Photo by Alison MacDougall, Kearney, Washington, DC

Geothermal energy

January 2025

KEARNEY | Energy Transition Institute

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This FactBook provides a comprehensive overview of geothermal energy, a renewable resource harnessed from the Earth's natural heat. It explores geothermal energy's origins, current and emerging uses, market trends, cost structures, and environmental impacts. The report delves into technological advancements, policy interventions, and business models, presenting a global perspective on geothermal energy's role in the energy transition.

Geothermal energy is derived from heat generated within the Earth's crust, replenished by radioactive decay and residual heat from the Earth's formation. Global geothermal gradients and heat fluxes vary due to geological conditions, such as volcanic and tectonic activity. Technologies adapted from the oil and gas sector are revolutionizing geothermal exploration and artificial reservoir development, enhancing the scope of extraction.

Historically only used for heating, geothermal energy has evolved into two mainstream applications: heat provision and electricity generation. Innovations in emerging exploitation systems, such as advanced and engineered geothermal systems (AGS and EGS), are expanding the potential for geothermal use. New geothermal applications include geothermal energy storage, data center cooling, green hydrogen production, and hybridization with other renewables such as solar PV. Geothermal can also be deployed in synergy with well-established industries, such as mineral extraction and carbon sequestration, further highlighting the versatility of geothermal.

While geothermal accounts for a small share of global energy, its technical potential is immense if emerging technologies mature to reach higher depths and temperatures. Current use of geothermal energy for heat and electricity represents less than 0.01 percent of its potential for each application. Unlocking the full potential of emerging geothermal technologies, AGS and EGS, requires more than USD 1 trillion, cumulatively, from 2025 to 2035.

The geothermal energy value chain encompasses a diverse network of stakeholders, from technology vendors to established power firms and start-ups. Long project timelines, high upfront costs, and specialized expertise characterize geothermal development. Collaboration with the oil and gas sector is rising, leveraging existing expertise and infrastructure to accelerate geothermal deployment.

Innovative business models are shaping geothermal energy's commercialization. Heat purchase agreements (HPAs) and power purchase agreements (PPAs) are fostering adoption, but challenges such as project economics and revenue certainty remain. The rise in geothermal power purchase agreements marks a new phase in the commercialization of emerging technologies.

Conventional geothermal energy is cost-competitive in many contexts, offering attractive levelized costs of heat (LCOH) and electricity (LCOE). However, emerging technologies such as EGS must achieve cost reductions to expand geographic applicability. Although high upfront investments remain a barrier for all power generation technologies, long-term advantages of geothermal include high-capacity factors, extended lifetimes, and possible returns on investment.

Policy interventions are critical to overcoming adoption barriers, including high upfront investment costs and technological risks. Research and development grants, feed-in tariffs, and public awareness campaigns have supported growth of geothermal globally. Notable examples include funding for innovative EGS systems in the US and EU, as well as financial incentives for heat pump adoption.

Geothermal energy is characterized by lower greenhouse gas emissions and limited land use compared to fossil fuels and other renewables. However, challenges include high water requirements for certain systems and radiation risks. Social acceptance remains a hurdle due to community concerns about induced seismicity and groundwater pollution, though geothermal energy supports job creation, particularly in developing economies.

This is an executive summary of the Kearney Energy Transition Institute's latest FactBook, Geothermal energy.

For the complete FactBook, please visit https://www.energy-transition-institute.com/factbooks.

Origin of geothermal energy

Geothermal energy is a form of renewable energy derived from Earth's heat stored in its crust. This heat originates from radioactive decay in the planet's core, residual heat from Earth's formation, and thermal exchanges of the shallower part of the crust with the atmosphere. Temperature increases by approximately 30°C per kilometer, with a global heat flux averaging 87 milliwatts per square meter. The availability of geothermal energy depends on geological factors such as volcanic activity, crust thickness, and fault networks, with regions of higher heat flow offering the greatest energy potential.

Scope definition

This FactBook intends to cover geothermal energy technologies beyond traditional heating and electricity generation. It includes systems leveraging the ground for heat pumps, energy storage, and high-temperature applications in untapped geological settings.

The focus is on technologies exchanging thermal energy with geological formations across all depths and temperatures (very low <30°C to high >150°C), with applications spanning from direct heat use to electricity generation, and thermal energy storage.

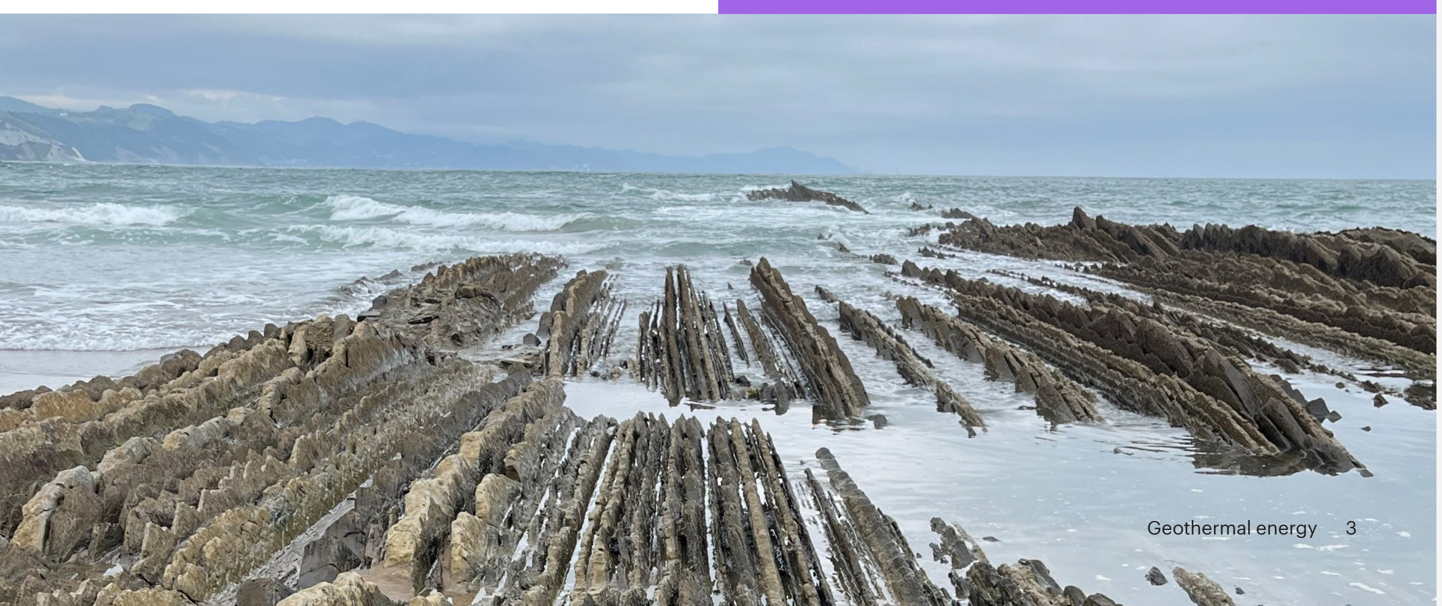
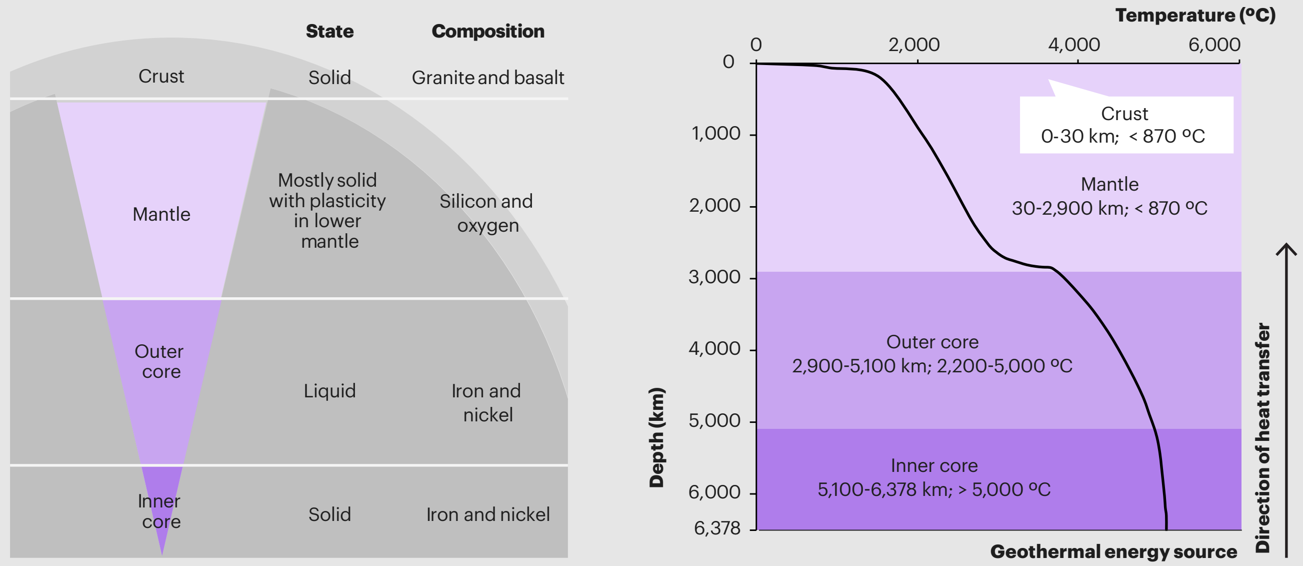


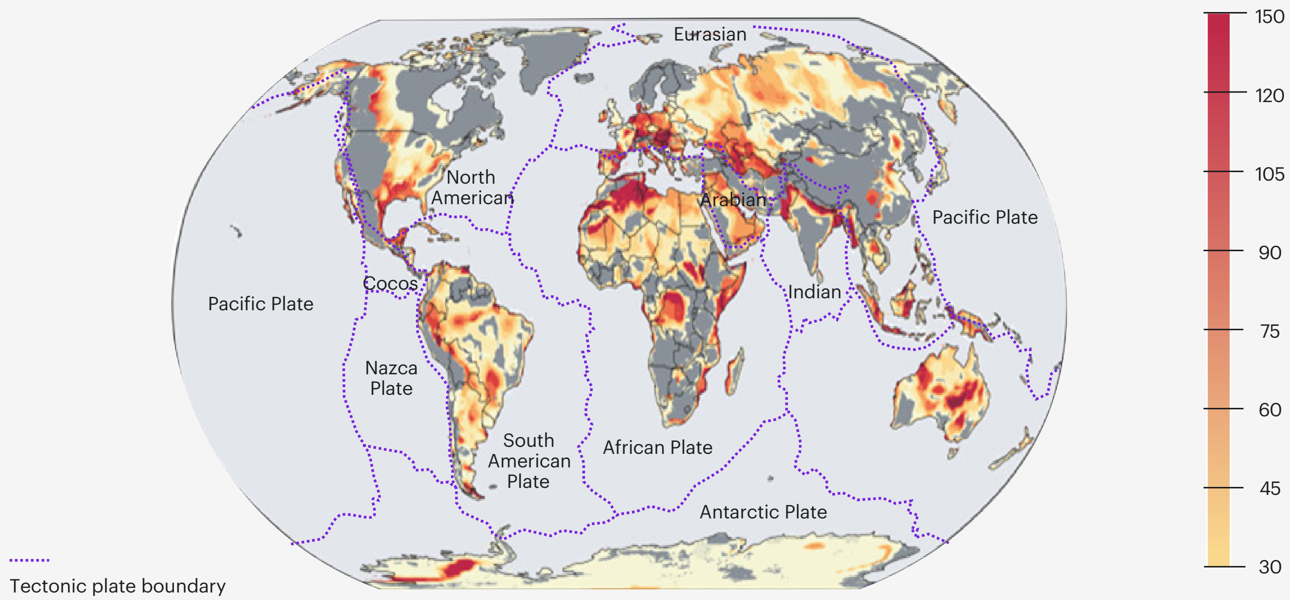
Figure 1
Geothermal energy systems from the Earth's core, which convects and conducts heat through the planet's layers to the surface



Sources: Ciucci, 2023, Innovative technologies in the development of geothermal energy in Europe; Earle, S., 2009, The Temperature of Earth's Interior; Geiger, 2019, Explainer: Earth - layer by layer; IEA, 2010, Renewable Energy Essentials: Geothermal; National Geographic, 2023, Geothermal Energy; Kearney Energy Transition Institute analysis

Figure 2
Geothermal energy availability

Global geothermal energy availability reflected by temperature distribution and tectonic plates
°C, 2020 at a depth of 3 km beneath the Earth's surface



Sources: EIA, 2022, Geothermal explained; Gutiérrez-Negrín, L.C.A., 2024, Evolution of worldwide geothermal power 2020-2023; Lund, W., 2024, Geothermal power; Kearney Energy Transition Institute analysis

Geothermal reservoirs are defined by a combination of temperature, geological formations, and reservoir conditions, such as natural porosity and the presence of fractures. These characteristics determine the quality of geothermal resources and their suitability for energy extraction, whether for heating or electricity generation. However, the distribution of geothermal energy is uneven across the globe, requiring targeted exploration efforts in high-potential areas.

Advancements in technology have enhanced the identification and utilization of geothermal resources. Techniques adapted from the oil and gas sector are now employed to explore and appraise geothermal sites more effectively. These technologies are also facilitating the development of artificial hydrothermal reservoirs that replicate naturally occurring systems.

Figure 3
Identification of geothermal prospects involves multiple methods inherited from the oil and gas industry

Geological methods	Geophysical methods	Geochemical methods	Drilling and well testing	Reservoir modeling and simulation
Study surface / subsurface geology to infer the presence of geothermal systems.	Measure physical properties of subsurface rocks to identify geothermal reservoirs.	Analyze chemical composition of fluids and gases to infer subsurface conditions.	Exploratory drilling is performed to directly investigate the geothermal resource, once potential sites are identified.	Data from various exploration methods is used to create static and dynamic reservoir models to simulate the geothermal systems and predict its behavior.
- Lithological surveys - Structural geology analysis - Surface mapping	- Seismic surveys - Rock properties surveys - Remote sensing and satellite imagery	- Water and gas sampling	- Temperature gradient wells - Exploration wells - Wireline logs - Flow testing	- 3D geological modeling - Reservoir numerical modeling

Geosciences methods **Drilling and modelling methods**

Sources: Kearney Energy Transition Institute analysis based on desktop research

Geothermal energy systems and technologies

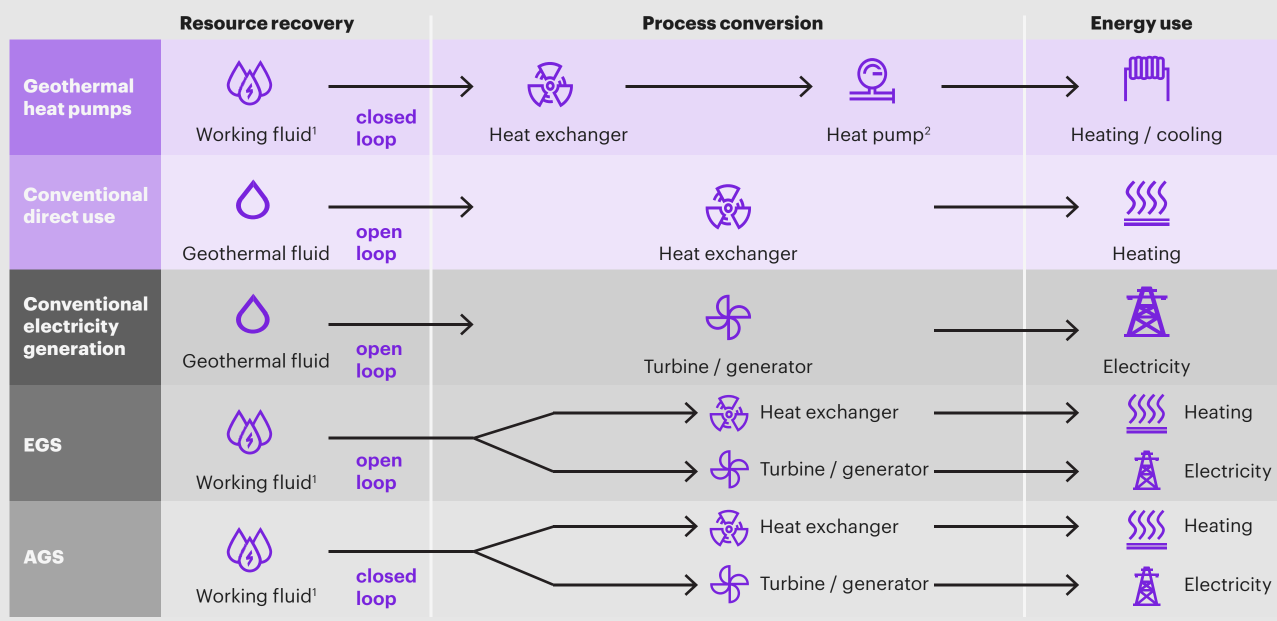
Geothermal energy has been utilized for millennia as a heat source and, for more than a century, as a means of electricity generation. Since the 2000s, advancements in technology have expanded its applications beyond traditional uses, solidifying its role in both heat provision and power generation.

The efficiency of geothermal heat and power systems is influenced by site-specific factors such as soil properties and thermal gradients, as well as system design to optimize heat transfer. Despite its potential, geothermal energy systems face risks such as thermal imbalance, resource depletion, and induced seismicity.

Geothermal energy systems include a variety of exploitation methods, such as geothermal heat pumps, conventional systems, advanced geothermal systems (AGS), engineered geothermal systems (EGS), and hybrid systems. These systems utilize different drainage designs, including open and closed loops, and employ vertical or directional well configurations depending on resource characteristics and project requirements.

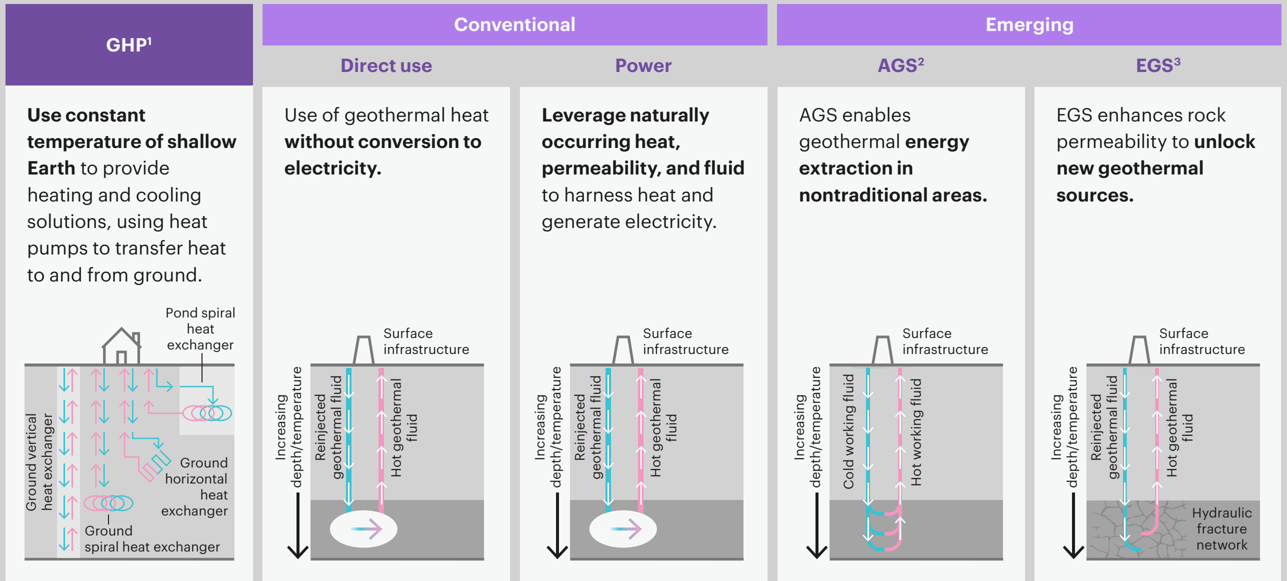
Figure 4
Working principle of geothermal heat provision and electricity generation

Leveraging the resource directly or transferring to other fluids



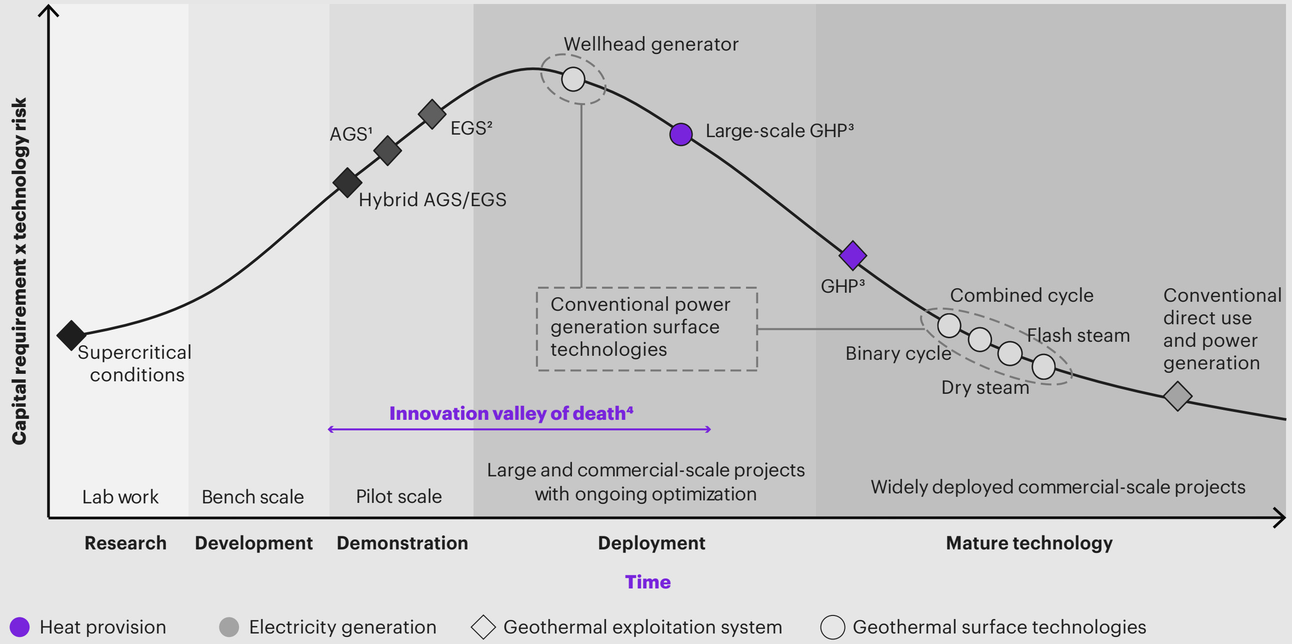
1. Working fluid can be water, an organic compound with a low boiling point, or a mixture depending on environmental regulations, safety considerations, and operating conditions. Working fluid traditionally refers to the fluid circulating through the turbine in a binary-cycle geothermal power plant. In the context of EGS, the term now also applies to the fluid pumped underground to extract heat from the reservoir.; 2. Heat pumps can be operated in reverse to deliver cooling.
Sources: EU Horizon Europe PUSH-IT, 2023, The Technologies; IRENA, 2020, Innovation Outlook: Thermal Energy Storage; IRENA, 2023, Global Geothermal Market and Technology Assessment; Kearney Energy Transition Institute analysis

Figure 5
There are a number of current and emerging technologies for the exploitation of geothermal energy



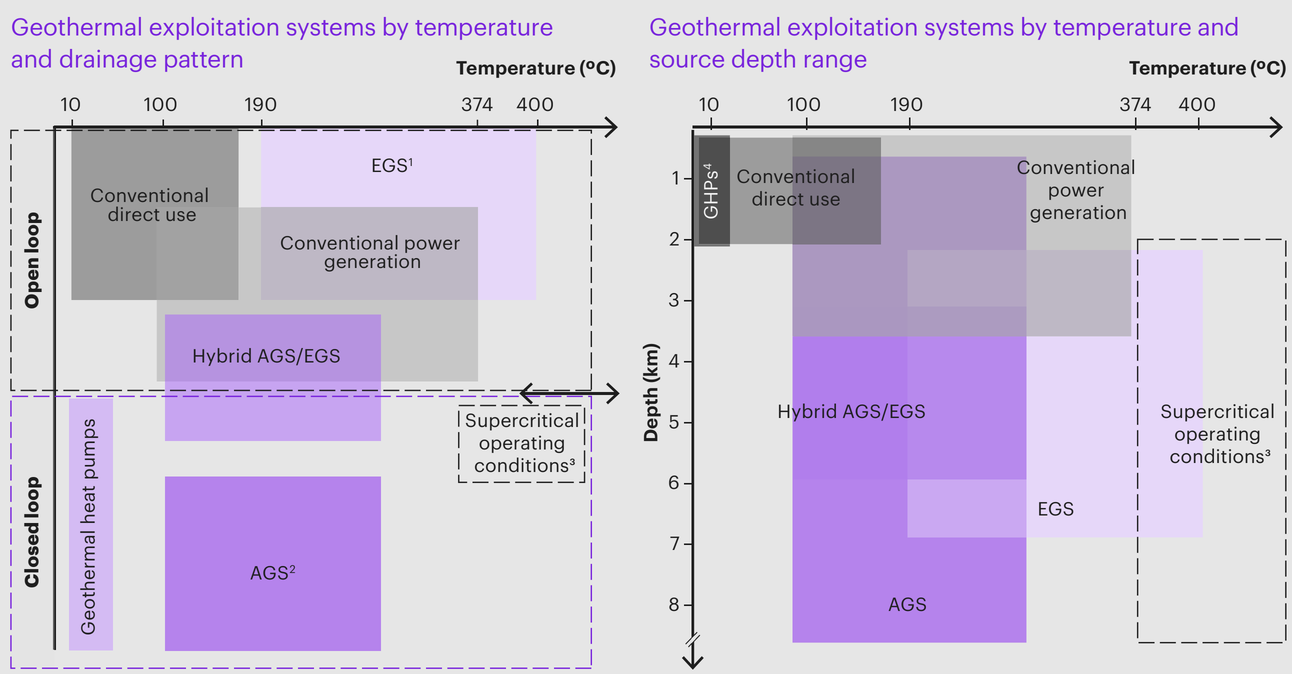
1. Geothermal heat pump; 2. Advanced geothermal system; 3. Engineered geothermal system
Source: Kearney Energy Transition Institute analysis

Figure 7
Maturity curve for geothermal exploitation systems and technologies



1. Advanced geothermal system; 2. Engineered geothermal system; 3. Geothermal heat pump; 4. Refers to a critical phase in new technology development where the initial momentum and early-stage funding have subsided, but the technology has not yet reached commercialization.
Sources: IEA, 2023, Clean Energy Technology Guide; Kearney Energy Transition Institute analysis

Figure 6
Geothermal exploitation systems by temperature, drainage pattern, and source depth range



1. Enhanced or engineered geothermal system; 2. Advanced geothermal system;
3. For example, pure water at temperatures exceeding 374°C and pressures exceeding 221 bar.; 4. Geothermal heat pumps.
Sources: Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; WU, A., 2024, Breaking Ground on Next-Generation Geothermal Energy; Kearney Energy Transition Institute analysis

Surface technologies for geothermal energy are tailored to the intended application. Heat provision relies on geothermal heat pumps and direct-use systems, while electricity generation is achieved through steam turbines employing surface technologies such as dry steam, flash steam, and binary cycles. Lower-temperature resources are typically used for heating, whereas higher-temperature resources are required for electricity production.

While most geothermal surface technologies are mature, only conventional exploitation systems are well established. Emerging technologies such as AGS and EGS show promise but remain under development. Research and development efforts are focused on improving well design, fracture control, and reservoir management for advanced systems, alongside innovations in surface technologies like geothermal heat pumps.

Current and emerging geothermal energy uses

Geothermal energy has long been utilized for heat provision in low-energy-intensive industrial and domestic settings, including space heating and cooling, bathing, recreation, and processes such as pulp and paper production. Electricity generation, though less widespread historically, has also been a significant application. The minimum temperature required from the geothermal source starts at approximately 10°C for heat provision and above 100°C for electricity generation.

Technological innovations enable new applications, such as powering and cooling data centers, producing green hydrogen, and co-locating with other renewables to complement generation profiles. Geothermal energy also provides opportunities for integration with other industries by extracting minerals such as lithium from geothermal brines, repurposing abandoned oil and gas wells, extracting a combination of hydrocarbon and steam from operating wells, and supporting carbon capture and storage.

Figure 8

Geothermal energy traditionally supplied heat and electricity for less-energy-intensive sectors, but increasingly addresses emerging demand and synergies

	Application	Heat provision	Electricity generation	Resource extraction
A Traditional uses	Space heating and cooling	Existing	Not applied	Not applied
	Bathing and recreation	Existing	Not applied	Not applied
	Agro-industry	Existing	Not applied	Not applied
	Low heat industry[1]	Existing	Existing	Not applied
B Emerging uses	Data centers	Existing	Existing	Not applied
	Renewable hybridization	Existing	Existing	Not applied
	Green hydrogen production	Existing	Existing	Existing
	Green ammonia production	Existing	Existing	Existing
C Synergistic uses	Mining industry	Existing	Existing	Existing
	Oil and gas industry	Existing	Existing	Existing
	CCS[2]	Not applied	Existing	Existing

● Existing ● Not applied

1. Pulp and paper processes, textile washing and dying, leather and fur treatment, etc.; 2. Carbon capture and storage
Sources: Kearney Energy Transition Institute analysis

Past and projected geothermal energy market growth

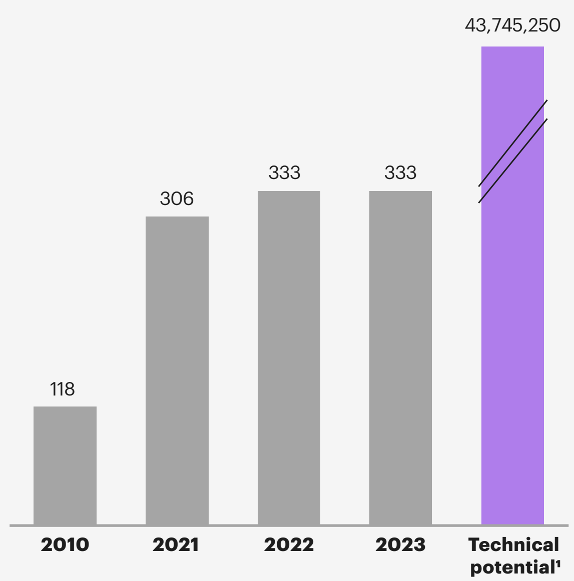
Geothermal energy has a global technical potential of 596 TW for electricity and 5,875 TW for heat. However, realizing this potential depends on the economic viability of geothermal projects. Currently, development is concentrated on easily accessible sites, while unlocking the remaining potential requires expanding the range of accessible locations through emerging technologies.

At present, geothermal energy utilization stands at approximately 333 TWh/year for heat provision and 100 TWh/year for electricity generation. These figures represent less than 0.01 percent of the global energy potential for each application, which is estimated at 43.8 EWh/year for heat and 4.4 EWh/year for electricity.

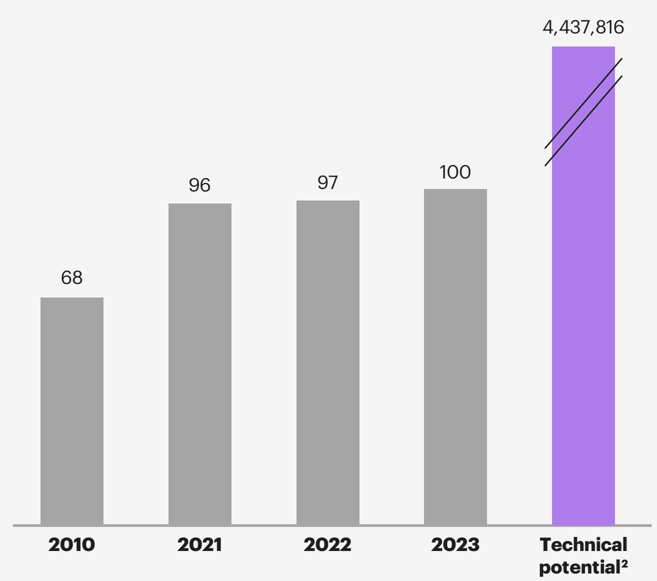
Figure 9

Geothermal technical potential

Geothermal heat provision and electricity generation relative to global technical potential
TWh/year, 2010-2023



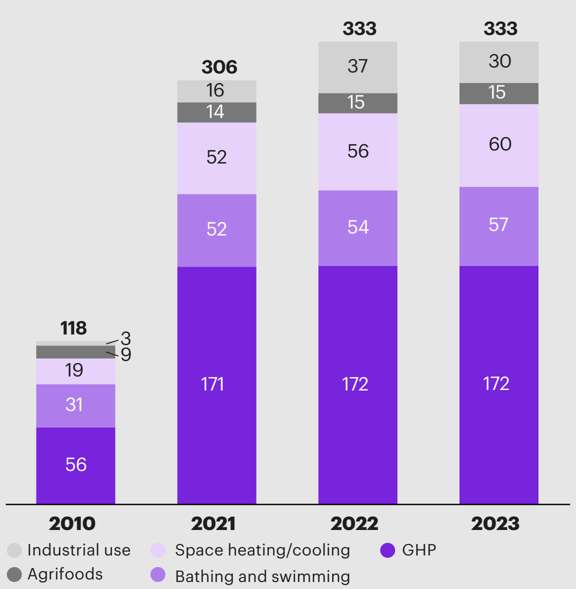
Geothermal electricity generation relative to global technical potential
TWh/year, 2010-2023



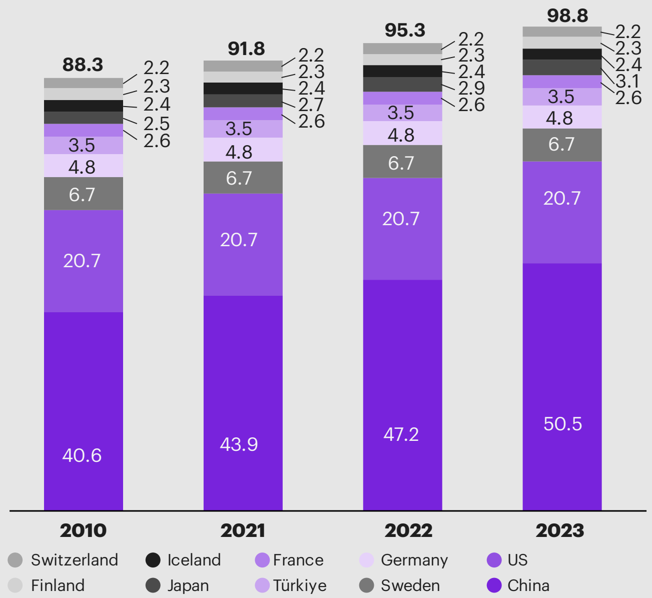
Note: Heat provision in this study is divided into direct use (industrial use, agrifoods, bathing and swimming and space heating), district heating and cooling (space heating and cooling) and geothermal heat pumps. 1. Considering a capacity factor of 40%; 2. Considering a capacity factor of 85%.
Sources: IPCC, 2014, Renewable Energy Sources and Climate Change Mitigation; IEA, 2023, World Energy Outlook 2023; IRENA and IGA, 2023, Global geothermal market and technology assessment; IEA, 2024, Renewables 2023; IEA, 2024, The Future of Geothermal Energy; Lund, J.W. and Toth, A. N., 2021, Direct utilization of geothermal energy 2020 worldwide review, Geothermics; IEA, 2024, World Energy Outlook 2024; Kearney Energy Transition Institute analysis

Figure 10
Geothermal heat provision

Geothermal heating generation by application
TWh/year, 2010-2023



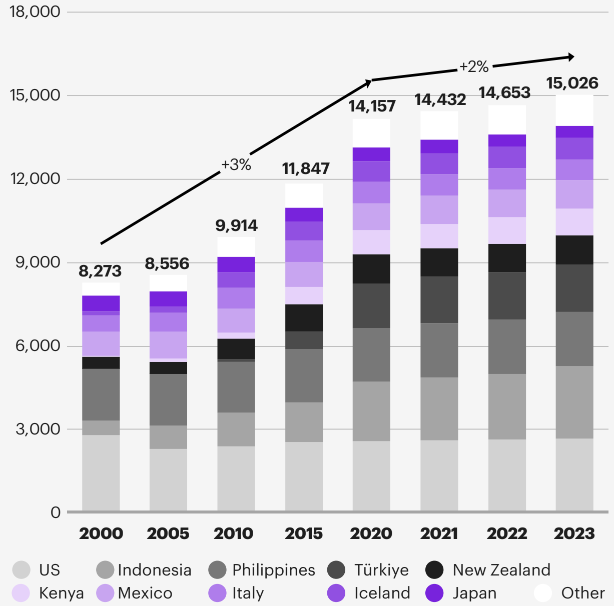
Top ten countries by geothermal heating installed capacity
TWh/year, 2010-2023



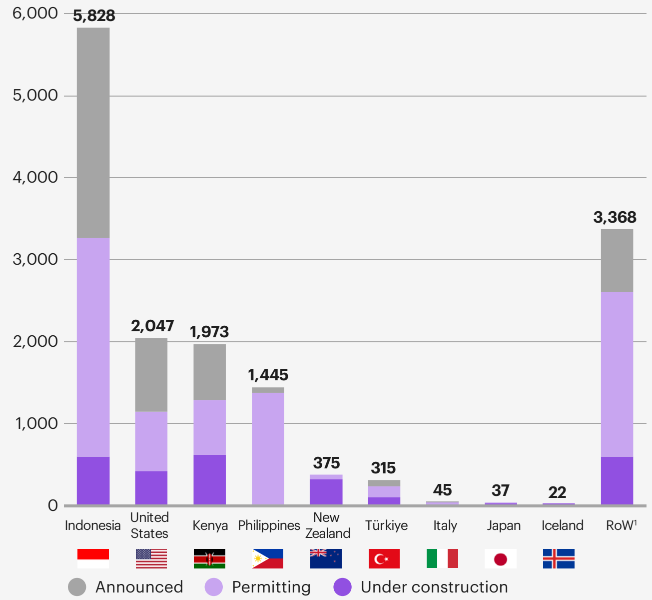
Note: The 2021-2023 capacity for geothermal heating and cooling applications is extrapolated from 2000 to 2020, while the 2022-2023 values for the top 10 geothermal countries from the 2020-2021 data.
1. Geothermal heat pump. Sources: IRENA and IGA, 2023, Global geothermal market and technology assessment; IEA, 2024, Renewables 2023; Lund, J.W. and Toth, A. N., 2021, Direct utilization of geothermal energy 2020 worldwide review, Geothermics; Kearney Energy Transition Institute analysis

Figure 11
Geothermal electricity generation

Installed geothermal electricity capacity by country
MW_e, 2000-2023



Pipeline of geothermal electricity capacity by country
MW_e, 2024-2034



1. Rest of world
Note: The data presented in the graph above, regarding announced, permitting, and under-construction projects, was extracted on September 2024.
Sources: IRENA, 2024, IRENASTAT Online Data Query Tool; IRENA and IGA, 2023, Global geothermal market and technology assessment; ThinkGeoEnergy, 2024, Top 10 Geothermal Countries 2023 – Power generation capacity; REN21, 2023, Renewables 2023 Global Status Report collection, Renewables in Energy Supply; Gutiérrez-Negrin, L.C.A., 2024, Evolution of worldwide geothermal power 2020-2023, Geothermal Energy; GlobalData, 2024, Geothermal Capacity by Power Plant data; Kearney Energy Transition Institute analysis

Geothermal heat pumps dominate heating applications, while China leads global geothermal heating capacity with 51 GW_{th} installed, representing 51 percent of the total capacity in 2023.

In today's electricity mix, geothermal contributes 0.3 percent, with potential to triple by 2030. Development is concentrated in 10 countries, led by the US, while Indonesia is driving new capacity with 38 percent of the pipeline.

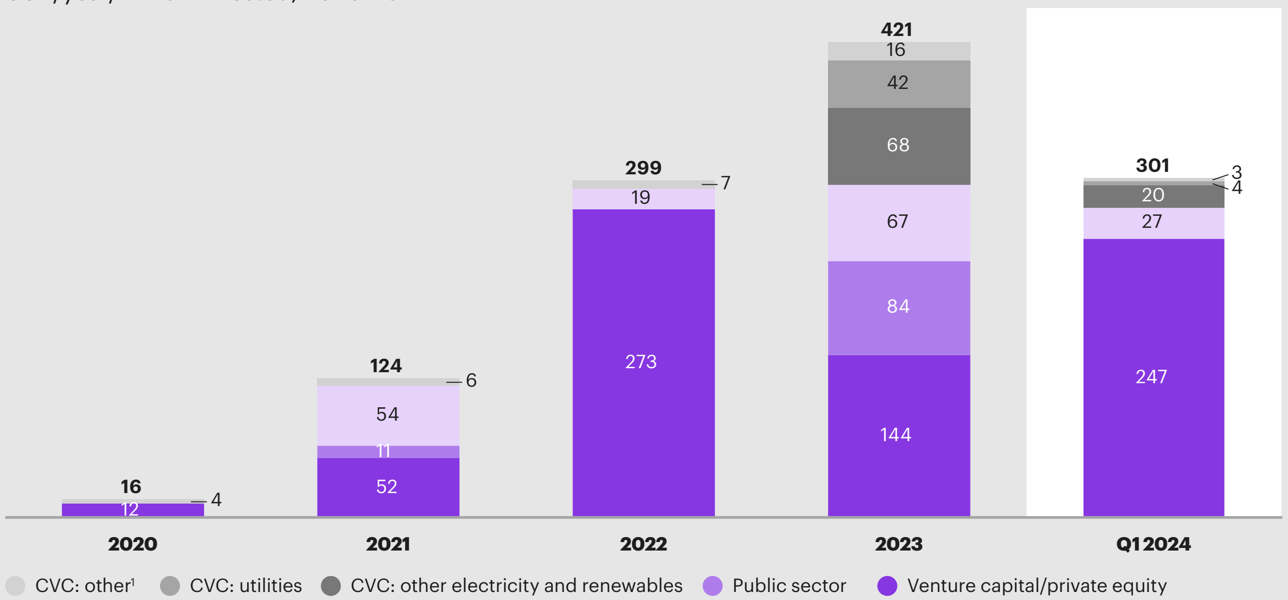
The number of geothermal wells drilled averaged 200 per year from 2015–2020. The drilling activity is projected to increase to 500 wells per year by 2025, driven by EGS and AGS advancements, with more than 10,000 active wells anticipated by 2030. However, most projects still rely on government support to succeed, due to the non-economic competitiveness of most of emerging geothermal solutions.

Start-ups are driving innovation in EGS and AGS, supported by rising venture capital investments, which grew from USD 368 million in 2022 to more than USD 420 million in 2023.

Geothermal investments surpassed USD 47 billion in 2023, comprising more than 5 percent of global renewable energy spending, with China contributing 70 percent. Unlocking the potential of emerging geothermal technologies, such as engineered geothermal systems (EGS) and advanced geothermal systems (AGS), requires cumulative investments of more than USD 1 trillion between 2025 and 2035 and USD 2.8 trillion between 2025 and 2050.

Figure 12
Public and private sector investments for emerging geothermal technologies

Annual investment in emerging geothermal by technology by investor type
USD/year/million invested, 2020-2024



1. Corporate venture capital
Sources: IEA, 2024, The Future of Geothermal Energy; Kearney Energy Transition Institute analysis

Geothermal value chain and project development

The geothermal energy sector is characterized by a fragmented and complex value chain, shaped by diverse applications and regional conditions. Successful geothermal heat pump and district system projects depend on precise resource assessment, tailored designs, efficient operations, and alignment of a full set of stakeholders across the value chain. Geothermal power project development, however, is a long-term endeavor, often spanning up to a decade from exploration to production.

The geothermal heat pump industry is highly competitive, with both global and regional players, while the district systems market is led by experienced manufacturers. These markets are fragmented and very local. The geothermal power sector, in contrast, relies on a specialized network of companies, with market concentration in component manufacturing and project development.

A growing trend is the involvement of traditional oil and gas companies in geothermal energy development. Leveraging their expertise in engineering, site identification, and wells repurposing, these players bring valuable capabilities to geothermal projects, expanding opportunities for collaboration and growth in the sector.

Japanese companies have emerged as key global suppliers of geothermal equipment, providing 67 percent of total equipment supplier capacity needed for electricity production. Traditionally, the geothermal power sector has been dominated by skilled operators, with the top 10 developers accounting for 57 percent of installed capacity (13.0 GW) and 39 percent of the pipeline (12.4 GW).

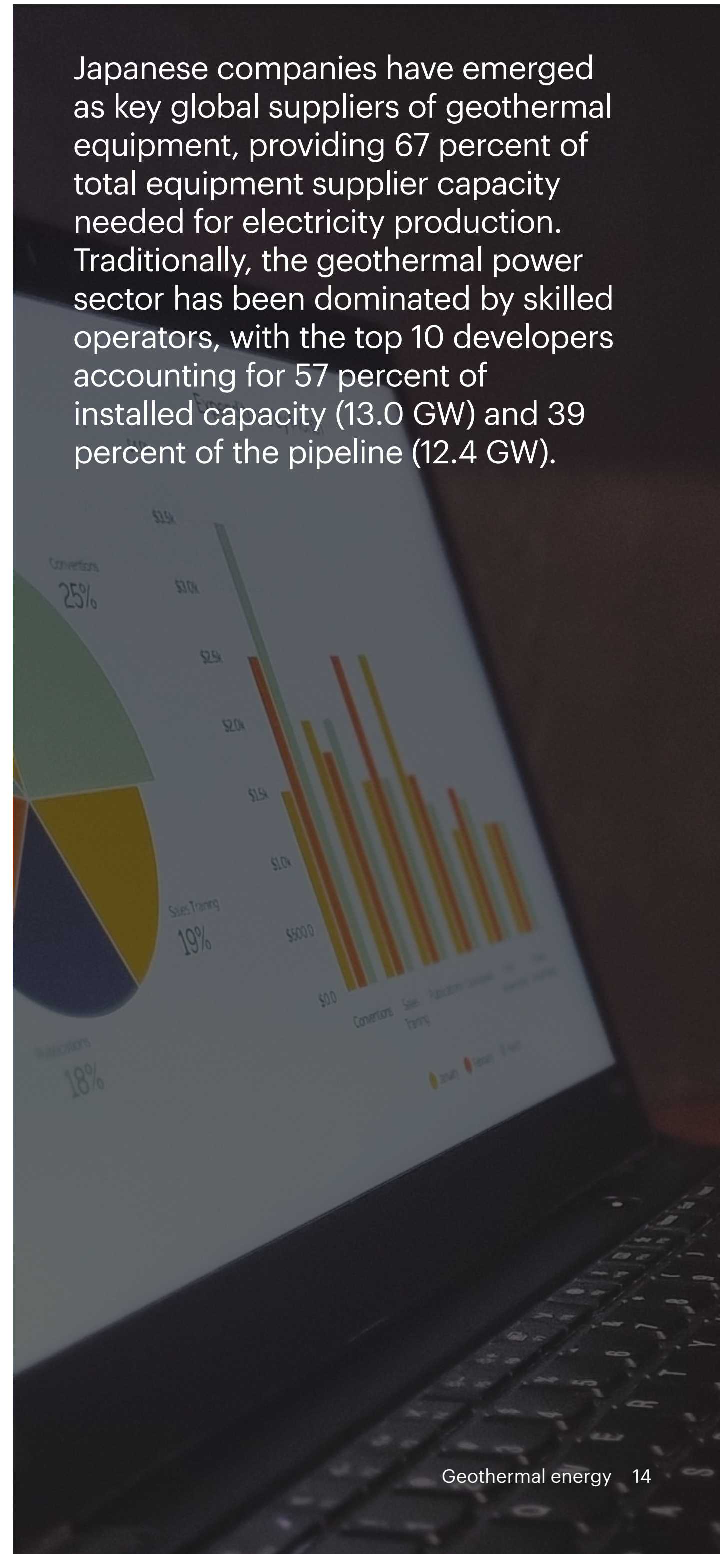
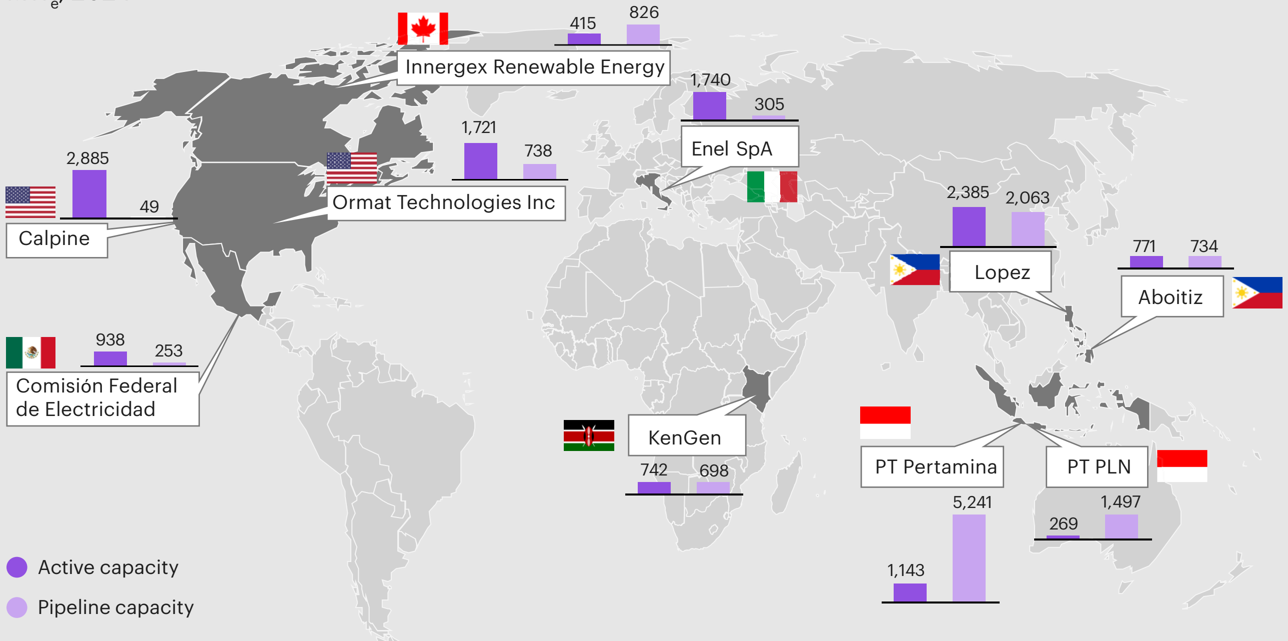


Figure 13

The conventional geothermal power industry has traditionally been dominated by operators with well-developed expertise

Geothermal electricity capacity of top 10 developers

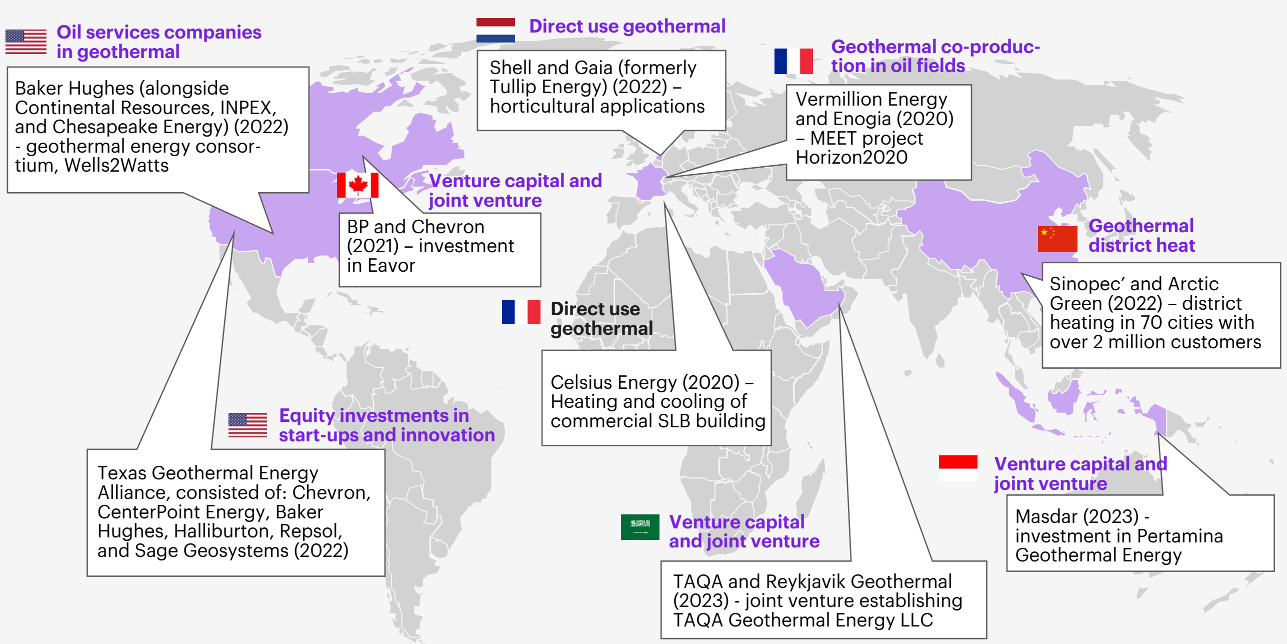
MW_e, 2024



Sources: GlobalData, 2024, Geothermal Capacity by Operator data; Kearney Energy Transition Institute analysis

Figure 14

Recent developments in the oil and gas geothermal industry



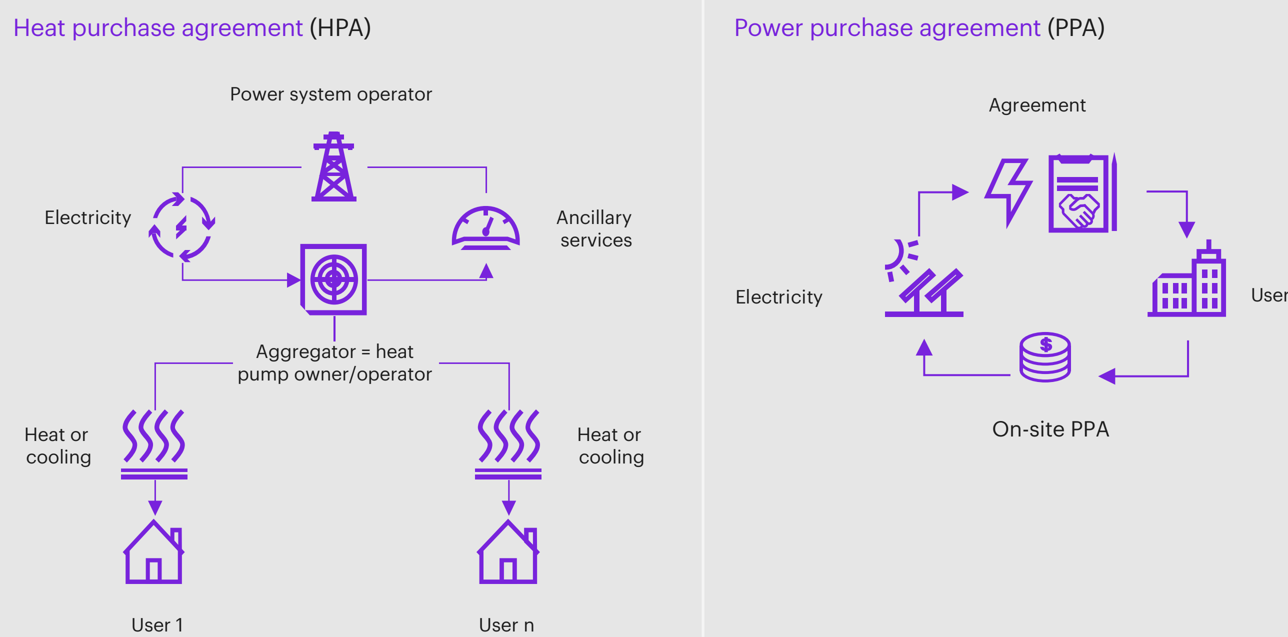
Sources: CMS, 2023, Oil & Gas and Geothermal: like steam, the oil & gas industry could rise to the occasion; Utility Dive, 2024, Geothermal developer Fervo Energy raises $244M as it builds 400-MW Utah project; Kearney Energy Transition Institute analysis based on desktop research

Business models for geothermal energy

Innovative business models are driving the adoption and commercialization of geothermal energy across various applications. For geothermal heat pumps, heat purchase agreements (HPA) under heat-as-a-service frameworks offer fixed pricing for heat networks and specific temperature settings, encouraging development. In district heating and cooling, business models vary widely. Some focus on selling heating and cooling services at pre-agreed prices, while others involve real estate companies investing in heat from multiple sources. Social initiatives also play a role in advancing these models.

Figure 15

Heat and power purchase agreement

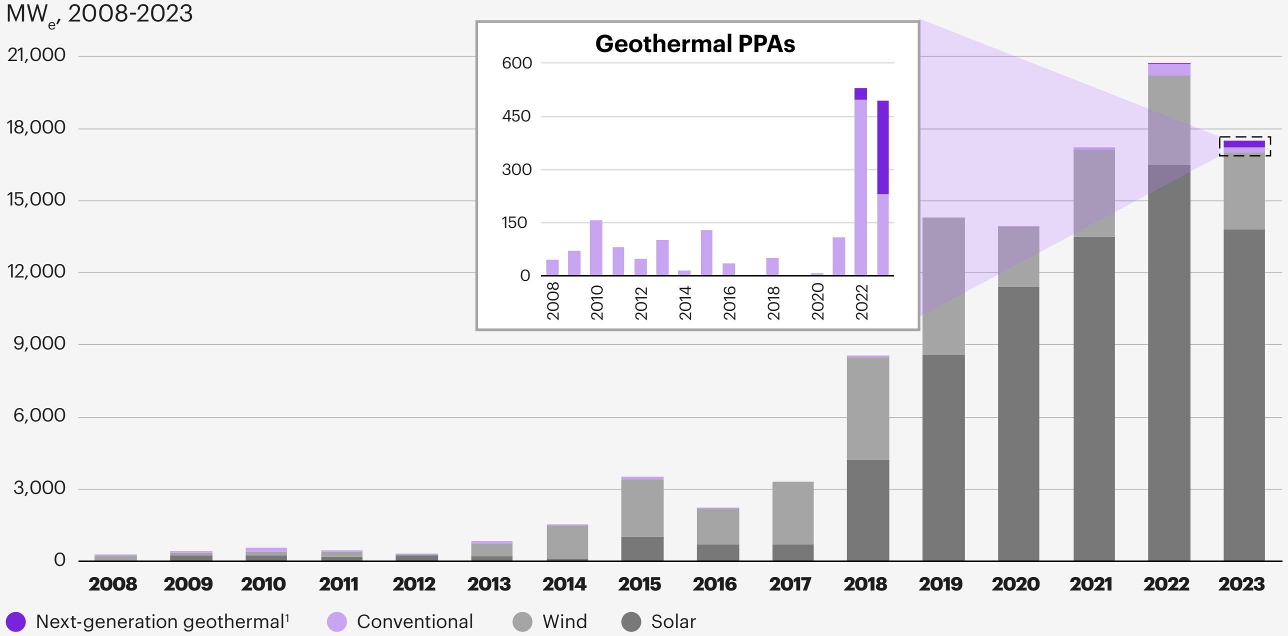


Sources: ClimateXChange, 2021, The potential of Heat as a Service as a route to decarbonisation for Scotland; IEA, 2024, The Future of Heat Pumps in China; Kircher, K. J. and Zhang, K. M., 2021, Heat purchase agreements could lower barriers to heat pump adoption, Applied Energy; Cluster TWEED, 2024, Smart contracts and virtual purchase agreement for water, heat and electricity; Kearney Energy Transition Institute analysis; Kearney Energy Transition Institute analysis

Figure 16
Geothermal power purchase agreements

Example

Renewables PPAs in the United States by technology type
MW_e, 2008-2023



1. According to BloombergNEF, next-generation geothermal includes EGS and AGS.
Sources: BloombergNEF, 2023, Next-generation geothermal technologies are heating up; BloombergNEF and The Business Council for Sustainable Energy, 2017-2024, Sustainable Energy in America 2017-2024 Factbook; ThinkGeoEnergy, 2024, Fervo signs 320-MW geothermal PPA with California utility; Fervo Energy, 2024, Fervo Energy Announces 320 MW Power Purchase Agreements with Southern California Edison; Kearney Energy Transition Institute analysis

For direct-use geothermal applications, primarily in industrial settings, business models are tailored to specific use cases. Their success often depends on regulatory support, financial incentives, and robust institutional frameworks. In electricity production, geothermal power purchase agreements (PPAs) are key to advancing the commercialization of emerging technologies.

Although geothermal PPAs represented less than 3 percent of renewable PPAs in the US in 2022, significant development occurred in 2024 with the agreement of a PPA for a 320 MW project, highlighting their growing competitiveness. However, the success of PPAs hinges on ensuring the constructed asset meets economic expectations under the contracted terms.

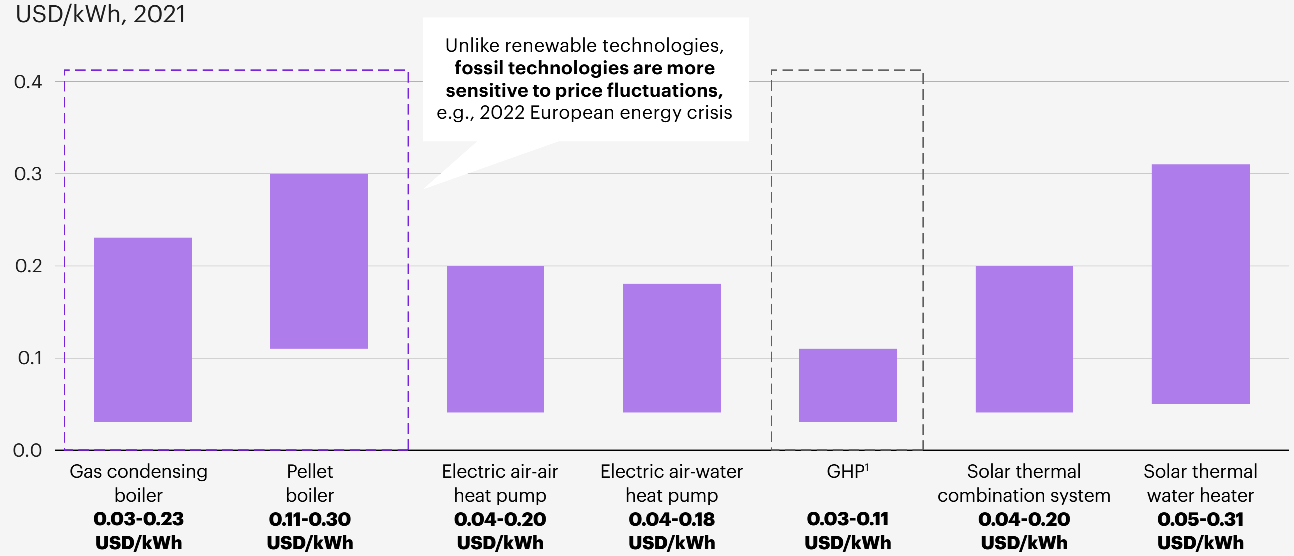
Cost of geothermal energy

Geothermal heat pumps offer a cost-effective heating solution, with levelized costs of heating (LCOH) ranging from 0.03–0.11 USD/kWh in Europe, competing with natural gas (0.03–0.23 USD/kWh). Geothermal district heating achieves even lower, though more varied, costs through economies of scale, at 0.004–0.417 USD/kWh.

Figure 17
Levelized cost of heat for heating technologies

Example

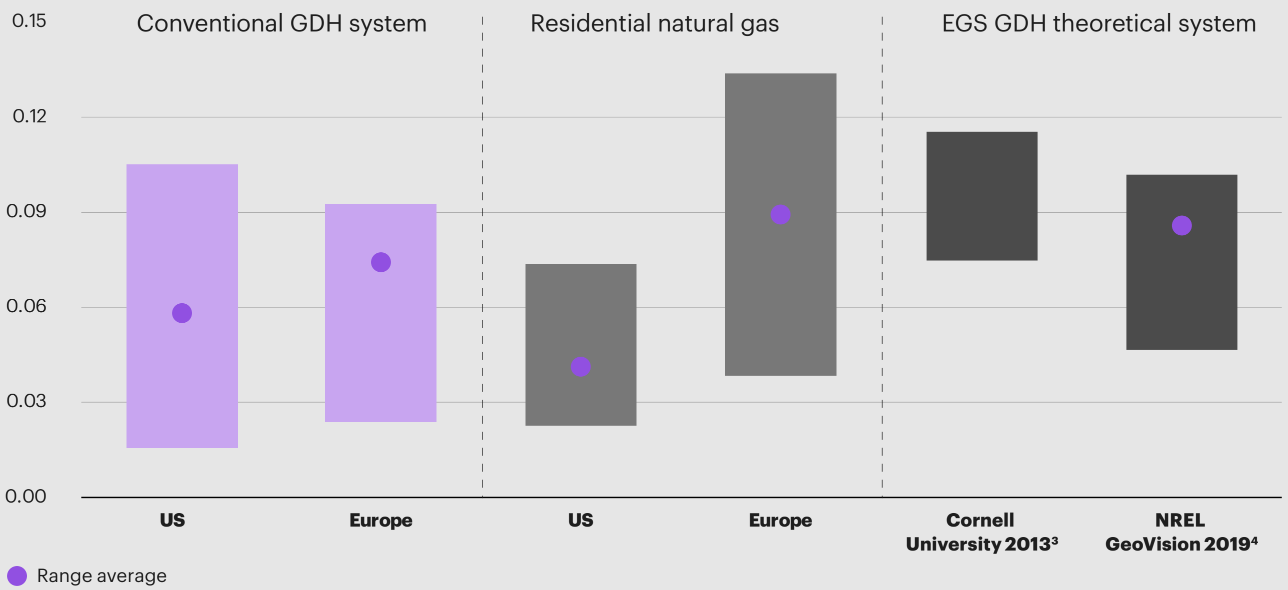
LCOH per selected technology
USD/kWh, 2021



1. Geothermal heat pump
Note: The ranges in the figure include the following countries: Canada, Denmark, France, Germany, United Kingdom and Sweden. The levelized cost of heating ranges shown here are simplified estimates provided for information. The calculation includes investment costs (including VAT., excluding ancillary costs and policy support), maintenance costs and fuel costs over the lifetime of the technology. It does not account for the cooling potentially supplied by reversible heat pumps. For GHP, we considered the lifetime of the borehole (assumed to last 60 years), with replacement of the compressor unit every 20 years. The calculation assumes constant average dwelling space and water heat demand for each country, constant average national end-user fuel prices at 2019 values (unless specified) and a 2% discount rate. In practice, parameters such as heat demand, total investment costs, technology lifetime and efficiency vary significantly across the building fleet, making each installation a specific case.Sources: IEA, 2021, Renewables 2021; NREL, 2021, 2021 US Geothermal Power Production and District Heating Market Report; Kearney Energy Transition Institute analysis

Figure 18
Levelized cost of heat for district heating technologies

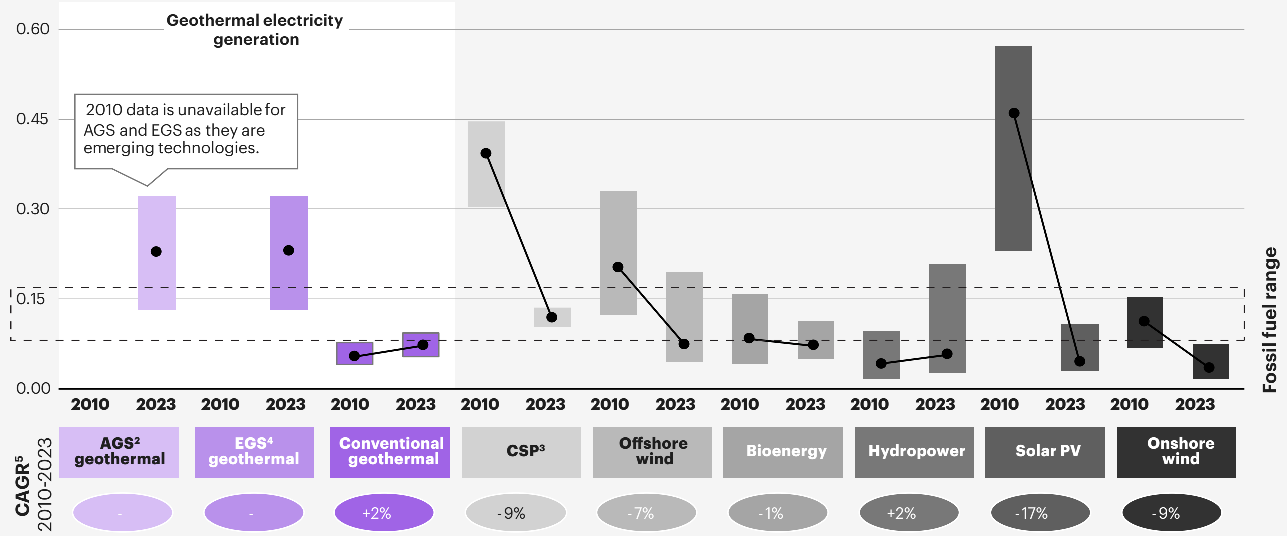
Worldwide comparison of geothermal district heating systems
USD/kWh 2021



1. Geothermal district heating; 2. Enhanced or engineered geothermal system; 3. Simulated LCOH values for EGS GDH systems in New York and Pennsylvania; 4. Simulated LCOH values for GDH systems nationwide using the dGeo tool in the GeoVision study.
Sources: NREL, 2021, 2021 US Geothermal Power Production and District Heating Market Report; Kearney Energy Transition Institute analysis

Figure 19
Levelized cost of electricity for power generation technologies

Global-weighted average LCOE[1] by power generation technology
USD/kWh, 2010 vs. 2023



1. Levelized cost of electricity; 2. Advanced geothermal system; 3. Concentrated solar power for which there is no value range given a lack of 2022 project data; 4. Enhanced or engineered geothermal system; 5. Compound annual growth rate. Sources: Altason, R.S. and Unnthorsson, R., 2015, Energy Return on Investment of Hydroelectric Power Generation Calculated Using a Standardised Methodology; CFI, 2024, Energy Return on Investment (EROI); IRENA, 2012, Concentrating Solar Power; IEA, 2024, The Future of Geothermal Energy; IRENA, 2024, Renewable Power Generation Costs in 2023; Latham, A. and Sharma, P., 24, Geothermal energy: the hottest low-carbon solution?; Madsen, T. N. and Kristensen, W.R., 2023, Major investors' returns on offshore wind sees drop after years of boom; Mansure, A.J., 2011, Are geothermal energy returns on investment high enough? McCloy, J., 2019, Solar ROI Calculator: An Easy Way to Determine Your Payback; NREL, 2024, 2024 Annual Technology Baseline; Wang et al., 2021, Energy return on investment (EROI) of biomass conversion systems in China: Meta-analysis focused on system boundary uni ication; Kearney Energy Transition Institute analysis based on desktop research

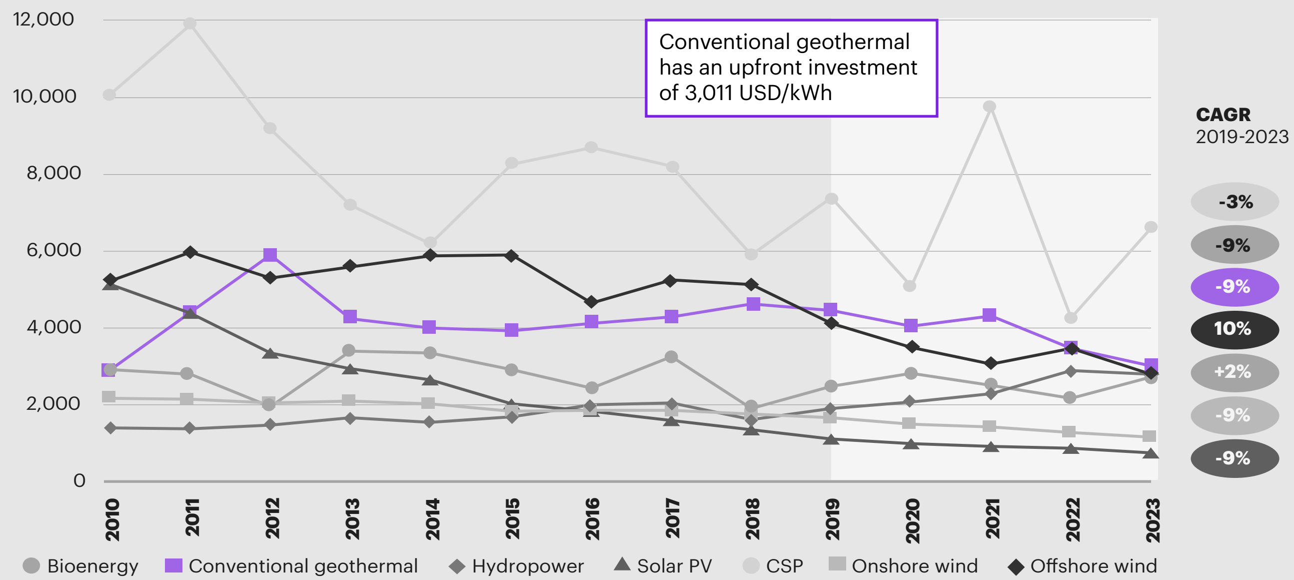
With a globally weighted average levelized cost of electricity (LCOE) of about 0.071 USD/kWh in 2023, conventional geothermal power remains higher than onshore wind (about 0.033 USD/kWh) and solar PV (about 0.044 USD/kWh). But it is a cost-effective alternative to fossil fuels (0.075–0.200 USD/kWh). Emerging technologies such as AGS and EGS, with an LCOE of about 0.230 USD/kWh, require cost reductions to expand their geographic applicability, especially as conventional site availability saturates.

Upfront investment is the primary cost driver for conventional geothermal power, representing about 80 percent of LCOE at 3,011 USD/KWh, higher than most renewables except concentrated solar power. These costs stem from the limited economies of scale, and extensive resource assessments. However, geothermal offers competitive long-term returns, with payback periods of 5 to 12 years and ROIs of 6 to 15 percent, supported by higher capacity factors and longer system lifetimes.

The comparison of the LCOE of conventional geothermal power with that of onshore wind and solar PV should also consider the different capacity factors of these technologies. Conventional geothermal power leads all renewables in capacity factor, averaging 82 percent in 2023, compared to solar PV, onshore wind, and offshore wind at 16 percent, 36 percent, and 41 percent, respectively. Unlike wind and solar, which are intermittent, geothermal power is almost fully dispatchable, offering greater reliability. Although operational and maintenance costs are high due to continuous reservoir management, this reliability ensures LCOE for conventional geothermal remains competitive with other renewable energy sources.

Figure 20
Upfront investment for power generation technologies

Global-weighted average upfront investment by power generation technology
USD/kWh, 2010 - 2023



Sources: IEA, 2024, World Energy Investment 2024; IRENA, 2024, Renewable Power Generation Costs in 2023; NREL, 2024, Annual Technology Baseline; Kearney Energy Transition Institute analysis

Policy intervention for geothermal energy

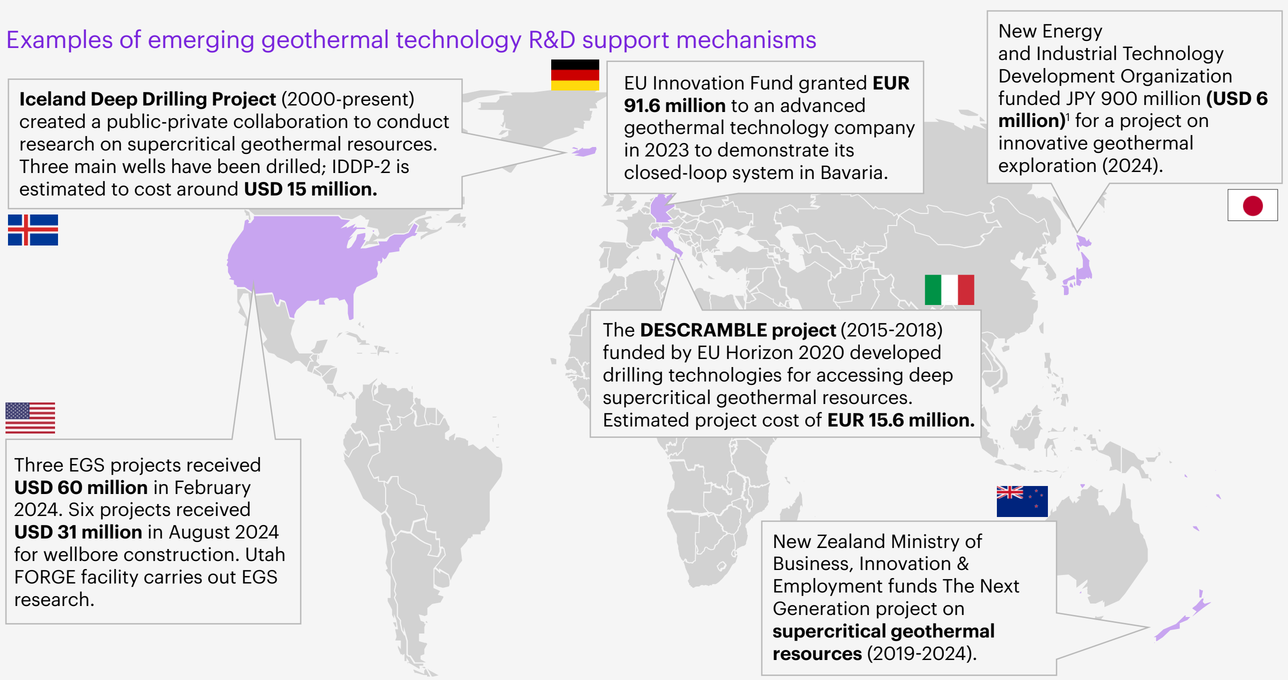
Energy policies play a critical role in promoting the adoption and commercialization of geothermal technologies by addressing key barriers, such as high upfront investment costs and technological risks (e.g., drilling operations, efficient heat transfer, and sustainable resource management). Initiatives such as research and development grants and feed-in tariffs help drive innovation and provide revenue certainty, strengthening the business case for investment.

Conventional geothermal power, while established, faces challenges from high upfront costs. Policies addressing financial risks, such as Türkiye's 10-year feed-in tariff for projects operational before 2026, have successfully spurred capacity expansion.

Emerging technologies benefit from a "supply push" through funding and knowledge-building efforts to reach demonstration stages. For instance, an advanced geothermal technology company received EUR 91.6 million from the EU Innovation Fund in 2023 to demonstrate its closed-loop system in Germany, while USD 60 million was allocated to three enhanced geothermal systems (EGS) projects in the US in 2024.

Figure 21
Emerging geothermal technology R&D support mechanisms

Examples of emerging geothermal technology R&D support mechanisms



1. Using a S1 2024 average exchange rate of 1 JPY = 0.006574 USD.

Sources: Descramble, 2018, DESCRAMBLE project; European Commission Directorate-General for Climate Action, 2023, The EAVORLOOP story: Harnessing the Earth's energy for a greener transition; Gallucci, M., 2024, Magma and hot rocks: Iceland seeks the future of geothermal energy, Canary Media; Hurst, N., 2016, Deep in the Heart of Iceland, There's a New Way to Tap the Earth's Energy, Smithsonian Magazine; NEDO, 2024, R&D for Innovative Technologies Applied to Geothermal Exploration and Exploitation; US DOE Geothermal Technologies Office, 2024, Funding Notice: Combined Wellbore Construction High Temperature Tools and Reservoir Thermal Energy Storage (RTES); Kearney Energy Transition Institute analysis

Figure 22
Leading GHP countries created demand-site mandates and incentives for heat pump adoption

Worldwide leaders in GHP capacity and supporting policies[1]

Country	Capacity MW_{th}, 2020	Sustainability policies	Financing frameworks
China	26,450	Central target of 65% building heat electrification by 2030, energy and carbon intensity targets in 14th Five-Year Plan.	Government funds set up to subsidize projects
US	20,230	State-level RPS,[2] national and state emissions targets.	IRA[3] 30% residential tax credit, 6-30% commercial tax credit, various state-level incentives.
Sweden	6,680	Carbon market price, EU targets.[4]	30% tax rebate on 35% of GHP cost, up to EUR 5,000.
Germany	4,400	Carbon market price, new fossil fuel boiler ban, EU targets.	Up to 30% of material and labor cost grant, 10% grant for replacing fossil fuel boiler.
Finland	2,300	Carbon market price, EU targets.	EUR 4,000 grant, up to 60% installation cost is tax-deductible.

1. Note that only about 15% of total heat pump sales globally are geothermal (ground-source) heat pumps. The fraction is greater in certain markets, such as Sweden and Finland, where air-source heat pumps are less efficient under cold weather; 2. Renewable portfolio standards; 3. Inflation Reduction Act; 4. Targets include Fit for 55 and RePowerEU, which aim to reduce CO2 emissions (by 55% by 2030) and increase energy independence (inter alia, reduce energy consumption by 11.7% by 2030), respectively.

Sources: EHPA, 2023, Subsidies for residential heat pumps in Europe; IEA, 2022, The Future of Heat Pumps; IEA, 2024, World Energy Investment 2024; IEA, 2024, The Future of Heat Pumps in China; IRENA, 2023, Global Geothermal Market and Technology Assessment; Lund, J. W. and Toth, A. N., 2021, Direct Utilization of Geothermal Energy 2020 Worldwide Review; Kearney Energy Transition Institute analysis

More mature technologies, such as geothermal heat pumps (GHP), thrive on a combination of demand- and supply-side policies. Leading countries in GHP capacity have accelerated technology development from demonstration to commercialization through financial incentives tied to energy transition goals.

District heating and cooling (DHC) systems are centralized and government-led, requiring strategic planning, particularly for next-generation DHC. These systems involve costly retrofits to transition from high-temperature fossil-based networks to low-temperature systems that integrate distributed heat sources and heat pumps. Government funding and public–private partnerships are essential to drive demand and support this transition.

Environmental impact and social acceptance

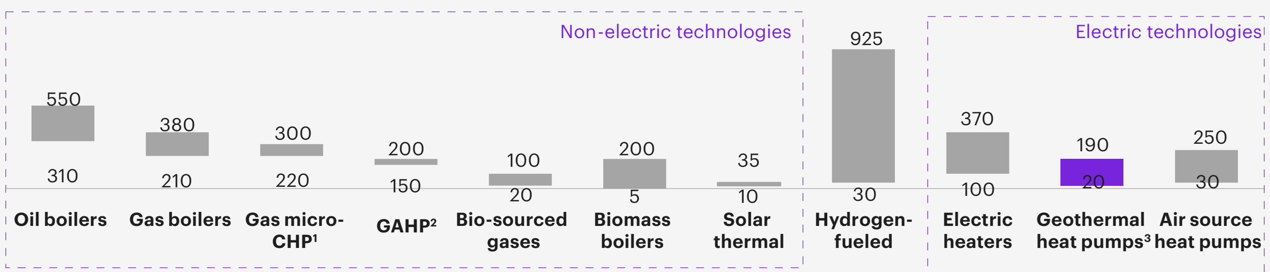
Geothermal heating and cooling systems have lower environmental impacts than fossil fuel-based systems but are influenced by the carbon intensity of the electricity used and can vary from 20 to 370 gCO_2-eq/kWh. Geothermal district heating and cooling systems reduce fossil fuel consumption and present a carbon footprint ranging from 6 to 470 gCO_2-eq/kWh.

Geothermal power produces fewer greenhouse gas emissions than traditional thermal sources, emitting 38 gCO_2-eq/kWh for conventional systems and 54 gCO_2-eq/kWh for enhanced geothermal systems (EGS), though these are higher than other renewables on a global average, but can be lower depending on the power mix of the country where the technologies are produced (see our Carbon emissions FactBook—e.g., up to about 57 gCO_2-eq/kWh for Solar PV). The wide carbon footprint range of conventional geothermal power generation is attributed to variations in the embedded GHG concentrations within geothermal reservoirs.

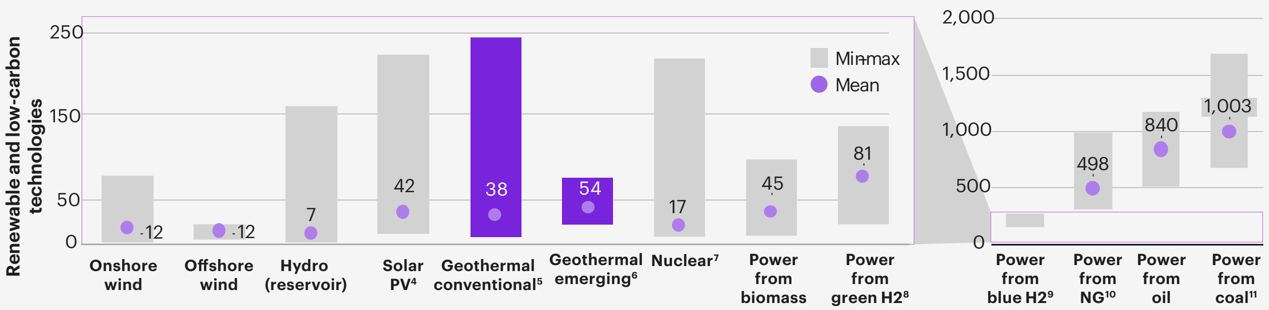
Figure 23

Life cycle assessment for selected heating, cooling, and power generation technologies

Carbon footprint for heating technologies in buildings (gCO_2-eq/kWh, 2016)



Carbon footprint for power generation technologies (gCO_2-eq/kWh, 2021)



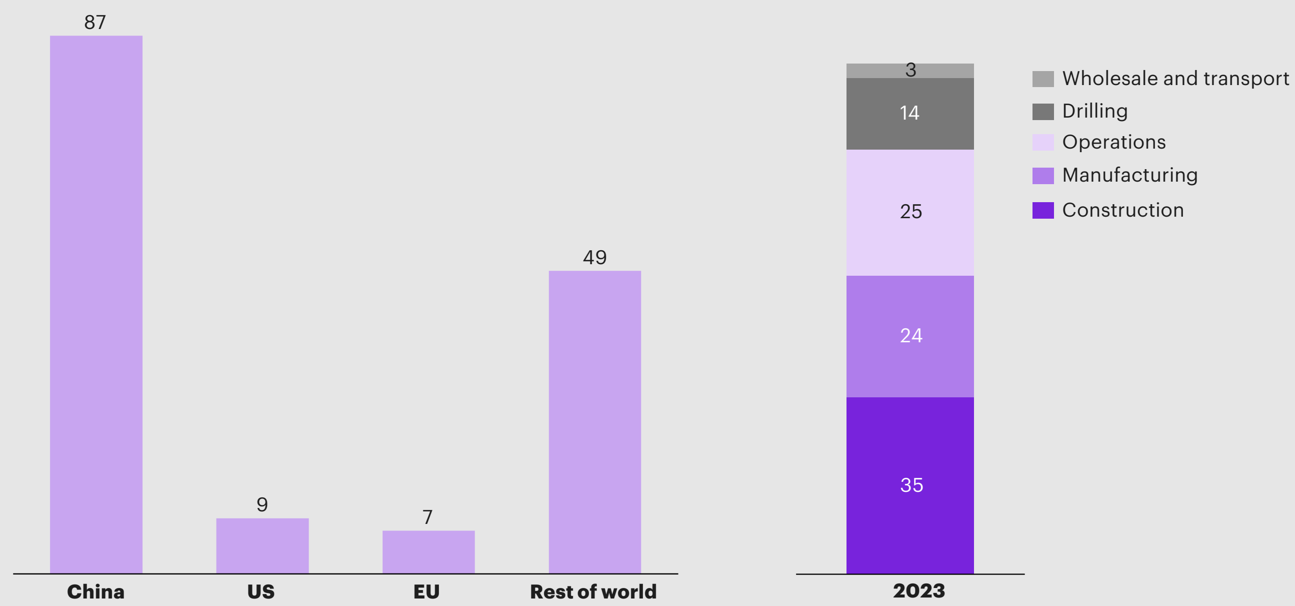
1. Gas micro combined heat and power is an emerging small-scale technology that uses gas in a boiler or fuel cell to generate both heat and electricity.; 2. Gas absorption heat pumps capture heat from the ground or air and transfer it inside a building, using a gas burner to operate the heat pumping cycle., 3. Also known as ground source heat pump; 4. Crystalline silicon, thin film; 5. Flashed steam; 6. Geothermal emerging technologies only include data on EGS. AGS data is unavailable in the literature as the technology is in its early commercialization phase, but it is known to produce no operational CO2 emissions.; 7. LWR, PWR, and BWR; 8. Green hydrogen values based on electrolysis from wind electricity with an overall yield of the power to hydrogen to power value chain of 22.8%; 9. Blue hydrogen values based on methane steam reforming with 93% carbon capture (with 0.2% fugitive methane emissions) with an overall yield of hydrogen to power value chain of 40.2%.; 10. Combustion turbine and combined cycle; 11. Subcritical, IGCC, fluidized bed and supercritical. Sources: Houses of Parliament Parliamentary Office of Science &Technology, 2016, Carbon footprint of heat generation; Litardo, J. et al., 2023, Air-conditioning life cycle assessment research: A review of the methodology, environmental impacts, and areas of future improvement, Energy & Buildings; Autelitano, K. et al., 2024, Towards life cycle assessment for the environmental evaluation of district heating and cooling: A critical review, Standards; NREL, 2021, Life Cycle Assessment Harmonization; Malek, A.E. et al., 2022, Techno-economic analysis of Advanced Geothermal Systems (AGS), Renewable Energy; Kearney Energy Transition Institute analysis

Figure 24

Social impact of geothermal technologies

Geothermal-for-power employment by selected region
Total thousand jobs, 2022

Geothermal-for-power employment by type
%, 2023



Sources: IRENA and ILO, 2023, Renewable energy and jobs: Annual review 2023; US DOE's Geothermal Technologies Office, 2019, GeoVision Analysis: Results, Opportunities, and Impacts; IEA, 2024, The Future of Geothermal Energy; Kearney Energy Transition Institute analysis

Geothermal also has one of the smallest land footprints, with most infrastructure located underground. However, some technologies pose radiation risks, in particular geothermal power has the highest exposure rates per unit of electricity generated among energy sources.

Geothermal energy provides significant social benefits, contributing about 1 percent of global renewable energy employment in 2022 and supporting more long-term jobs than other power generation technologies. In 2023, geothermal power employed 140,000 people globally, with 59 percent in construction and manufacturing, and 80 percent of jobs located in developing economies. Including heating and cooling applications, geothermal employment increases to 250,000 jobs.

The geothermal energy industry is offering an alternative to the oil and gas sector by leveraging synergies in construction, drilling, and operations, while providing opportunities for workers transitioning from oil and gas roles.

Acknowledgements

The Kearney Energy Transition Institute wishes to acknowledge the following people for their review of this FactBook: Dr. Charles Kutscher, Fellow at the Renewable and Sustainable Energy Institute from the University of Colorado and former director of the NREL Buildings & Thermal Sciences Center, as well as Dr. Adnan Shihab Eldin, Claude Mandil, Richard Forrest, Antoine Rostand, Martha J. Crawford, Erik Peterson, and Maria de Kleijn, members of the Kearney Energy Transition Institute board. Their review does not imply that they endorse this FactBook or agree with any specific statements herein. The review/assessment is based on reviewers' views and opinions but does not necessarily reflect the positions of entities they represent.

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The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. The Institute is dedicated to combining objective technological insights with economic perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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