Columbia Business School
Climate Knowledge Initiative

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Geothermal Heating and Cooling

Executive Summary

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Cite as: Wagner *et al.* "Geothermal Heating and Cooling," Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

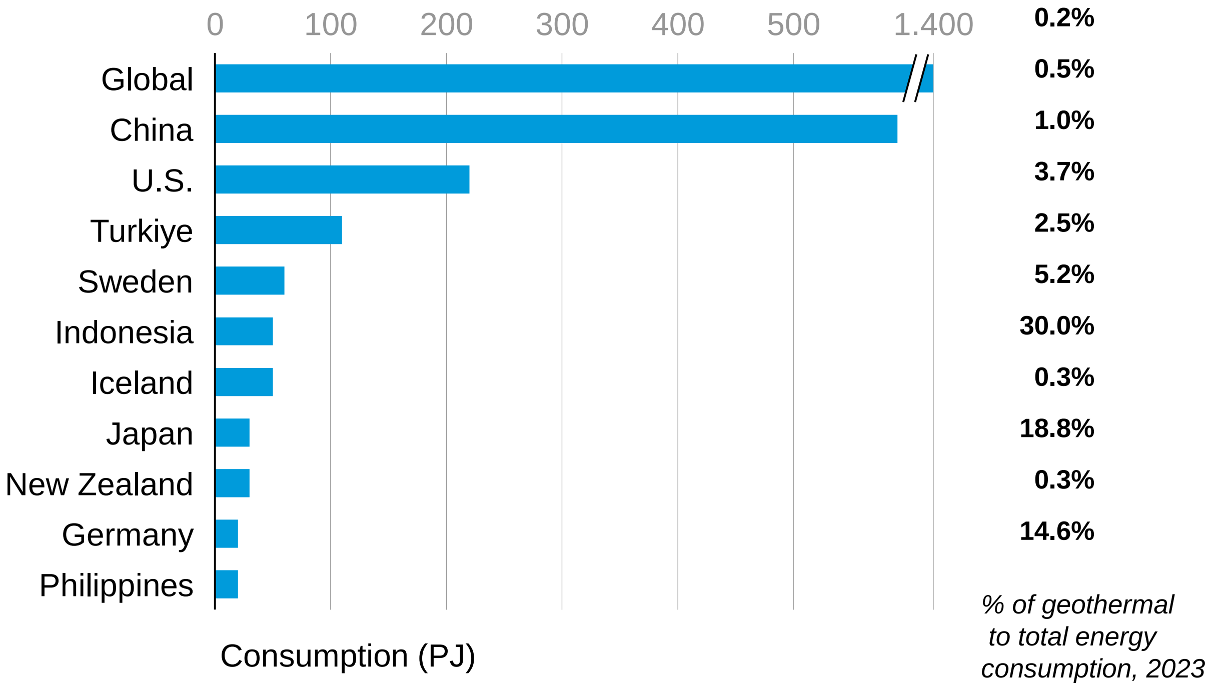
- **Heating and cooling**
  - **Production**
    - **Geothermal heat pumps**
    - **Direct-use heat**
  - **Storage**
    - **Underground thermal energy storage**
      - Borehole thermal energy storage
      - Aquifer thermal energy storage
      - Mine thermal energy storage
      - Cavern thermal 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).

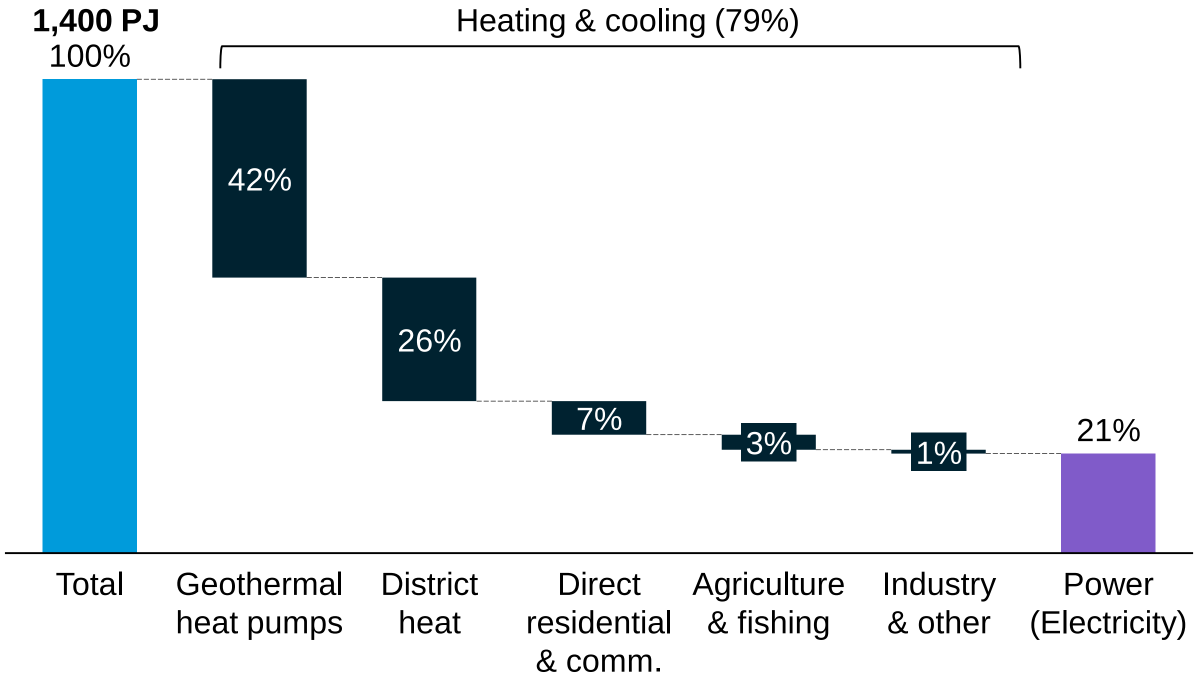
Credit: Sevgi Helin Tilkicioglu, Una Oljaca, Pia Doris Morrow, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Heating and Cooling,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

Total final geothermal energy consumption by consuming countries, 2023



Total final geothermal energy consumption by application, 2023



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

Sources: The Future of Geothermal Energy (IEA, 2024).
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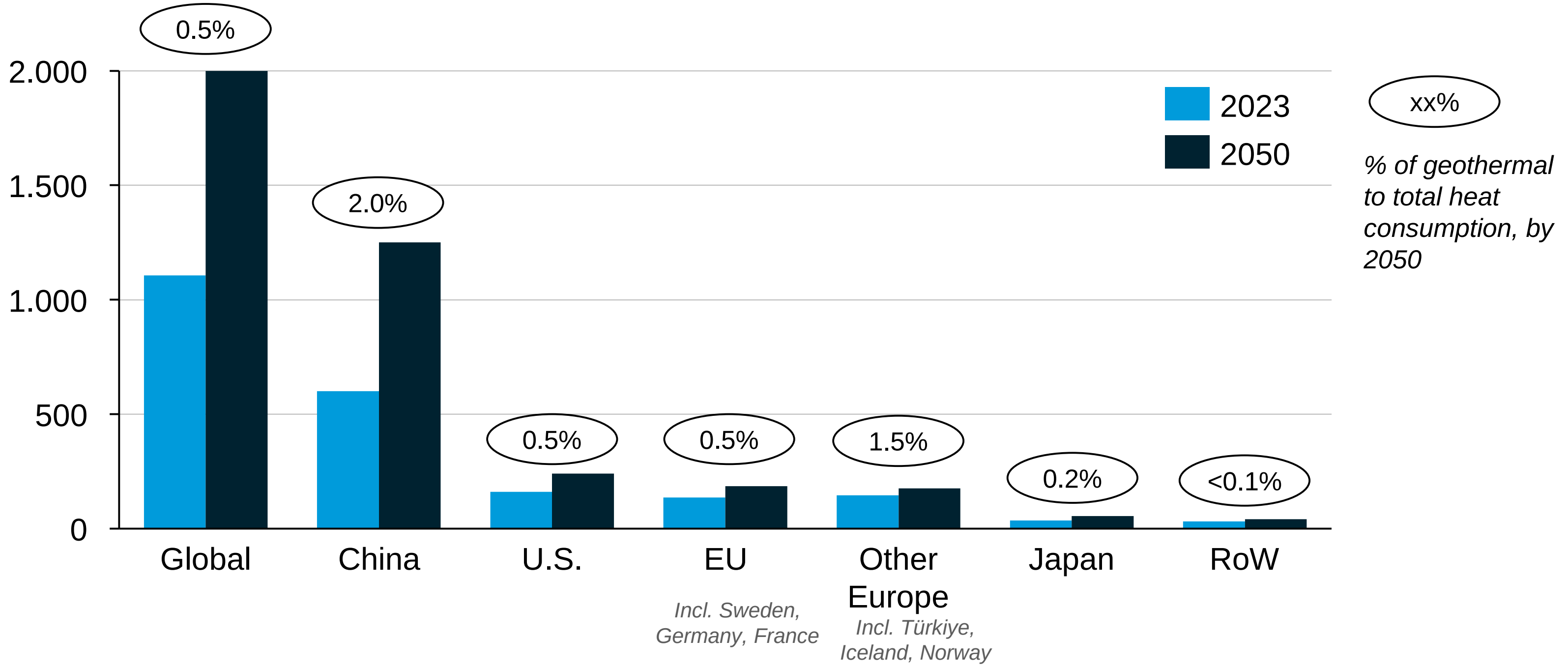
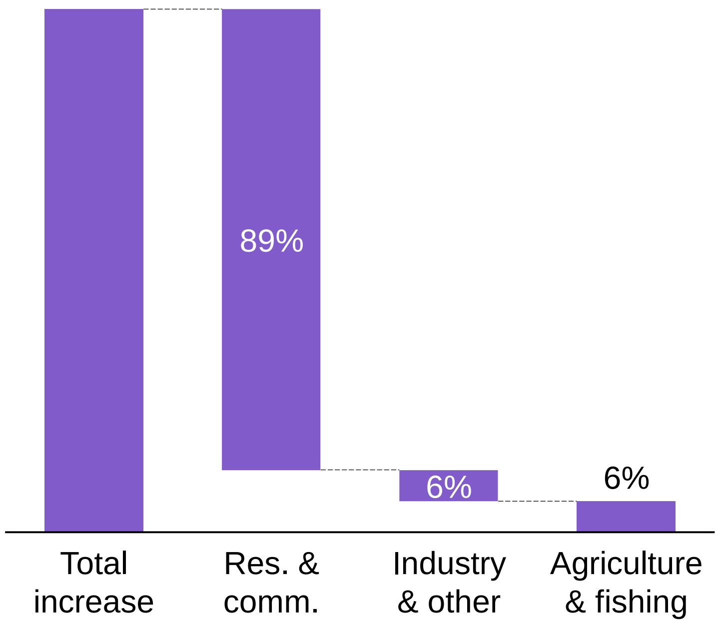
By 2050, geothermal heating use is projected to almost double, driven largely by China and building and district heating

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



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



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

Sources: The Future of Geothermal Energy (IEA, 2024).
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Geothermal heating & cooling technologies are proven, deployable solutions for decarbonizing building thermal loads

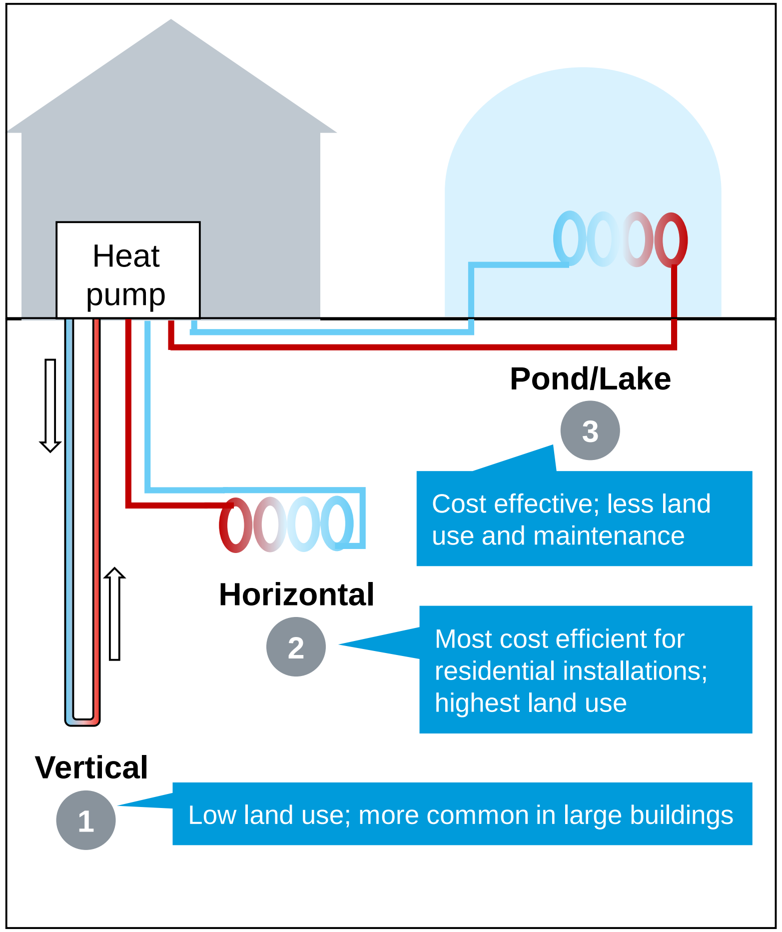
	Geothermal Heat Pumps (GHPs)	Direct-Use Geothermal	Underground Thermal Energy Storage (UTES)
Description	Constant temperatures are harnessed via open- or closed-loop fluid circulation and transferred through heat pumps.	Hot water from naturally occurring underground reservoirs is used directly for heating applications.	Seasonal energy storage in underground formations such as boreholes (BTES) or aquifers (ATES) accommodates later use.
Depth range	50-300 meters	400-2,000 meters	20-1,000 meters
Temperature	4.5-21ºC	20-150ºC	0-100ºC
Alternative to	• **Air-source heat pumps** • Boilers/propane heaters	• Coal, oil, gas boilers used for district heating systems	• Peaking fossil fuel systems • Boilers and furnaces
Advantages	• High COP (3-5) • Peak load reduction • Weather resistance	• Suitable for large-scale applications • Can target higher temperature	• Energy savings and grid energy use optimization • Low land use
Barriers	• **Site specificity** • Skilled workforce needs	• **Site specificity** • Limited use slowing cost reductions	• Site specificity • Heat loss over time • Cost and efficiency uncertainties
Cost	**US$66-$109/MWh**	**US$66-$109/MWh**	**N/A**

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

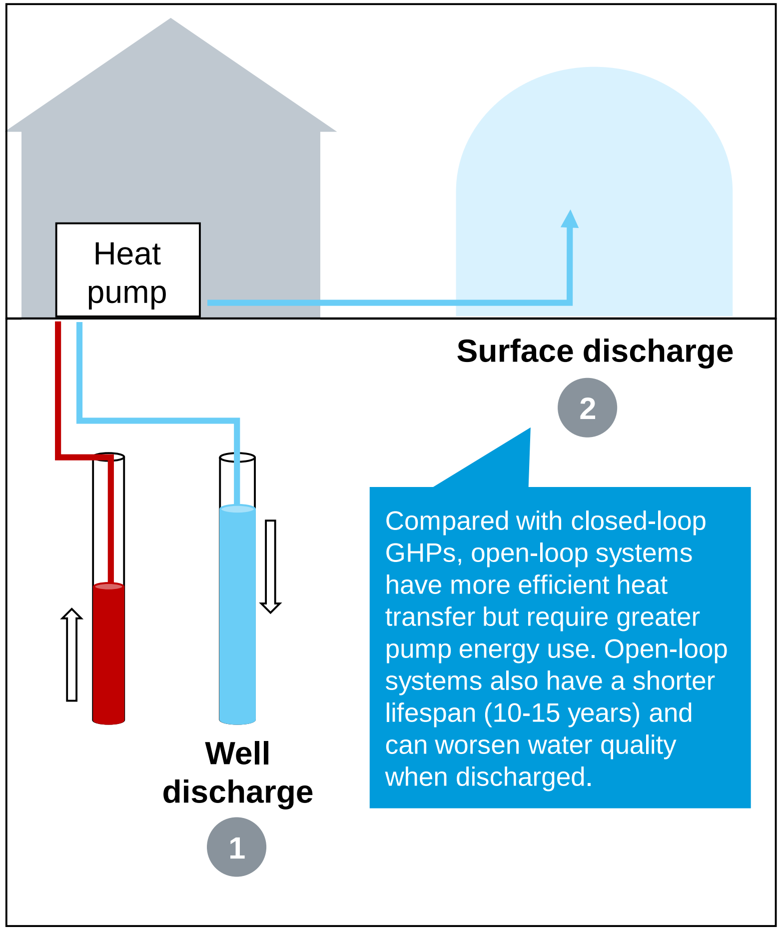
Credit: Una Oljaca, Pia Doris Morrow, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Heating and Cooling,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

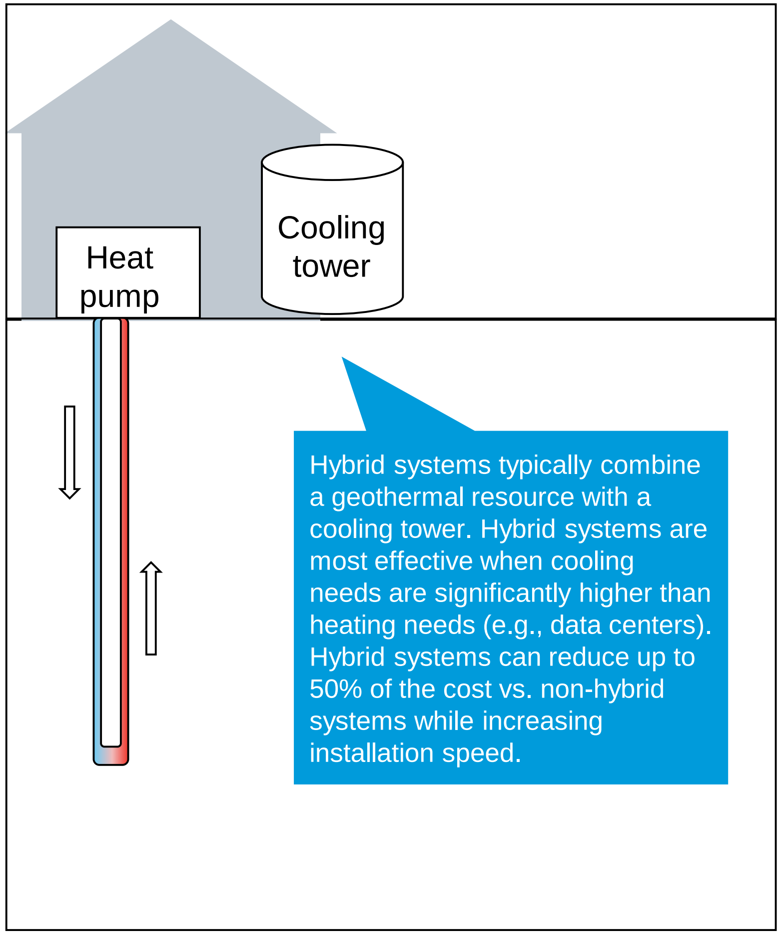
Closed loop



Open loop



Hybrid



Sources: Geothermal Heat Pumps, Underground Thermal Energy Storage (DOE, 2012); Direct utilization of geothermal energy 2020 worldwide review (Geothermics, 2021); Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); Open-Loop vs. Closed-Loop Ground Source Heat Pumps (Energy Vanguard, 2023).
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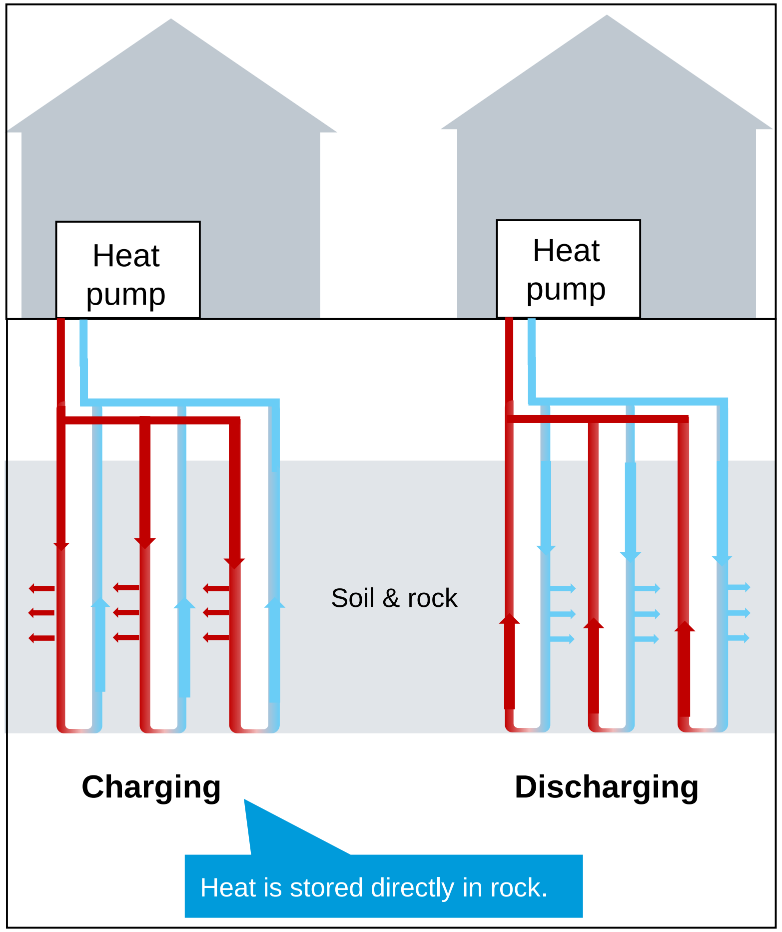
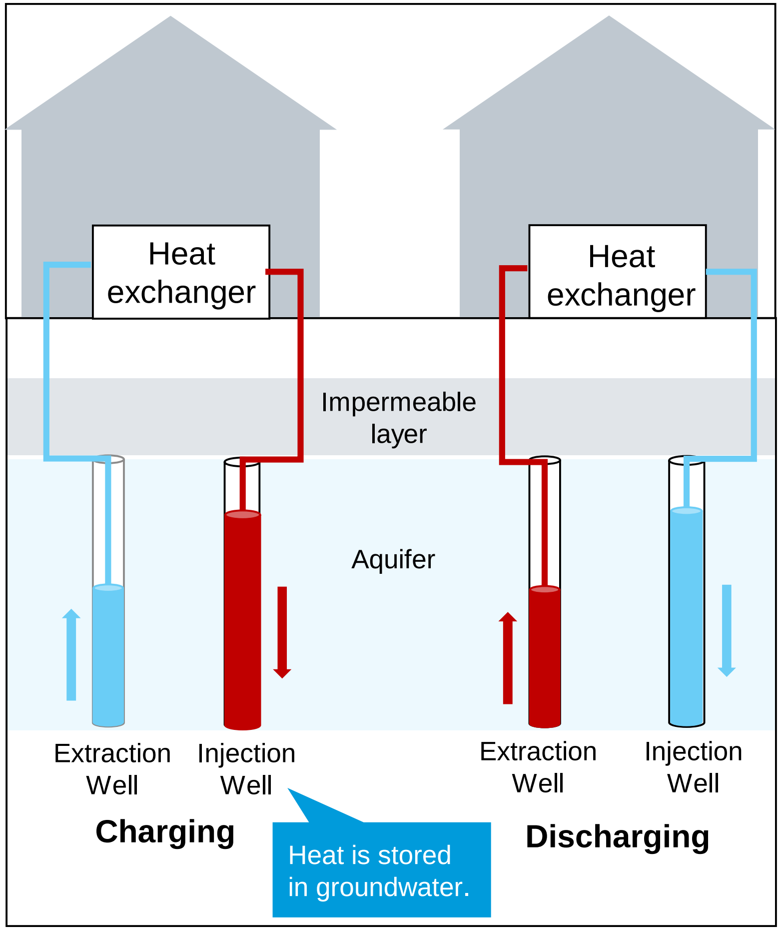
Underground thermal energy storage supports renewable energy integration, but adoption is limited by infrastructure needs

Borehole thermal energy storage (BTES)



Aquifer thermal energy storage (ATES)



BTES and ATES Compared

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

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

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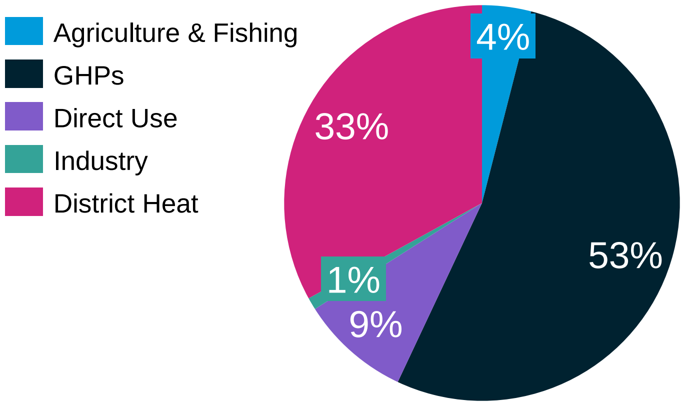
Next-generation geothermal may bypass resource-related limitations of conventional geothermal, opening new avenues for scaling the industry

Conventional geothermal is limited by geographical and temperature constraints…

Geothermal heating and cooling consumption by application globally



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

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

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

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

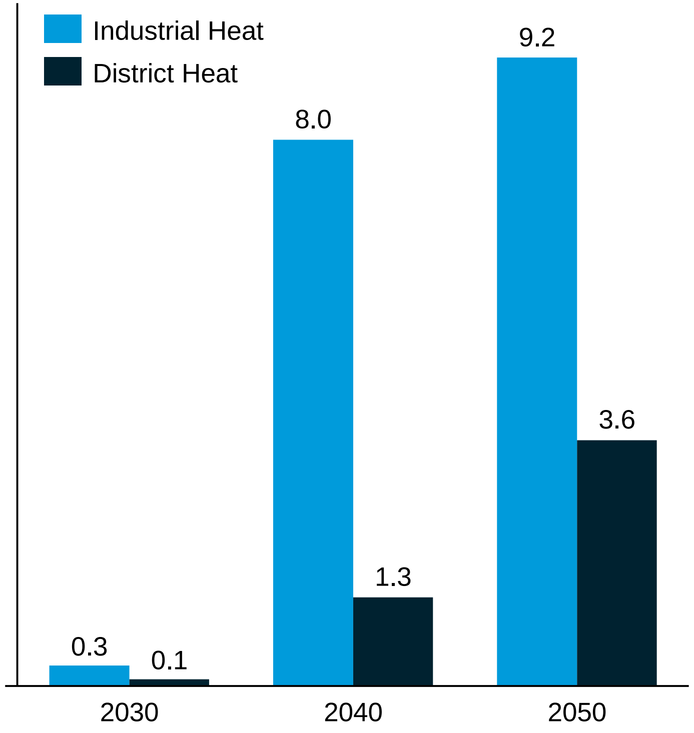
Industrial Heat

- In a low-cost APS scenario, next-generation geothermal could **economically displace ~3 EJ of fossil fuel consumption by 2035** for industrial heat globally (10% of industrial heat <200ºC) and **almost 10 EJ by 2050** (35% of industrial heat <200ºC).
- Up to **230 Mt of CO_2 emissions** could be avoided.

District Heat

- In a low-cost scenario, next-generation geothermal could capture **20% of district heating growth** between 2035 and 2050.
- **Investment costs below US$4,000/kW** would make next-generation geothermal district heating cost competitive.
- **Co-generation (CHP) plants are an economically attractive application** due to revenue generation from electricity shares

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



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

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

Key challenges along the geothermal value chain

Geothermal supply challenges of geothermal heat pumps (GHPs) and underground thermal energy storage (UTES)

- **Exploration & raw materials**
  - Copper — *Deep dive* A
  - HDPE — *Deep dive* B
  - Glycol
  - Methanol
  - Steel
- **Development & drilling**
  - Drilling rigs — *Deep dive* C
  - ASHPs vs. GHPs — *Deep dive* D
  - Semiconductors
  - Compressors
- **Operations & maintenance**
  - Skilled workforce — *Deep dive* E
  - Thermal imbalance
  - Scaling & fouling
- **End of life**
  - Disposal
  - Site restoration

Observations

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

Note: See subsequent slides for deep dives on the challenges highlighted above.
Sources: CKI analysis (2025).
Credit: Pia Doris Morrow, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner *et al.* “Geothermal Heating and Cooling,” Columbia Business School Climate Knowledge Initiative (10 March 2026).

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

Global Collaboration	Global collaboration on geothermal energy – particularly heating and cooling – lags behind other renewables, slowing innovation and increasing risk. Stronger, more large-scale collaboration is a priority.
Workforce Development	Geothermal expansion will require a skilled workforce in engineering, geology, and drilling sectors. Transitioning the oil and gas workforce will streamline geothermal workforce development.
Research & Development	Poor funding infrastructure for geothermal exploration and drilling drives up investment costs and slows technological progress. Strong funding mechanisms will be necessary to speed geothermal deployment.
Risk Mitigation	Geothermal projects have higher predevelopment risks compared with other renewable energy technologies due to complex geological and subsurface conditions. Mitigating risk is critical in lowering project costs.

Observations

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

Sources: The Future of Geothermal Energy (IEA, 2024); Global Geothermal Market and Technology Assessment (IRENA, 2023).
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Leveraging oil & gas capabilities can lower geothermal power costs and accelerate deployment

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

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

Sources: The Future of Geothermal Energy (IEA, 2024); Global Geothermal Market and Technology Assessment (IRENA, 2023); Barriers to Next-Gen Geothermal (IFP, 2023); Can Zanskar use AI to de-risk conventional geothermal? (Latitude Media, 2025).
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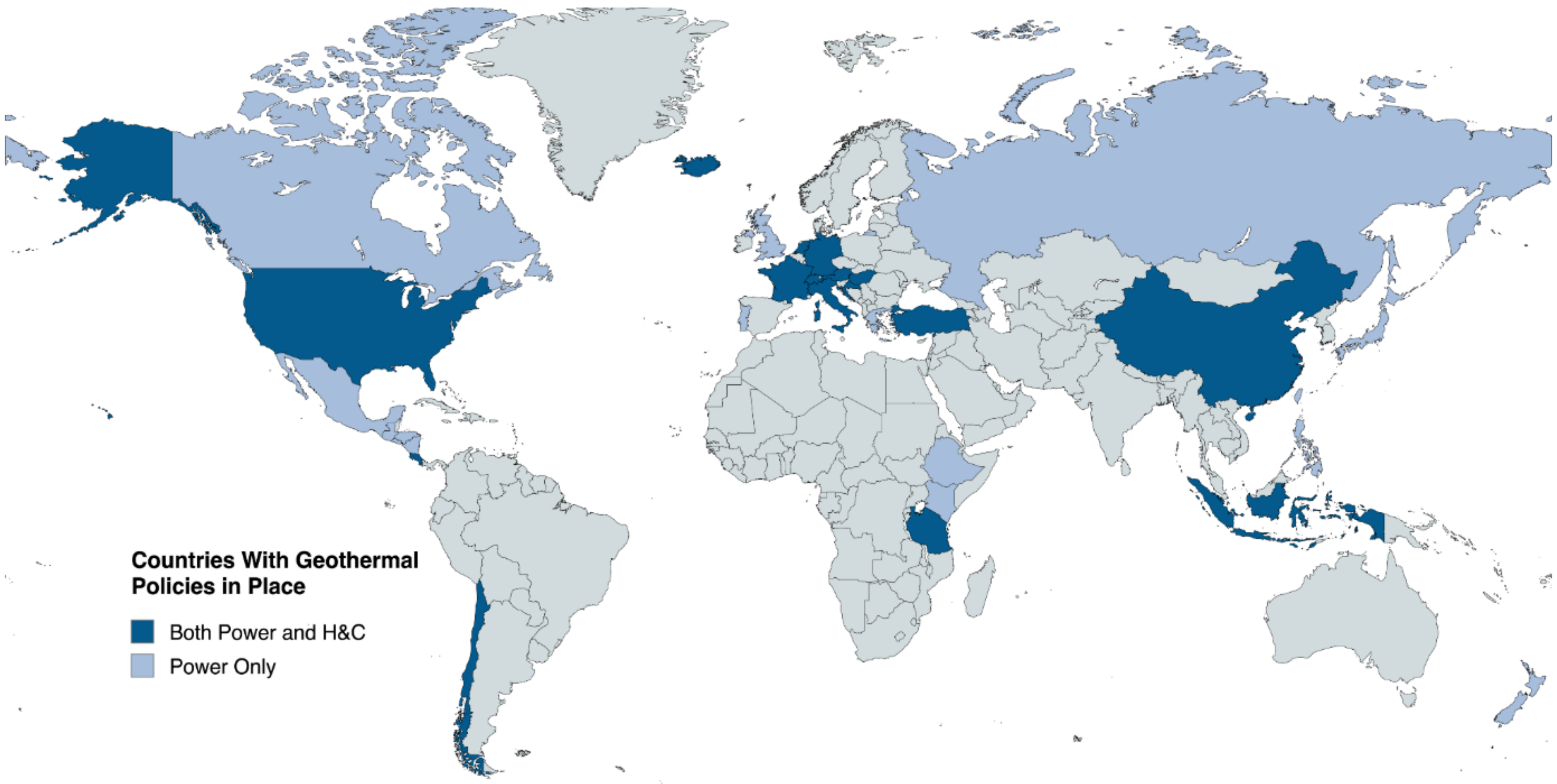
Europe leads in geothermal heating & cooling regional policy adoption and collaboration; rest of the world lags behind

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



Observations

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

Sources: Geothermal Energy Database (IGA, 2024); The Future of Geothermal Energy (IEA, 2024); Global Geothermal Market and Technology Assessment (IRENA, 2023).
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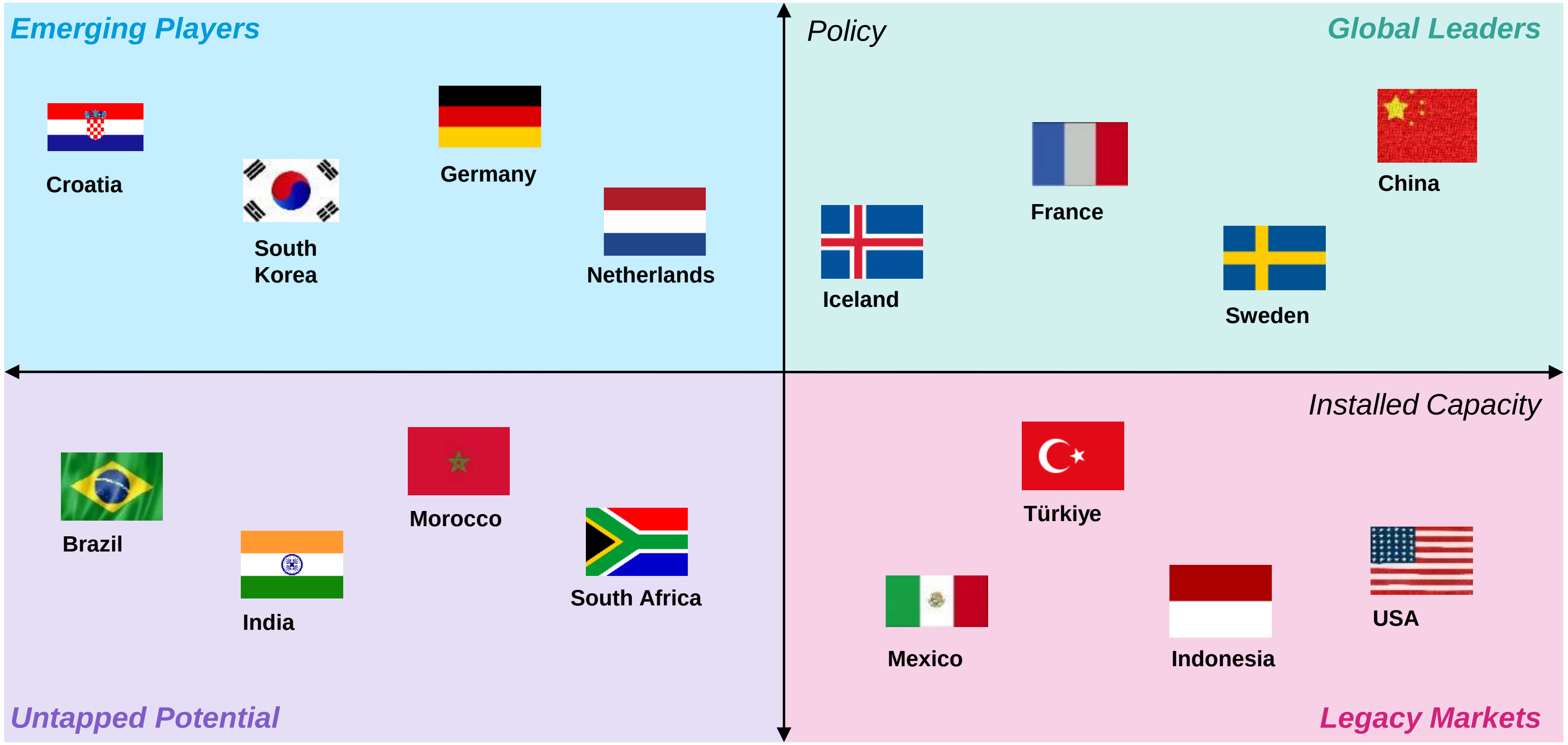
While strong policy support is concentrated in China and Europe, installed capacity grows even in subpar policy landscapes

Global policy and installed capacity matrix for geothermal heating & cooling



Observations

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

Sources: The Future of Geothermal Energy (IEA, 2024); Global Geothermal Market and Technology Assessment (IRENA, 2023); Geothermal Energy Database (International Geothermal Association, 2024).

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

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

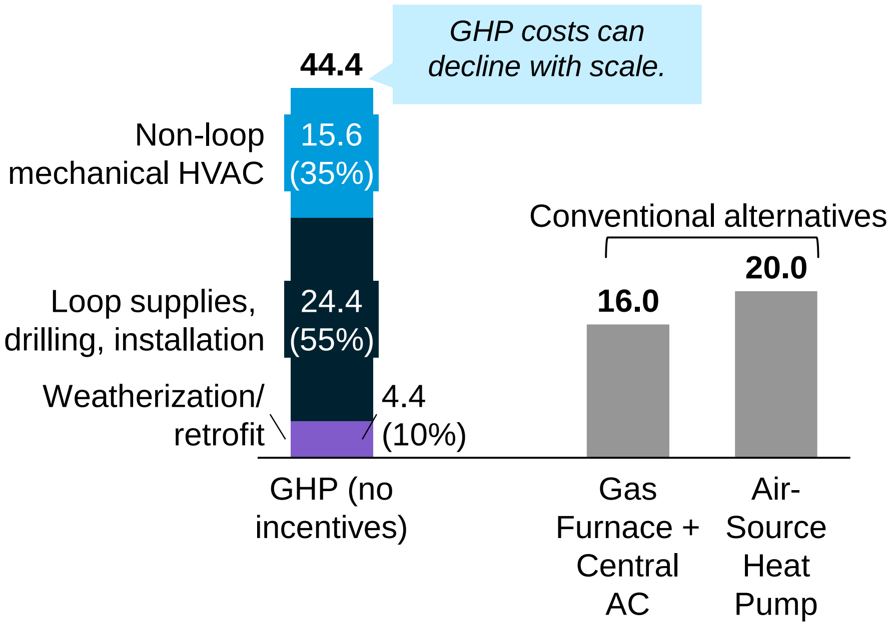
Sources: Kenya Geothermal Report (World Bank, 2015); Green Bond Report (Landsvirkjun, 2018); Geothermal Grant (U.S. DOE, 2020); Tiwi-Makban Project (ADB, 2010).

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

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

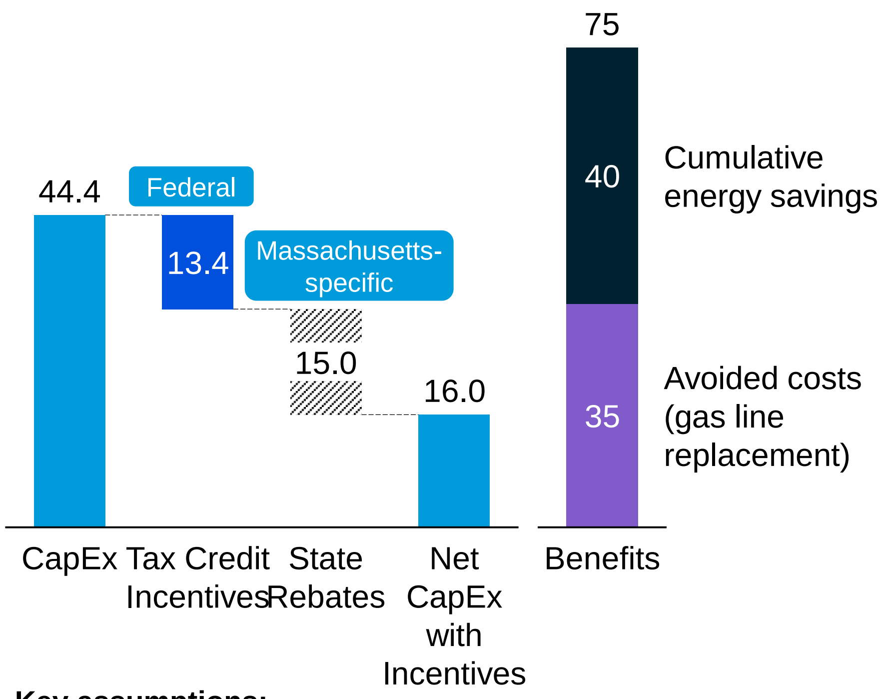
Est. median CapEx of HVAC U.S. residential ($K/household)

~4 ton/household capacity assumption



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

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



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

Observations

All U.S. states:
- ROI **without** tax credit: **3-4%**
- ROI **with** tax credit: **6-7%**
- Massachusetts specific:
- ROI with tax credit and state rebates: 13-14%

- Tax credits help break the biggest barrier – high upfront costs – making GHPs more accessible and financially viable.
- Incentives are key to unlocking mass adoption and reaching DOE's Liftoff goal of **7 million homes by 2035.**

Sources: Pathways to Commercial Liftoff: Geothermal Heating and Cooling (DOE, 2024); GeoVision (NREL, 2020); Residential Energy Consumption (EIA, 2021); GHP Installation (Energy Sage, 2023); HVAC Installation Cost (HomeAdvisor, 2023).
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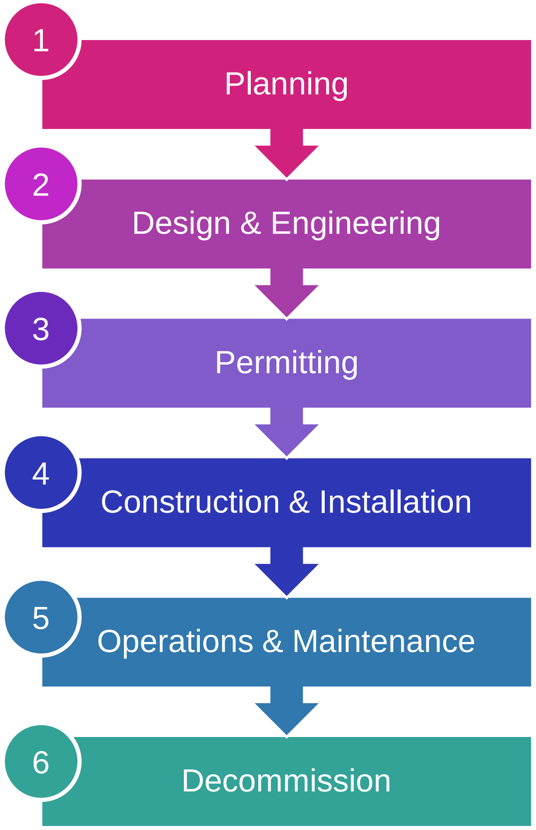
Identifying key stakeholders is crucial to successful deployment of a geothermal heating & cooling project

Key deployment stages and stakeholder engagement map



Stage	Key stakeholders	Key activities
1	Site owners/building operators	• Provide site access and building data
1	Geologists and geothermal consultants	• Conduct subsurface and thermal analysis, execute feasibility assessment
1	Local utilities	• Assess infrastructure for integration
1	Community organizations	• Facilitate local engagement and feedback
1	Project developers and investors	• Initiate and fund planning
2	Local, state, and environmental regulators	• Approve land use and drilling activities, ensure compliance
2	Legal advisors	• Prepare and submit legal compliance documents
3	Engineers and HVAC designers	• Design system layout and HVAC compatibility
3	Software modelers	• Run thermal simulations to optimize performance
3	Building architects	• Incorporate system into building design
4	Drilling contractors	• Drill boreholes and install piping systems
4	Construction crew	• Install mechanical and electrical infrastructure
4	Site safety and quality assurance officer	• Ensure field safety and risk compliance
5	Facility managers and maintenance contractors	• Oversee operation, handle routing servicing and repairs
6	Local authorities	• Authorize decommissioning procedures
6	Restoration contractors	• Restore landscaping and ecological balance

Sources: CKI analysis (2025).
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3 The average permitting process in the U.S. takes 45 months on average and includes 14+ responsible agencies

Permitting process in the U.S.

Until construction completion

Land Use
Land lease
Right of way
1-6 months

Exploration
Exploration permit/license
3-12 months

Drilling
Well drilling permit
2-6 months

Environmental
Environmental impact assessment
NEPA Review
6-36 months

Water Use
Water rights
Extraction permit
2-12 months

Construction
Building permit
Mechanical permit
1-3 months

15-75 months until construction completed

If hybrid power generation

Grid connection
Interconnection agreement
Grid access permit
3-9 months

+ 3-9 months

Until end of life

Operation
Operational license
1-6 months

Decommission
Plan for decommission/ closure
3-12 months

+ 4-18 months including end of life

Multilevel responsible agencies

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

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

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

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

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CKI Geothermal Team

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