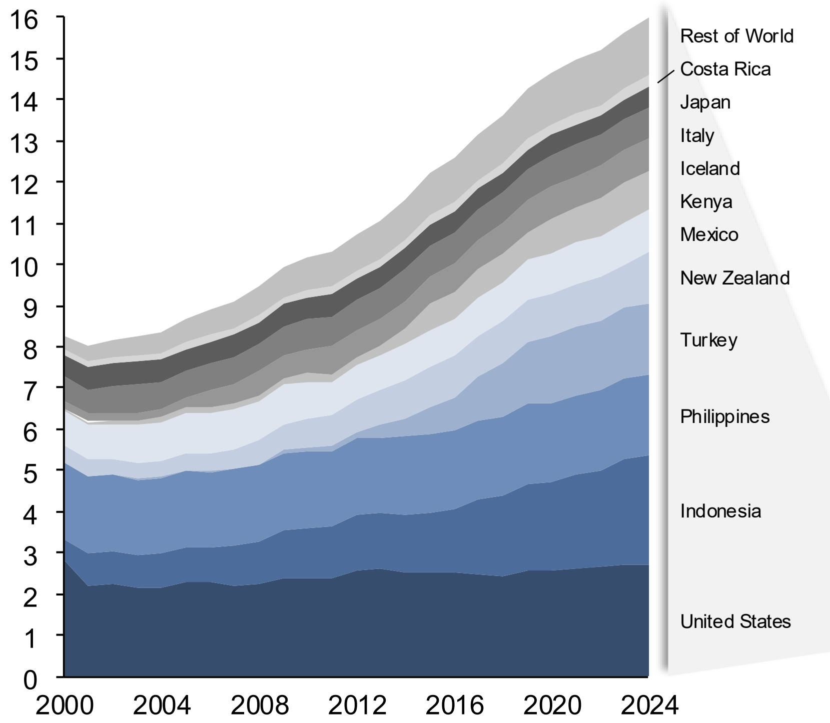
With vast untapped thermal resources and emerging technological advancements, geothermal power is primed for a breakout decade

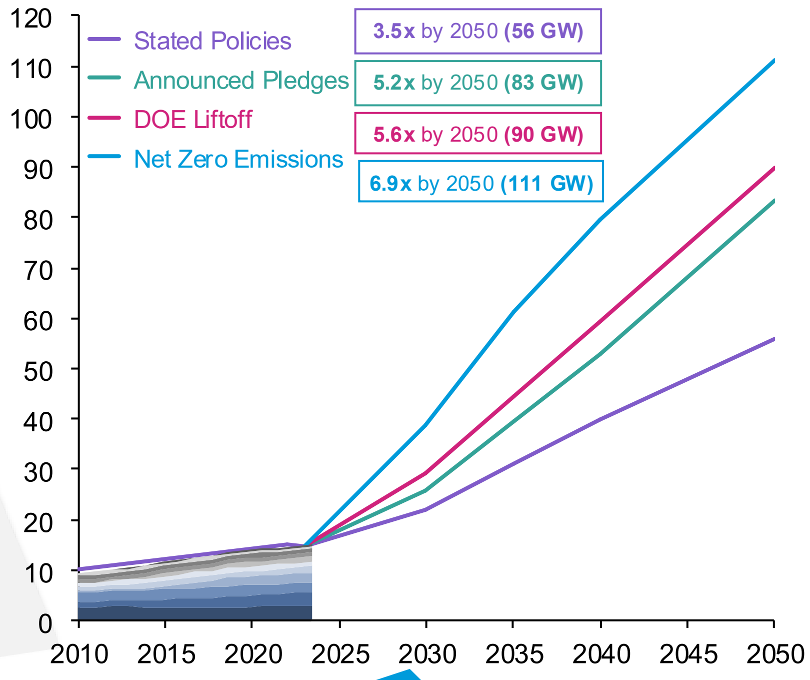
Potential of proven oil & gas reserves vs. 1% geothermal resources*, trillion MWh



Historical installed geothermal capacity by country, GW



Projected global geothermal under different scenarios, GW



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

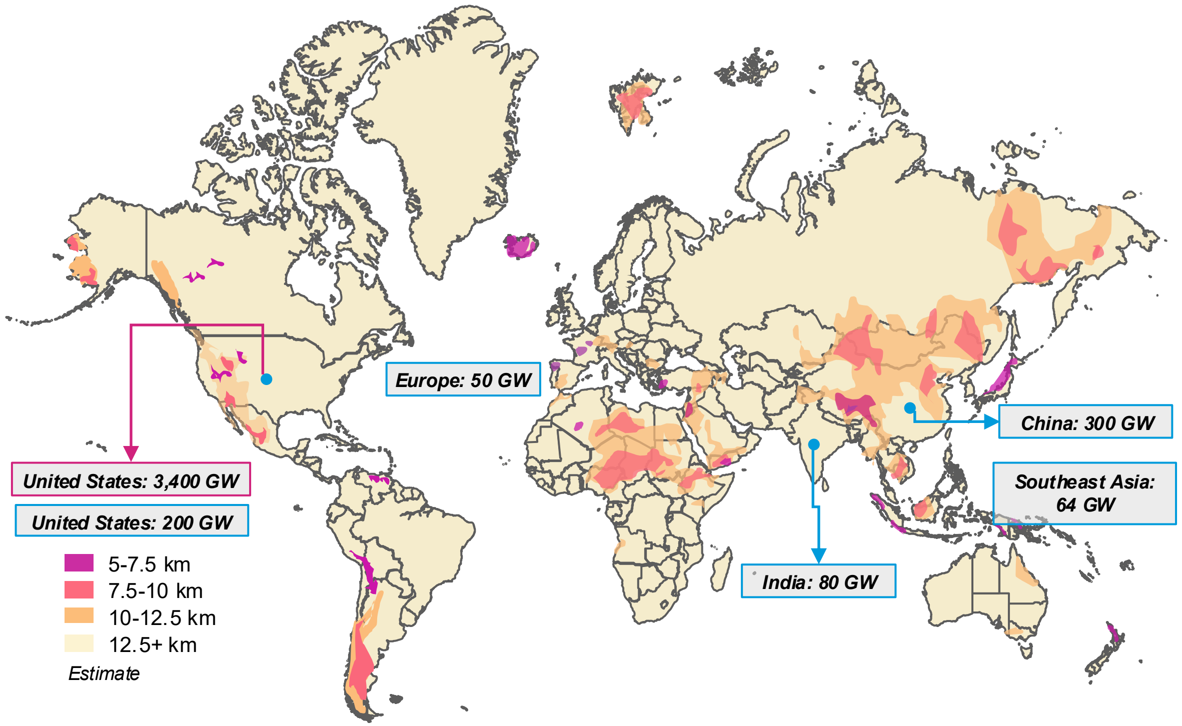
*One barrel of oil/gas is roughly equivalent to 1.7 MWh. There are about 1.5 trillion proven reserves of oil/gas x 1.7 MWh = 2.55 trillion MWh of potential fossil energy remaining (50-year supply remaining).

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

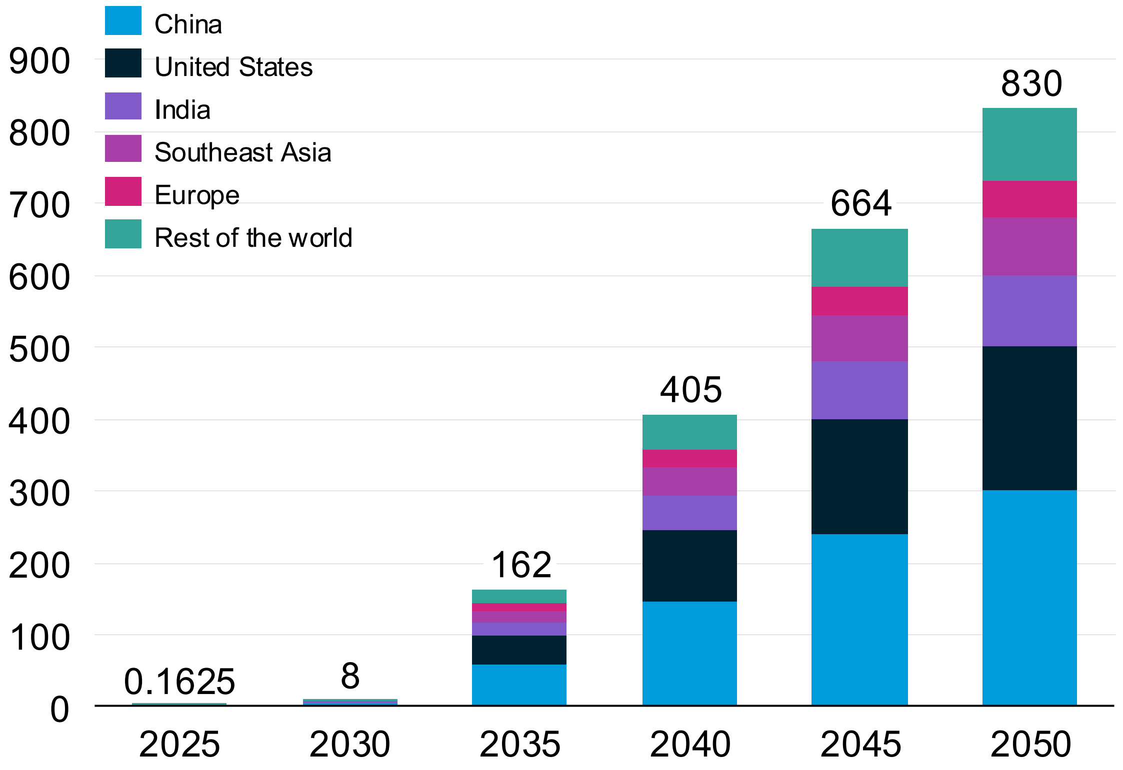
Credit: Zacharia Thurston, Pia Doris Morrow, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* "Power and Electricity," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

Global EGS hotspots concentrated in emerging economies



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



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.**

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).

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

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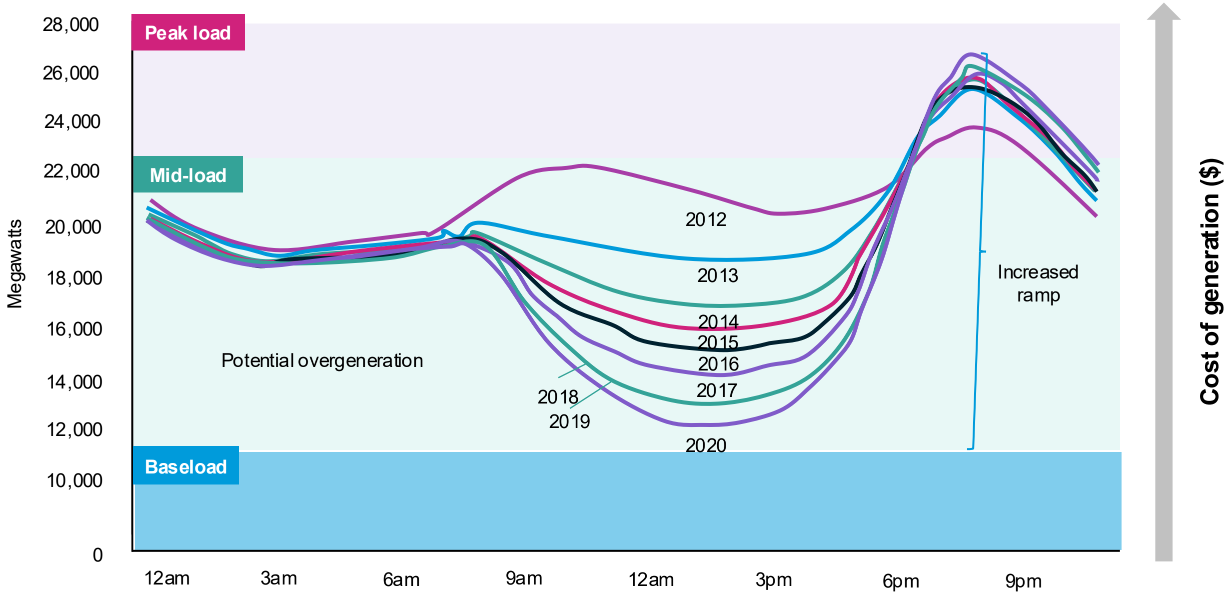
Geothermal power offers clean baseload capacity to replace retiring coal plants and prevent overreliance on peaker plants

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

Hourly net load (year average) in California



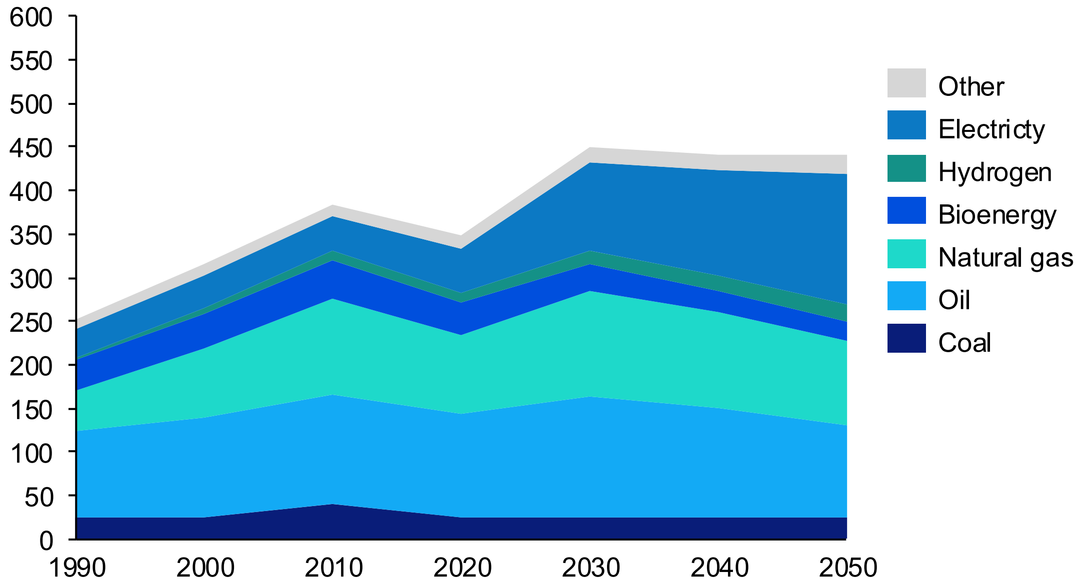
What is baseload?

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.* “Power and Electricity,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

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

	Barrier	Description	Impact on Deployment	Emerging Solutions
Major Barriers	**Exploration Risk & Cost**	High upfront cost for resource identification; drilling success uncertain	Major cost bottleneck; limits financing	AI/geophysical modeling, remote sensing, cheaper slim-hole drilling
Major Barriers	**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
Major Barriers	**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
Major Barriers	**Materials & Corrosion Resistance**	Equipment degradation in harsh conditions (heat, pressure, minerals)	Raises O&M costs and reduces lifetime of wells	High-temp alloys, ceramics, coatings
	Power Conversion Efficiency	Efficiency drops at lower temperatures; limited by thermodynamic cycles	Restricts viable sites; reduces energy output	Supercritical CO_2 cycles, binary cycle optimization
	Monitoring & Reservoir Management	Hard to track subsurface dynamics and avoid induced seismicity	Safety/regulatory constraints; performance loss over time	Fiber-optic sensing, real-time data analytics, seismic monitoring
	Transmission & Integration	Geothermal sites often remote; grid connection costs high	Slows scalability and investment interest	Colocation with industrial heat users, modular systems
	Public & Regulatory Challenges	Concerns about seismicity, permitting delays	Adds time and uncertainty to projects	Streamlined EGS permitting frameworks

Sources: Enhanced Geothermal Shot Analysis for the Geothermal Technologies Office (NREL, 2023); What Are the Challenges in Developing Enhanced Geothermal Systems (EGS)? Observations from 64 EGS Sites (Worldgeothermal.org, 2021).
Credit: Zacharia Thurston, Pia Doris Morrow, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner *et al.* “Power and Electricity,” 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	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).
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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 and Electricity," 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.

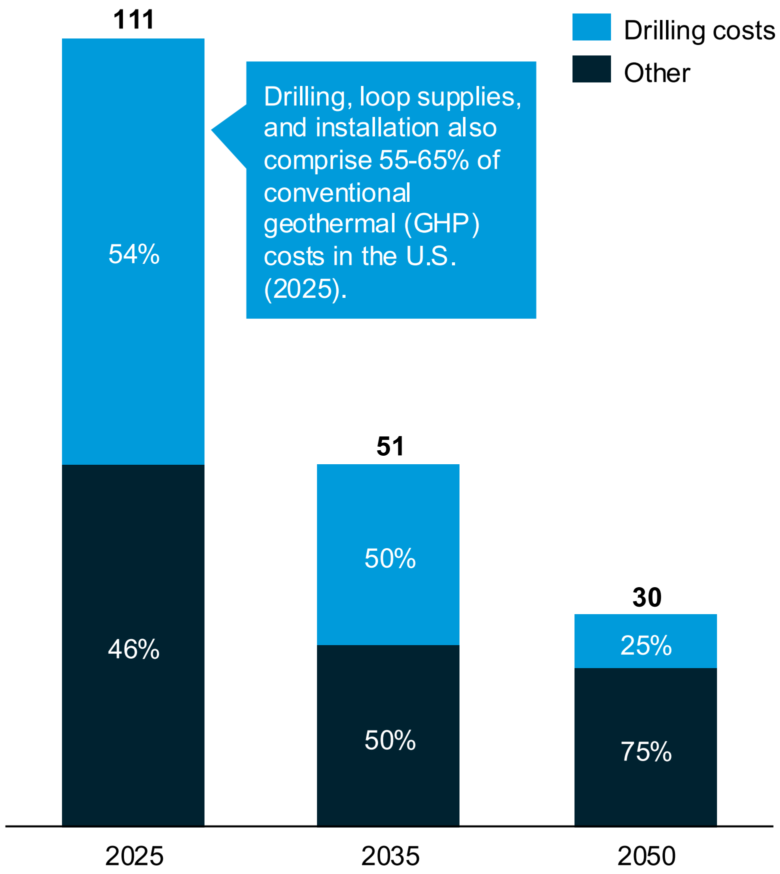
High-Pressure Water Jet-Assisted Drilling

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)



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).

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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.

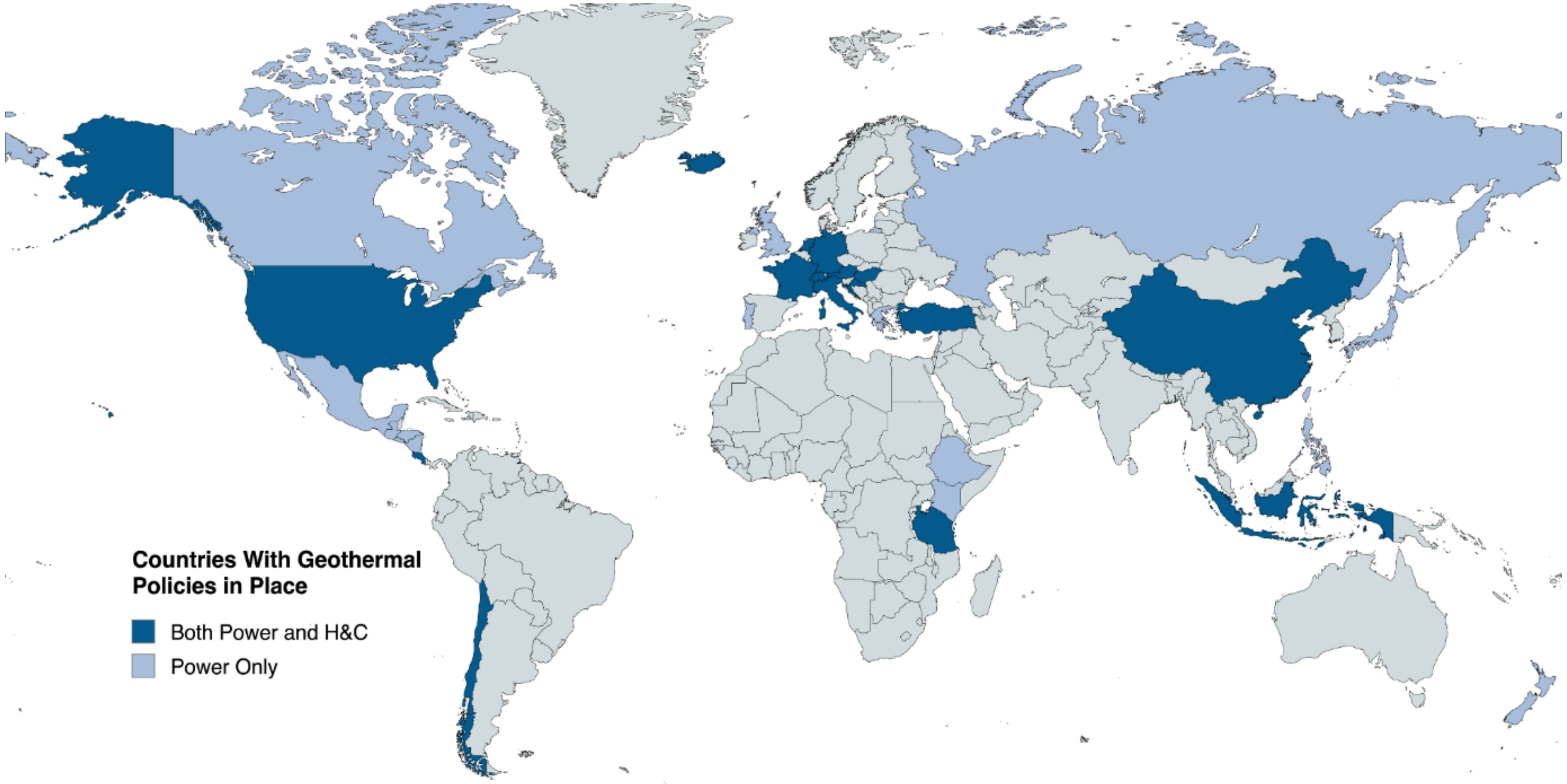
Observations

- 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 Policy scenario** (China, U.S., and Europe together account for 80% of this growth).
- Almost **two-thirds of geothermal power capacity additions between 2024 and 2030** are expected to be policy-driven – primarily tax credits, fixed tariffs, and premiums.

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

Scale	Power Generation	Heating & Cooling
Global	ESMAP Energy Sector Management Assistance Program 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	GRMF A Catalyst for Geothermal Development 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 **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	JICA **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.	giz SICA Sistema de la Integración Centroamericana Paz Desarrollo Libertad Democracia 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 and Electricity," 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.

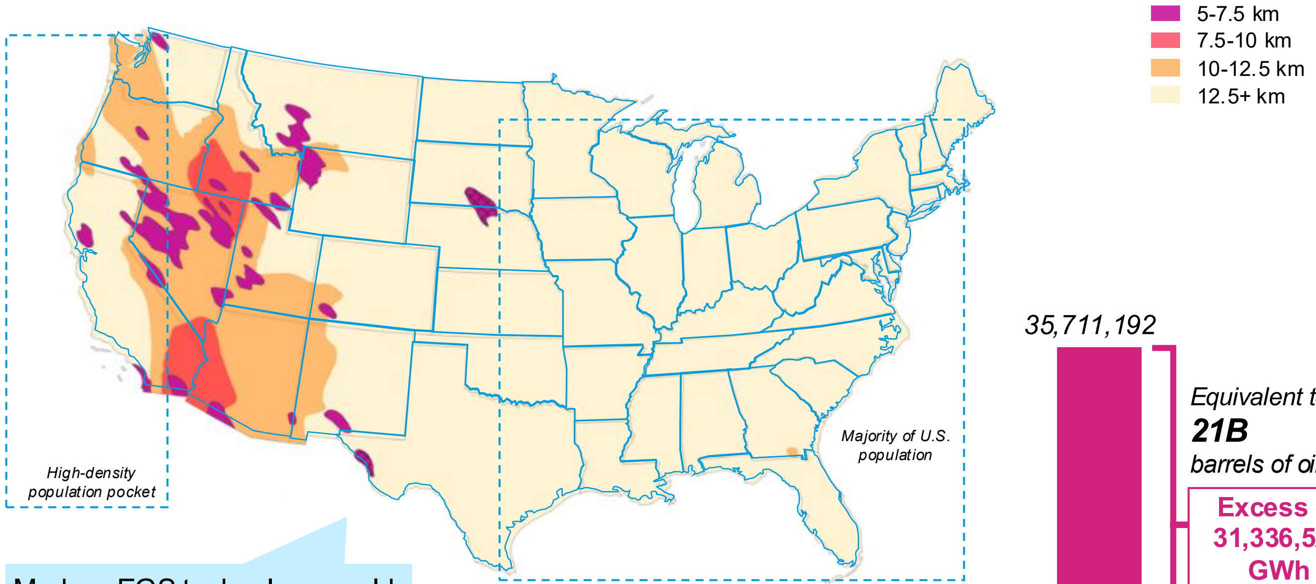
2009-16 — Obama Era
- DOE's Geothermal Tech program advances EGS demonstrations.

2017-21 — Trump 1.0:
- Rollbacks in environmental policies broadly ease permitting; renewable incentives are de-emphasized.

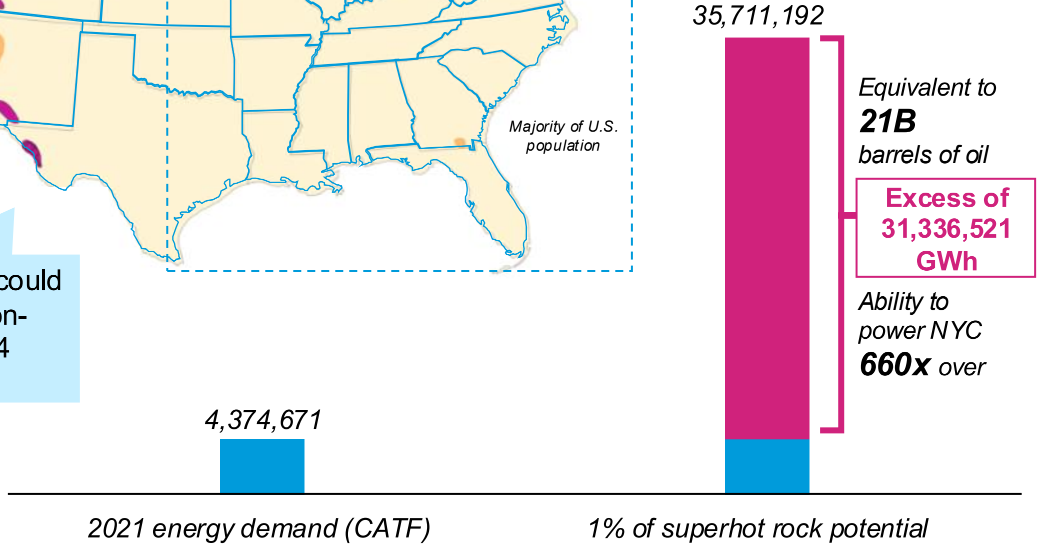
2021-24 — Biden: Bipartisan Infrastructure Law (2021) + IRA (2022)
- Provides broad support of renewable energy development, support for DOE funding for EGS; geothermal included in net-zero planning.

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.



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

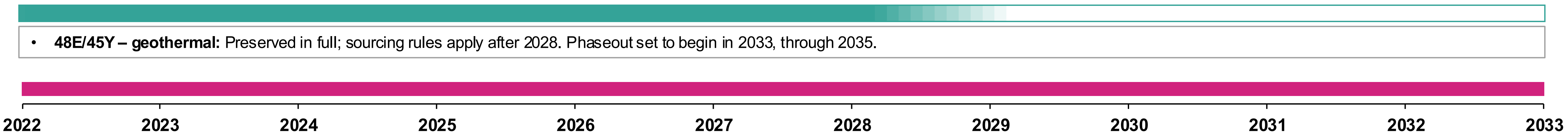
OBBBA keeps IRA 45Y and 48E incentives for geothermal power until 2035; foreign entity of concern (FEOC) rules apply after 2026

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.

Preserved   Early expiration



- **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.

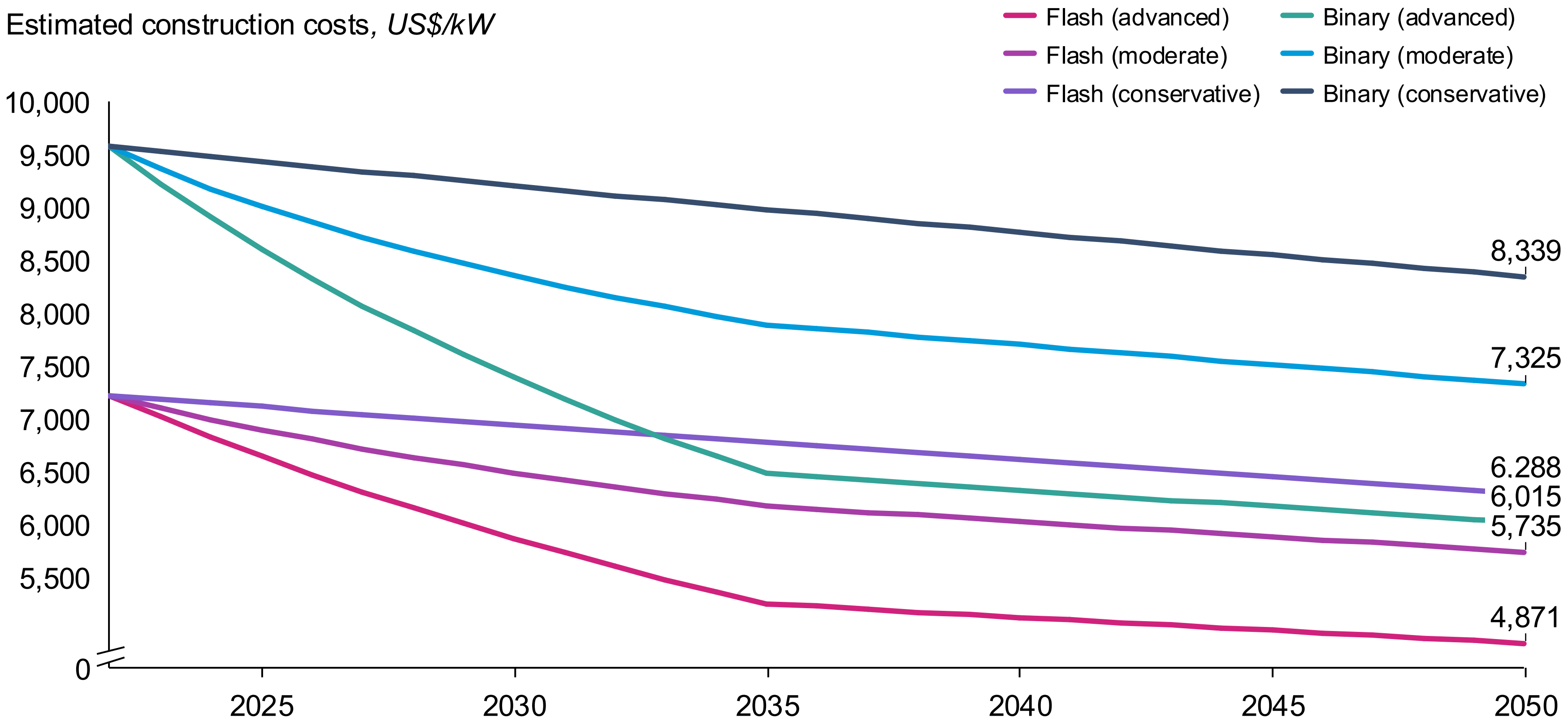
The GTO's programs are building toward their strategic goal of **supplying 60 GW of EGS and hydrothermal resources deployment by 2050.**

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

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

Estimated construction costs, *US$/kW*



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 and Electricity,” 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*

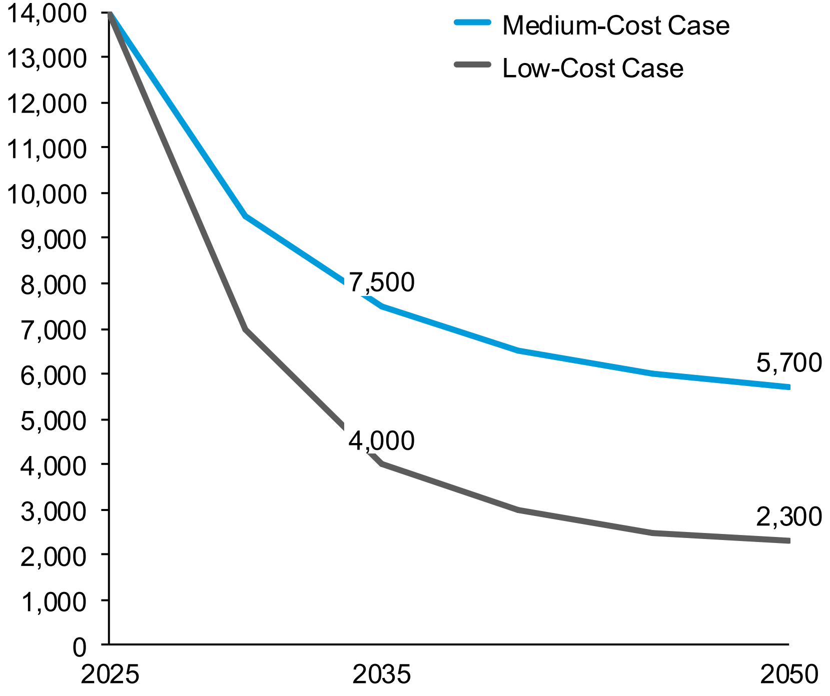
	Fervo, U.S.	Rift Valley, Kenya	Sarulla, Indonesia
Technology	**Next-gen** geothermal (EGS, advanced drilling, and fiber optics)	**Conventional** geothermal (mixture of flash and binary)	**Conventional** geothermal (flash steam)
Risk profile	**Moderate technology risk:** While EGS has been de-risked by 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).

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

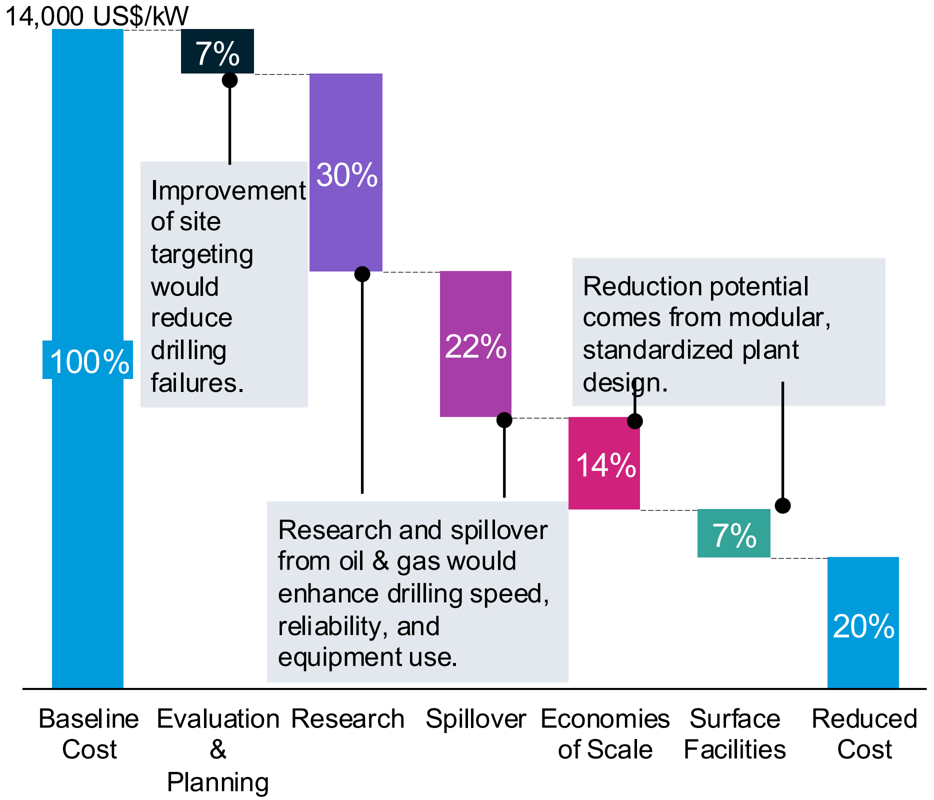
Next-gen geothermal construction costs are projected to drop ~60-80% by 2050 …

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, *%*



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

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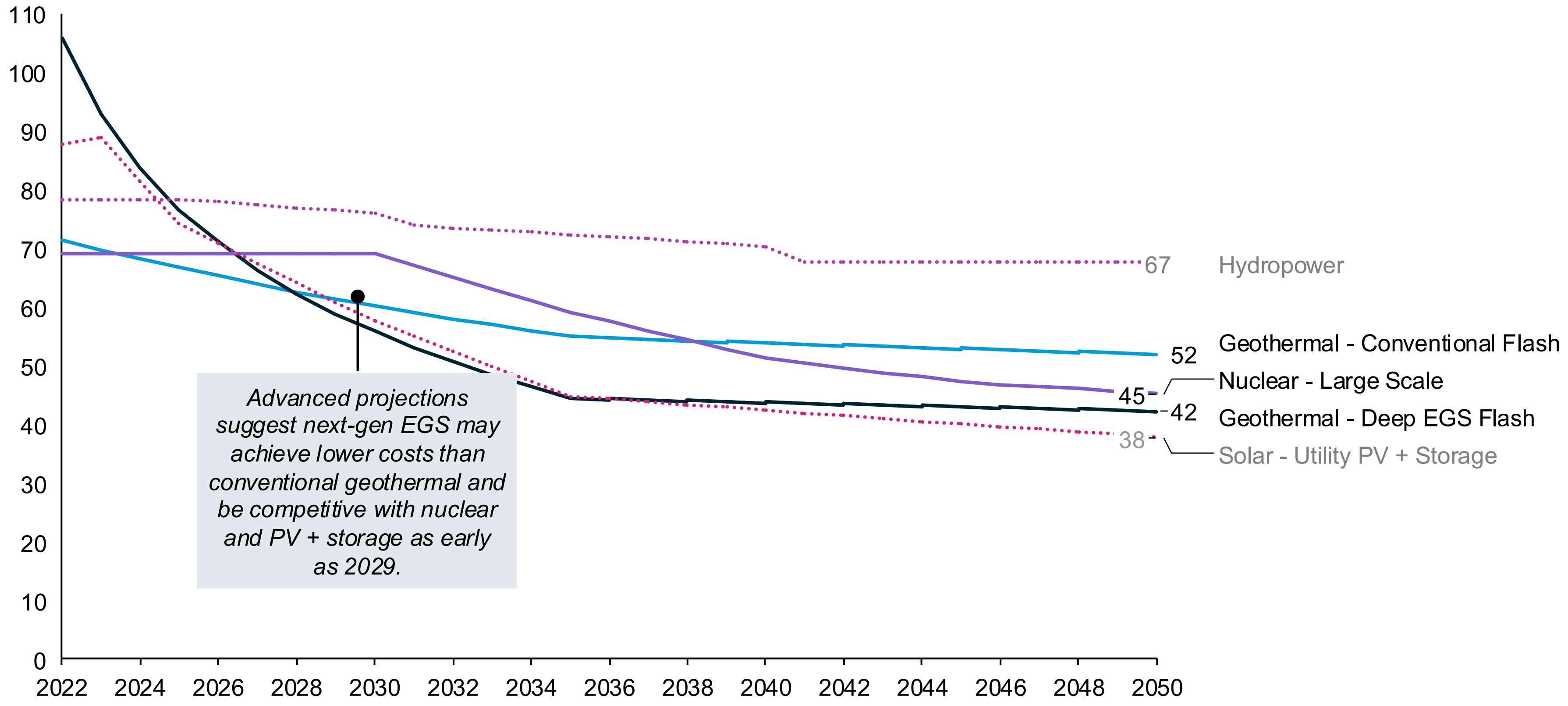
Geothermal LCOE is on track to compete with hydro, nuclear, and solar PV + storage, through O&G transfer and policy-led de-risking

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



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 and Electricity,” 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

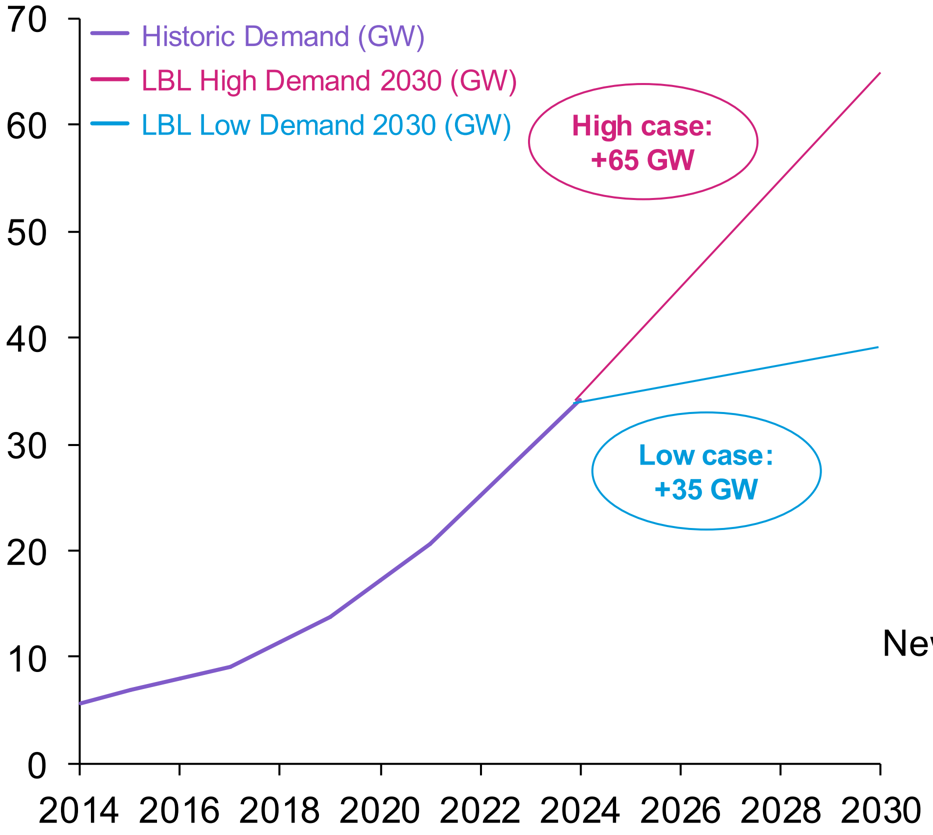
	Geothermal	Hydro	Nuclear	Wind	Solar
Resource availability & scalability	**Scalable in select locations,** high upfront costs, deep drilling needed	**Limited** scalability due to size *(smaller hydro projects more feasible vs. larger dams)*	**Limited** scalability due to high investments and long construction 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.

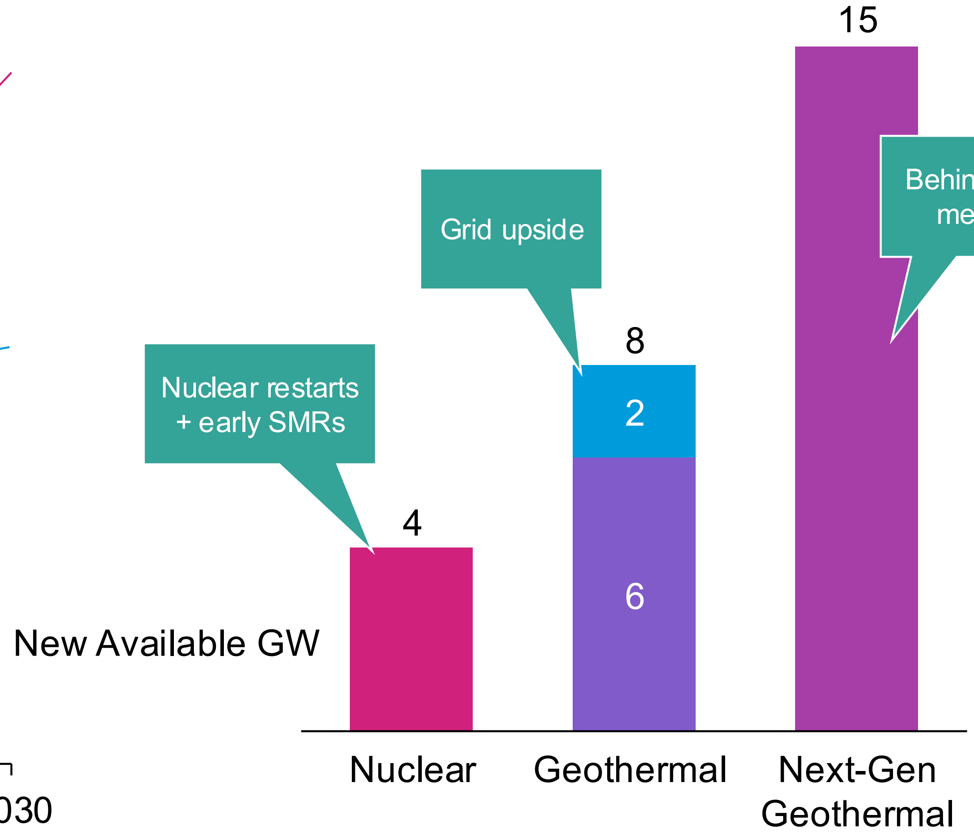
Sources: LCOE report (Lazard, 2025); U.S. Energy Information Administration Annual Energy Outlook (DOE, 2022); Geothermal Basics (DOE, 2025); Beyond Levelized Cost (SLB, 2025).

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

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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).

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).

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