Geothermal energy

Turning up the heat

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KEARNEY | Energy Transition Institute

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About the FactBook: Geothermal energy

The FactBook explores the working principles of geothermal energy for its key applications, considering the nuances between conventional approaches and emerging technologies that seek to exploit its full potential. The FactBook subsequently analyzes the past and projected market growth for geothermal energy and provides an overview of value chain development and business model design. Finally, the FactBook studies the competitiveness of geothermal energy with renewable and fossil-based alternatives from a cost perspective, explores the role of policy intervention in mitigating the key barriers to geothermal development, and highlights the environmental and social impacts of this technology.

About the Kearney Energy Transition Institute

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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Agenda (1/2)

Agenda (1/2)

Foreword

Geothermal energy has been harnessed for millennia, **traditionally used for heat provision** in relatively low-temperature settings (space heating, bathing, and process industries), and for **electricity generation** leveraging medium to high temperature sources.

Going beyond what is traditionally considered geothermal energy (i.e., direct heating and electricity production), **this report considers technologies that leverage the ground as a source / sink for heat pumps and as a means for energy storage, as well as emerging technologies harnessing higher temperature in previously unexploited geological settings.**

The geothermal technologies considered in this report conduct thermal energy exchange (extraction or storage) with geological formations, whatever the depth or temperature at which the exchange occurs, independent of maturity or economic competitiveness.

– **The technologies in scope cover a broad range of underground temperature**, from very low (< 30°C), low (30-90°C), and medium (90-150°C) to high (> 150°C),

– **As well as a large set of applications** from direct use of heat to conversion into electricity, or even the storage of thermal energy.

This versatility enables geothermal energy to contribute to a wide range of sectors, including residential heating, industrial processes, agricultural applications, and power generation.

As the energy transition progresses, geothermal energy has the potential to make significant contributions:

– **Heating and cooling** currently account for **~50% of global energy demand** and contribute to more than 40% of global energy-related carbon dioxide emissions; cleaner and more efficient methods of heating and cooling are critical to a decarbonized world.

– As **electrification and variable renewables** increase in the power mix, additional clean and dispatchable electricity generation options are key to ensure a secure energy supply.

Geothermal energy encompass three main categories of technologies[1], each with its own characteristics and applications

	Conventional			Emerging
	Geothermal heat pumps	Direct use	Power	AGS/EGS
Definition	– Technologies that use the constant temperature of the shallow earth to provide heating and cooling solutions. These systems utilize heat pumps to transfer heat to and from the ground.	– Use of geothermal heat without converting it to electricity, such as for space heating and cooling, food preparation, industrial processes, etc.	– Conventional geothermal systems are those having naturally occurring conditions of heat, permeability, and fluid presence. These systems are traditionally used to produce geothermal electricity from the geothermal heat.	– Advanced geothermal systems (AGS) are deep, large, artificial closed-loop circuits in which a working fluid is circulated and heated by subsurface rocks. – Engineered geothermal systems (EGS) are artificial geothermal reservoirs are created by drilling wells and injecting water to frack the rocks and create permeability.
Availability	– Everywhere at shallow depths	– Limited to locations with available hydrothermal reservoirs with fluids typically <100°C	– Limited to locations with available hydrothermal reservoirs with >100°C fluids	– Location with high ground temperature gradients but lacking water and porosity
Depth	– Shallow	– Variable	– Variable	– Deep
Temperature range	– Between >4 and 21°C	– Between 10 and 170°C	– Between >100 and 374°C	– Between 100 and 400°C
Loop	– Closed loop	– Open loop	– Open loop	– Closed loop/open loop
Applications	– Heating and cooling for buildings – Seasonal storage	– Heating for industrial activities requiring low temperatures, recreational bathing	– Electricity	– Electricity and heat

1. This report does not focus on geothermal energy storage. This early-stage technology is briefly described in the appendix, as a limited number of projects and information is currently available.

Sources: Enel, 2023, All the advantages of geothermal energy; IEA, 2024, World Energy Investment 2024; IRENA, 2024, Renewable Power Generation Costs in 2023; Gonzales, V., 2020, Geothermal Energy 101; LowCarbonPower, 2023, 1% of global electricity is generated from Geothermal; desk research on heating and cooling; Kearney Energy Transition Institute analysis

Geothermal energy responds in different ways to some of these challenges lying ahead as the energy mix evolves

	Conventional			Emerging
	Geothermal heat pumps	**Direct use**	**Power**	**AGS/EGS**
Lower emissions	– Geothermal heat pumps are **among the lowest carbon footprints** among electric and non-electric heating technologies, with **20-190 gCO_2e/kWh.**	– Direct use carbon footprint is poorly documented. The CO_2e/kWh is dependent on the geothermal brine composition. Nonetheless, geothermal direct use saved 126.4 tons of CO_2 by replacing oil for heating in 2020.	– Generates about **95% less CO_2** than fossil fuel fuels, with **~38 gCO_2e/kWh** relative to ~1,003 gCO_2e/kWh for coal and ~498 gCO_2e/kWh for natural gas.	– Generates about **95% less CO_2** than fossil fuel fuels, with **~38 gCO_2e/kWh** relative to ~1,003 gCO_2e/kWh for coal and ~498 gCO_2e/kWh for natural gas.
Longer lifetime	– Geothermal heat pumps have a lifetime of **20-50+ years**, compared to 15-30 years+ for gas boilers.	– Geothermal direct use has a lifetime of **~30 years**.	– Grid-scale facilities have a **~25 year** lifespan.	– AGS and EGS are expected to have a lifetime of **20-30 years**.
Small space requirement	– Similar above-surface requirements as other heating alternatives		– Geothermal plants have **relatively smaller footprint** – ~0.45 km^2/TWh compared to ~120 km^2/TWh for wind and ~20 km^2/TWh for solar photovoltaic.	– **Land-use intensity values for AGS and EGS are currently unavailable** but are expected to be comparable to conventional geothermal systems.
Competitive levelized cost	– **Geothermal district heating** has a levelized cost of heat between **0.02-0.14 USD/kWh**. For **residential** systems, the costs range from **0.03-0.11 USD/kWh**.	– **Geothermal direct use** has a levelized cost of heat between **0.02-0.10 USD/kWh**.	– **Conventional** geothermal has a levelized cost of electricity of **~0.071 USD/kWh, making it highly competitive with fossil fuels, which range from 0.075 to 0.200 USD/kWh**.	– LCOE of **unconventional** technologies is between **1.5 and 4 times higher**.
Improved energy security	– Reduce reliance on fossil fuel imports of heating systems		– Reduce reliance on fossil fuels for electricity – Near unlimited supply, unlike finite fossil fuels.	– Reduce reliance on fossil fuels for electricity/heat – Near unlimited supply, unlike finite fossil fuels.
Increased industrialization	– Decentralized and scattered value chain, with greater localized investment and local players		– Potential to develop new and local value chains for raw materials needed in energy transition technologies (e.g., lithium production)	– Leverages expertise and technologies from the oil and gas sector, including advanced drilling and reservoir management.
Others	– Offers heating and cooling provision, instead of only heat	– Provides direct heat for **diverse applications**, with **high efficiency** and **minimal infrastructure requirements.**	– No need of critical minerals and materials – Greater availability compared to variable renewables and can operate as baseload in some cases.	– Greater availability compared to variable renewables and can operate as baseload in some cases.

1. Origin of geothermal energy

Origin of geothermal energy

Geothermal definition

– Geothermal is a form of **renewable energy** that is derived from the Earth's crust's natural heat.

– Geothermal heat originates from the planet's core and is **continuously replenished by the decay of radioactive elements, as well as residual heat from the Earth's formation.**

– The temperature increases with depth at an **average gradient of ~ +30ºC/km of depth** and an average heat flux of ~87mW/m² globally.

Geothermal energy source

– **Geothermal thermal gradient varies significantly due to local geological conditions,** which include volcanic and tectonic activity, variations in crust thickness, and fault networks.

– Heat radiates more easily toward the surface, creating regions with greater geothermal energy, but which are **unevenly distributed across the globe**.

– Key characteristics define geothermal reservoirs' quality, based on a combination of **temperature ranges, geological formation, and reservoir conditions** (natural porosity and fractures) can create favorable subsurface conditions for geothermal energy extraction.

Geothermal resource identification

– **Technologies from the oil and gas sector** are now being used in an effort to explore, appraise, and create artificial hydrothermal reservoirs that mimic the naturally occurring ones that have been used to power the world's commercial geothermal power plants to date.

1.0 Chapter summary

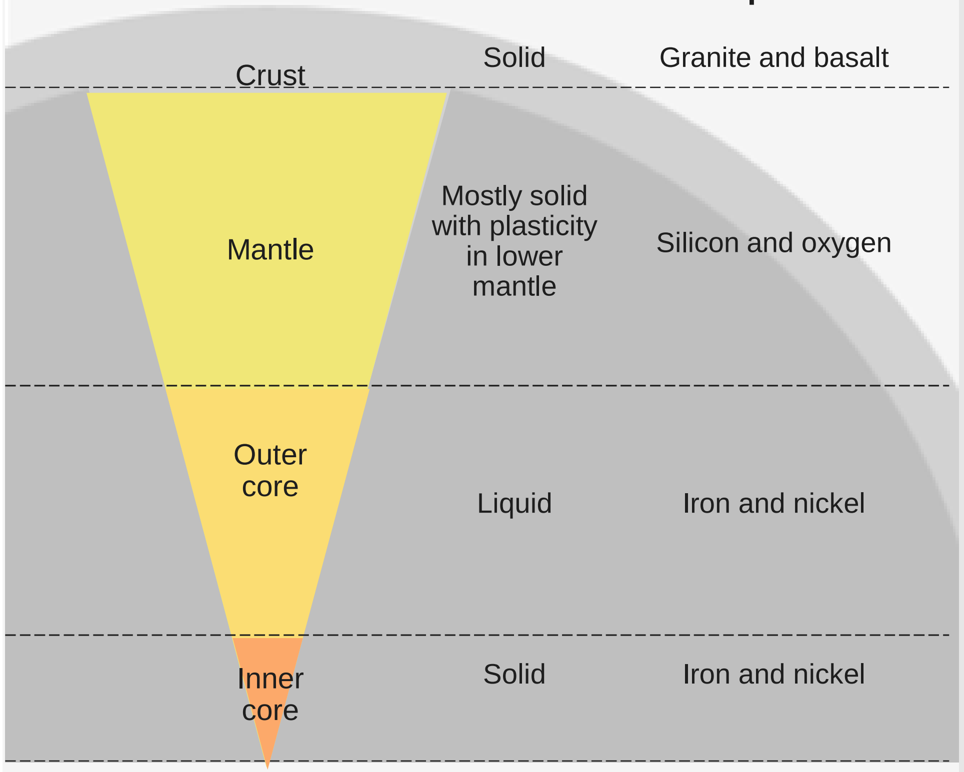
Geothermal energy refers to thermal energy transferred from beneath the Earth's solid surface

Heat transfer via the core's temperature gradient and magma flow to naturally occurring water and steam reservoirs at ~87 mW/m^2 creates stores of geothermal energy.

1.1 Geothermal energy definition

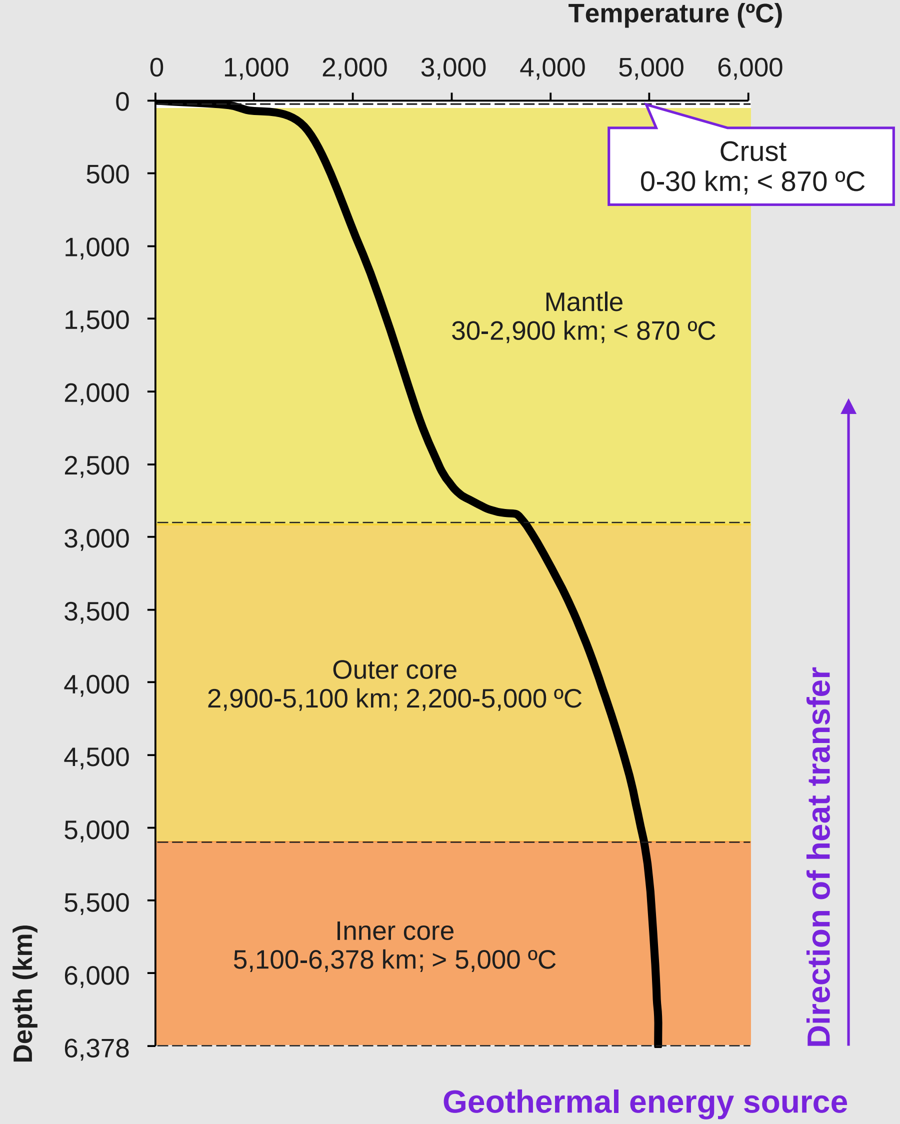
Geothermal energy stems from the Earth's core…

Geothermal energy **primarily stems from the heat stored in the Earth's core**, transferring heat to natural resources. **Radioactive decay of isotopes, such as uranium and thorium,** in the mantle and crust also contribute to geothermal energy potential.



	State	Composition
Crust	Solid	Granite and basalt
Mantle	Mostly solid with plasticity in lower mantle	Silicon and oxygen
Outer core	Liquid	Iron and nickel
Inner core	Solid	Iron and nickel

…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

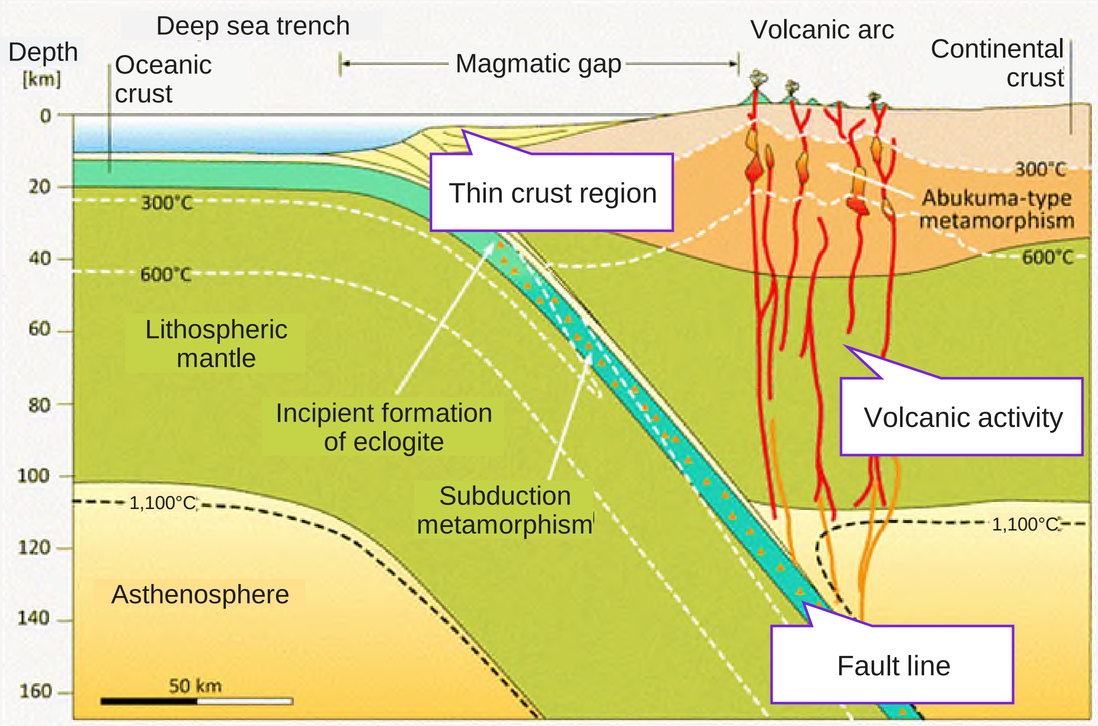
The crust’s tectonic movement creates areas of high geothermal activity for energy extraction

More easily accessible geothermal sources are located on or near tectonic plate borders…

- Availability of geothermal energy is dictated by the Earth’s geology, reflected by **varied temperature distributions at any given depth, represented by isotherms.**
- Areas of **high geothermal activity** correspond to active tectonic areas (subduction, rift) and volcanic areas (including “hotspots”)

Volcanic activity	**Magma rises toward Earth’s surface,** heating surrounding water and rocks to create reservoirs of hot water and steam, often manifesting as hot springs, geysers, and fumaroles.
Thin crust regions	**Hot spots are plumes of hot mantle material rising from deep within the Earth mantle.** A hot spot track can be formed over time as the tectonic plate moves over the hotspot (e.g., Hawaiian island).
Fault lines	**Increased permeability at fault lines allows water to seep through the Earth’s crust,** where it is heated by hot rocks or magma, and then return to the surface as hot water or steam (or accumulate to create a reservoir).

…where plates diverge and converge to induce volcanic and seismic activity



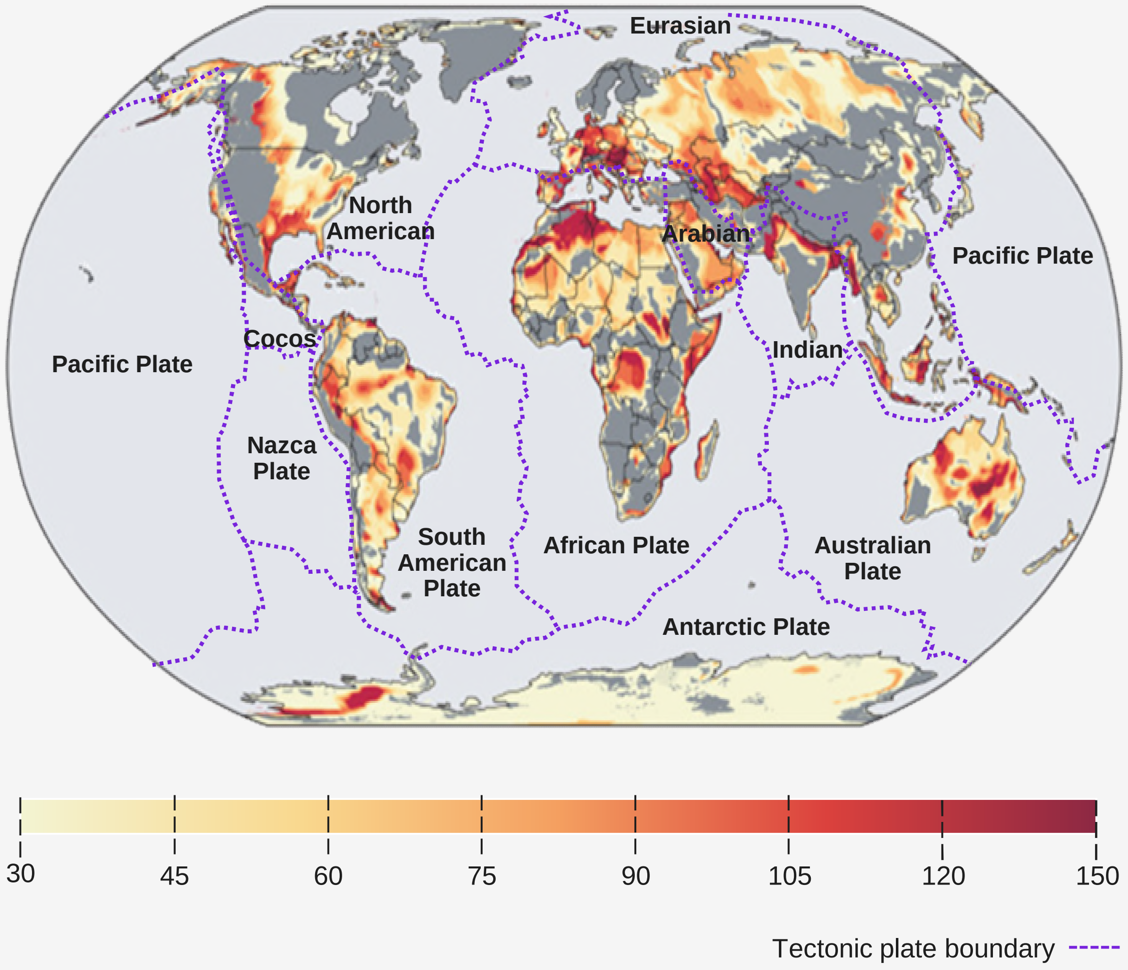
Sources: Frisch, W, 2014, Paired Metamorphic belt from Encyclopedia of marine geosciences; US National Park Services, Hotspots, accessed in January 2025; Kearney Energy Transition Institute analysis

The availability of geothermal energy is unevenly distributed across the globe and is influenced by plate tectonics

Illustrative

Global geothermal energy availability reflected by temperature distribution and plate tectonics

ºC, 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

Key zones of high geothermal activity

- **Pacific Ring of Fire** is a circle of geothermal activity formed by the collision of the Pacific Plate with the Australian, Eurasian, North American, and South American plates, creating geothermal sources in Indonesia, Japan, and the eastern USA.
- **Mid Atlantic Ridge** sits beneath Iceland, witnessing the divergence of the Eurasian and North American plates, which create a volcanic arc activity, compounded by the Earth's thin crust and the Reykjanes and Kolbeingsey fault lines.
- **East African Rift System** encompasses Kenya, Ethiopia, and Tanzania, referring to favorable geothermal energy conditions due to a divergent boundary where the African Plate splits; home to several active and dormant volcanoes, such as Erta Ale and Mount Kilimanjaro.
- **Mediterranean Region,** namely Italy, Greece, and Türkiye, fall in the boundary of the African and Eurasian plates.

1.2 Geothermal energy source

Geothermal energy sources are characterized by specific geologic features

Geothermal resources are present in all geological contexts; however, **readily accessible resources have favorable parameters in their natural state,** namely sufficient energy and fluid that can readily flow for effective convective heat transfer.

1.2 Geothermal energy source

I Temperature

Temperature of the reservoir formation and fluids, resulting from the Earth's thermal gradient and other specific heat sources (e.g., magmatic intrusion, hot fluid circulation, etc.)

- Energy extraction to date has considered geothermal resources **< 374 ºC.**
- Past 374 ºC, naturally occurring water is **supercritical,** behaving as gas with highly corrosive fluid.

< 100 ºC

100 ºC

190 ºC

374 ºC

> 374 ºC

Existing development (< 100 ºC to 374 ºC)

II Geologic setting

Includes the natural and physical properties of the reservoir and its surrounding geological formations (e.g., lithology, structural features, formation thickness)

- Ideal locations **often in proximity to tectonic plate boundaries.**
- Preference for specific rock types that **facilitate movement of water or steam for heat transfer.**

III Reservoir conditions

A set of physical parameters that controls the reservoir properties and behavior (e.g., porosity, permeability, wettability, temperature, saturation and composition of fluids, etc.)

- Reservoir requires **a sufficient volume of water or steam** for heat transfer.
- Rock formations must offer **sufficient porosity, fractures, and pressure for water or steam to circulate.**

	Rock type	*Natural porosity*[1]	*Natural fractures*
	Sedimentary (max depth 15 km)	●	◕
	Metamorphic	◔	◑
	Igneous	○	◔

● High ○ Low

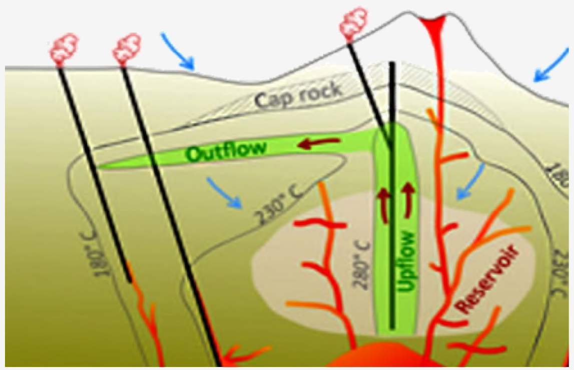
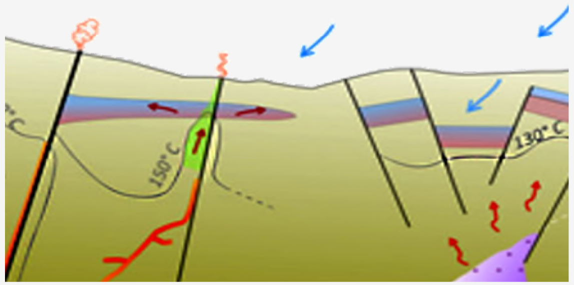
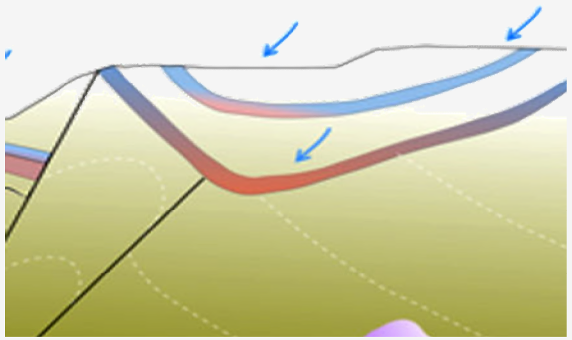
1. Natural porosity in metamorphic formations is highly variable depending on the intensity of the metamorphosis.
Sources: Kearney Energy Transition Institute analysis

Differences in geologic setting are reflected by the temperature of the geothermal source and severity of subsurface manifestations

Illustrative

Most of the existing conventional geothermal power plants are located in sedimentary rocks with temperature ranges above 100°C.

Indicative temperature ranges

	190-374ºC	100-190ºC	< 100ºC
			
Thermal energy source	Earth's core temperature gradient, magmatic intrusion, and volcanic activity.	Earth's core temperature gradient and magma intrusion.	Earth's core temperature gradient.
Most common host rock	Igneous rocks (e.g., granite, basalt)	Metamorphic rocks (e.g., andesite, gneiss), sedimentary rocks	Sedimentary rocks (e.g., sandstone, limestone)
Surface effects	Boiling springs, stream fields, fumaroles	Well-established hot springs, damaged soil, steam	Warm springs, mild soil alteration, limited steam

- Permeable sedimentary formations
- Basement rock
- Fold
- a) Granite; b) Radioactive granite
- Undifferentiated fault
- D) Dyke; S) Sill
- Active volcano
- Fumarole, hot/warm spring
- Meteoric water
- Hot water
- Heat
- a) Cold; b) Hot aquifer
- Isotherm (heat anomalies)

1. Geological formation that contains and transports geothermal fluids, such as hot water or steam.

Sources: Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; Kearney Energy Transition Institute analysis

1.2 Geothermal energy source

Identification of geothermal prospects involves multiple methods inherited from the oil and gas industry (1/2)

Geosciences methods

The identification and assessment of geothermal resources is a multidisciplinary process aimed at creating a comprehensive picture of the subsurface conditions that is essential for successful geothermal energy development.

1.3 Geothermal source identification

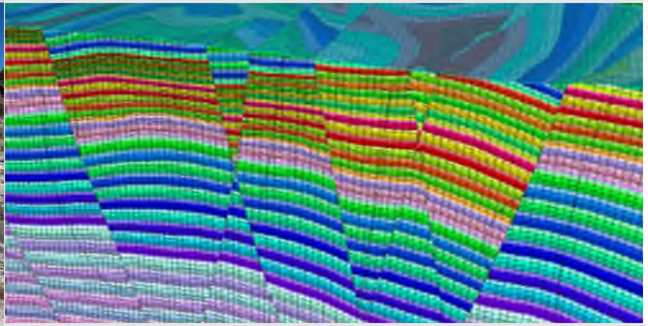
Geological methods

Study surface / subsurface geology to infer the presence of geothermal systems.

- **Lithological surveys**: characterize and map the types of rock generally associated with geothermal systems (e.g., volcanic rocks).
- **Structural geology analysis**: analyze geological structures, fault and fracture networks (crucial for fluid circulation in geothermal reservoirs) to infer subsurface geological conditions.
- **Surface mapping**: identify geothermal features such as hot springs, fumaroles, geysers, and altered ground areas.

Geophysical methods

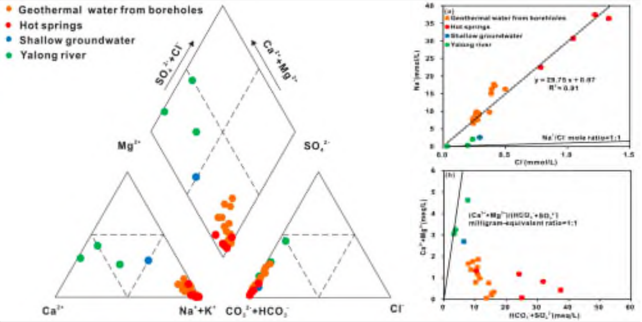
Measure physical properties of subsurface rocks to identify geothermal reservoirs.



- **Seismic surveys**: 2D/3D imaging of subsurface to characterize geological layers and occurrence of faults, fluids, and gases.
- **Rock properties surveys (gravity, magnetic, electric resistivity)**: measure various physical parameters to determine rock properties (lithology, porosity, fluid, etc.).
- **Remote sensing and satellite imagery** (Thermal Infrared Imagery, Landsat Imagery): use satellite and airborne tools to detect surface heat anomalies and geological features.

Geochemical methods

Analyze chemical composition of fluids and gases to infer subsurface conditions.



- **Water and gas sampling**: analyze chemistry and composition of geothermal fluids (e.g., hot springs water; CO_2, H_2S, and CH_4) to get insights on temperature, pressure, and depth of the geothermal reservoir and gas-water interactions.

Sources: Kearney Energy Transition Institute analysis based on desktop research

Identification of geothermal prospects involves multiple methods inherited from the oil and gas industry (2/2)

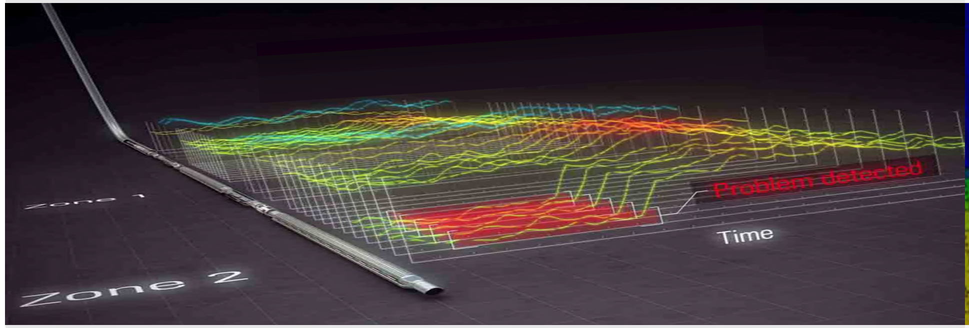
Drilling and modelling methods

The identification and assessment of geothermal resources is a multidisciplinary process aimed at creating a comprehensive picture of the subsurface conditions that is essential for successful geothermal energy development.

1.3 Geothermal source identification

Drilling and well testing

Exploratory drilling is performed to directly investigate the geothermal resource, once potential sites are identified.

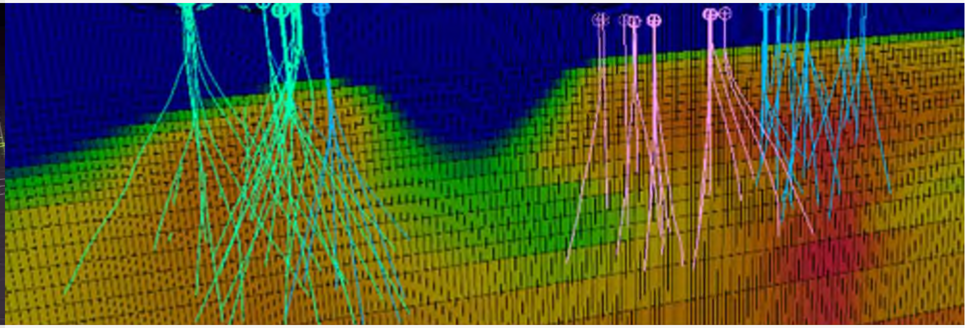


– **Temperature gradient wells**: shallow wells are drilled to measure the temperature at different depths to observe the subsurface temperature gradient.
– **Exploration wells**: deeper wells are drilled to directly access the geothermal reservoir, providing data on temperature, pressure, permeability, and fluid composition.
– **Wireline logs**: tools are lowered into drilled wells to measure various properties such as temperature, pressure, and rock and fluid properties
– **Flow testing**: after drilling, wells are tested to determine the production capacity by measuring the flow rate of geothermal fluids and the pressure response over time. This helps evaluate the potential energy output of the resource.

Sources: Kearney Energy Transition Institute analysis based on desktop research

Reservoir modeling and simulation

Data from various exploration methods is used to create static and dynamic reservoir models to simulate the geothermal system and predict its behavior.



– **3D (static) geological modeling**: combine geological, geophysical, and geochemical data into a 3D numerical model of the subsurface to visualize the geothermal system, refine exploration and geothermal development plan.
– **Reservoir (dynamic) numerical modeling**: integrate geological layers with reservoir properties (porosity, permeability, fluid content, pressure, temperature) to simulate the fluid flow, heat transfer, and pressure changes in the geothermal reservoir over time, helping to estimate the longevity and productivity of the resource and optimize the overall geothermal resource exploitation.

2. Geothermal energy systems and technologies

Geothermal energy systems and technologies

Past and present geothermal energy use

– Harnessed for millennia as a heat source and used for electricity for more than a century, innovation has moved **beyond the conventional applications of geothermal since the 2000s**.
– Currently harnessed for two mainstream applications–**heat provision and electricity generation**.

Working principle of geothermal heat and power production

– **Key factors influencing the efficiency** of geothermal heat and power systems include site-specific elements like soil properties and thermal gradients, and system design for effective heat transfer.
– Potential risks include **thermal imbalance**, **resource depletion, and induced seismicity**.

Geothermal exploitation systems

– **Reservoir exploitation methods:** geothermal heat pumps, conventional, advanced geothermal systems, engineering or enhanced geothermal systems, and hybrid systems,
– **Drainage systems:** open or closed loops,
– **Well design:** vertical, or directional.

Geothermal energy surface technologies

– **Heat provision:** geothermal heat pumps and direct use,
– **Electricity generation:** which are steam turbines including dry steam, flash steam, binary cycle, etc.

Geothermal systems features and performance

– **Lower temperature resources** are not suitable for electricity production and are **used primarily for heat provision**, **while sufficiently hot resources** are typically commercialized for **electricity generation**.

Technology maturity

– **Most geothermal surface technologies are mature**; however, **among exploitation systems**, only conventional geothermal are well established, while emerging technologies, such as **AGS and EGS, remain less developed**.

Geothermal R&D

– Research for exploitation systems is focused on **well design and planning, fracture control, and reservoir management** for advanced and engineered geothermal systems.
– The research for surface technologies has been mostly concentrated around **geothermal heat pumps.**
– The rush for innovation of exploitation systems and conversion technologies is reflected in the different **number of patents filed annually**.

2.0 Chapter summary

Since the 2000s geothermal innovation has moved beyond the conventional use of geothermal

The first documented geothermal district heating system, **Chaudes-Aigues in France, was developed in the 14th century** and is still operated today.

2.1 Past and present geothermal energy use

Timeline of geothermal energy commercialization

1818 — **François Jacques de Larderel first to harness energy for industrial use**, **inventing new way to extract boric acid from hot springs.**

1830 — **Asa Thompson first to commercialize geothermal energy** by charging 1 USD to use baths fed by hot springs.

1892 — **First geothermal district heating system established in Boise,** heating >200 homes and 40 businesses.

1904 — **Italian scientist, Piero Ginori Conti, first to use geothermal energy to power small generator,** which illuminated several light bulbs.

1907 — **Hot Lake Hotel, one of the first buildings to use geothermal energy as its primary heat source,** constructed in Oregon.

1913 — **First commercial dry steam power plant, Larderello, constructed.** Dry steam plants are the oldest forms of geothermal power and formed the basis for future designs.

1948 — **First commercial geothermal heat pump operational in Oregon,** pioneering large-scale commercial application of heat pumps.

1960 — **Geysers Geothermal Complex**, **the world's largest geothermal power plant,** constructed north of San Francisco on a 30-square-mile site, powered by steam from >350 geothermal wells.

1963 — **Wairākei Power Station opened in New Zealand;** the second geothermal power plant in the world and **first flash steam-powered plant.**

1967 — **First geothermal binary cycle** power plant operational.

2006 — **Chena Hot Springs Resort in Alaska** installed first power plant to produce energy at temperatures below boiling point of water.

2007-2016 — **Germany's Landau plant** (2007) and **France's Soultz plant** (2016) were the first two commercial-scale **EGS** power plants.[1]

2024 — **Eavor started constructing the first AGS commercial project** in Bavaria south of Munich near Geretsried, Germany.[2] The project is expected to produce energy by 2024.

1. The enhanced geothermal systems concept originates in the early 1970s from the "Hot Dry Rock" project at the Fenton Hill site in New Mexico, US.; 2. Advanced geothermal systems

Sources: Kearney Energy Transition Institute analysis based on desktop research

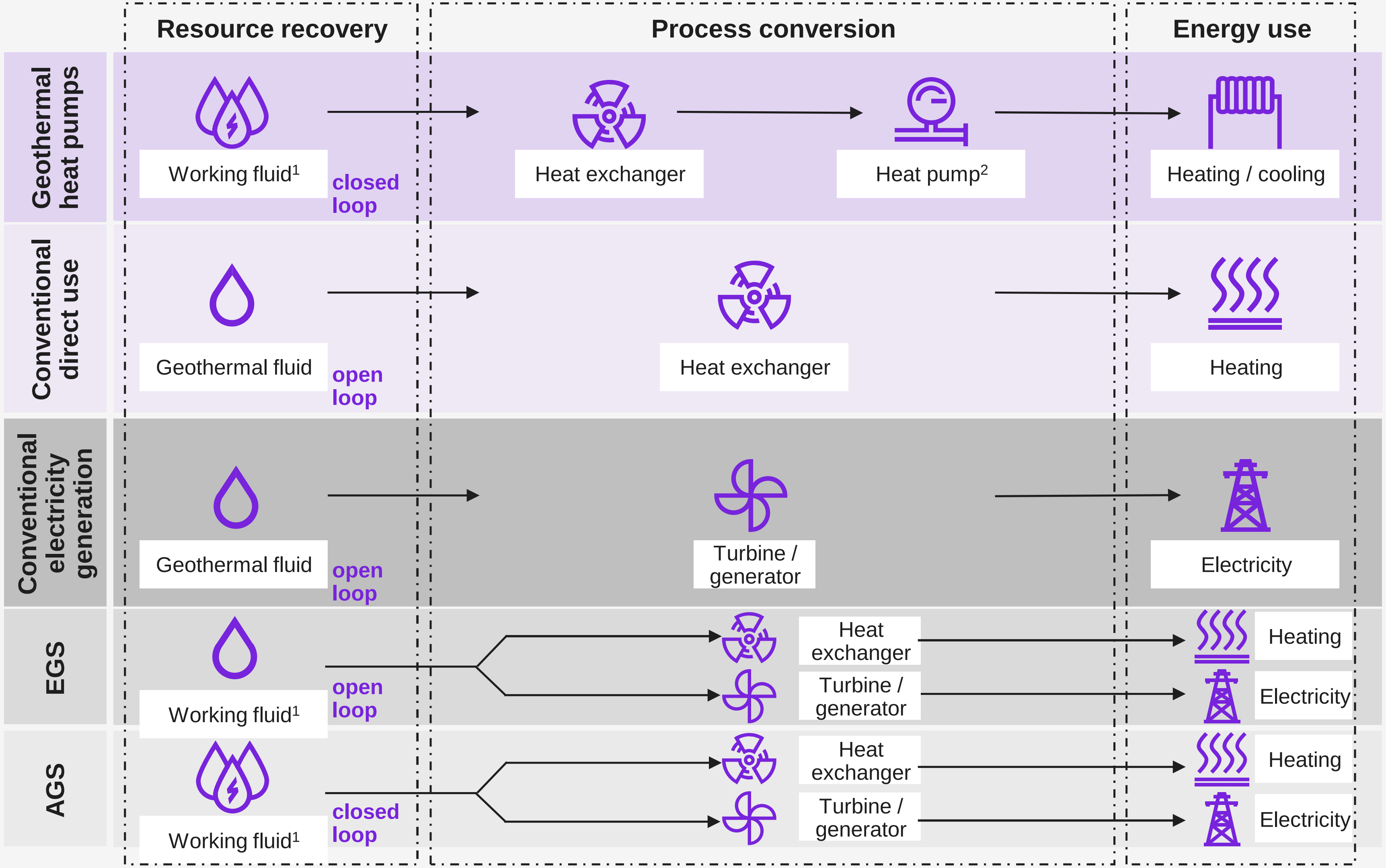
Geothermal energy is currently harnessed for two mainstream applications (heating/cooling and electricity)

Non-exhaustive; illustrative

2.1 Past and present geothermal energy use

Working principle of geothermal heat provision and electricity generation

Leveraging the resource directly or transferring to other fluids

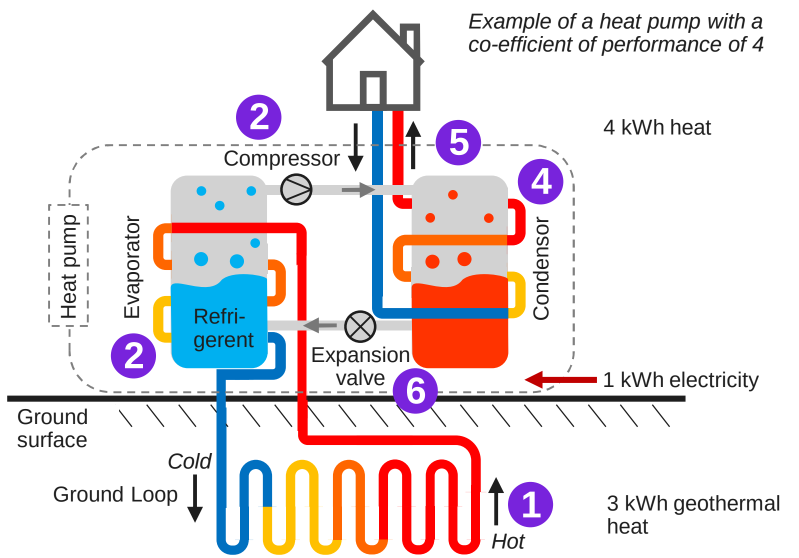


1. Working fluid can be water, an organic compound with a low boiling point, or a mixture depending on environmental regulations, safety considerations, and operating conditions. Working fluid traditionally refers to the fluid circulating through the turbine in a binary-cycle geothermal power plant. 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.

Geothermal heat pumps leverage Earth's stable temperatures, transferring heat for efficient heating and cooling

Working principle of geothermal heat extraction



1. **A ground loop absorbs thermal energy** from the Earth and transfers it **to a working fluid**, circulating through an open or closed ground-loop system.
2. **The working fluid enters the evaporator** (heat pump), **transferring the absorbed heat to a refrigerant**, which evaporates and becomes a low-pressure vapor.
3. The vapor is compressed, increasing its temperature and pressure.
4. The high-temperature, high-pressure **vapor flows through the condenser, releasing heat, and the refrigerant condenses into a liquid.**
5. **Heat is transferred to the building** via radiators, underfloor heating, or air ducts. **For cooling, the cycle is reversed**, transferring heat from the building to the ground.
6. **The refrigerant passes through the expansion valve,** reducing its pressure and temperature, then re-enters the evaporator to restart the cycle.

Key factors in system efficiency

Soil properties	Density, diffusivity, moisture, temperature, thermal conductivity,…
Climate and piping system	Distribution pipe network's condition, humidity and temperature of surrounding air, indoors temperature settings, size and type of pumps,…
Ground heat exchanger	Borehole number, depth, diameter, heat conductivity, flow rate, pipe and trench length, temperature of inlet fluid,…
Heat pump unit	Number of heat pumps, efficiency of compressor, flow rates and pressure of condenser / evaporator, temperatures of condenser / evaporator inlet fluid,…
Supplementary heat / cold source	Method of connection / distribution, rate of fluid flow, temperature of inlet fluid, type of working fluid,…

Potential risks

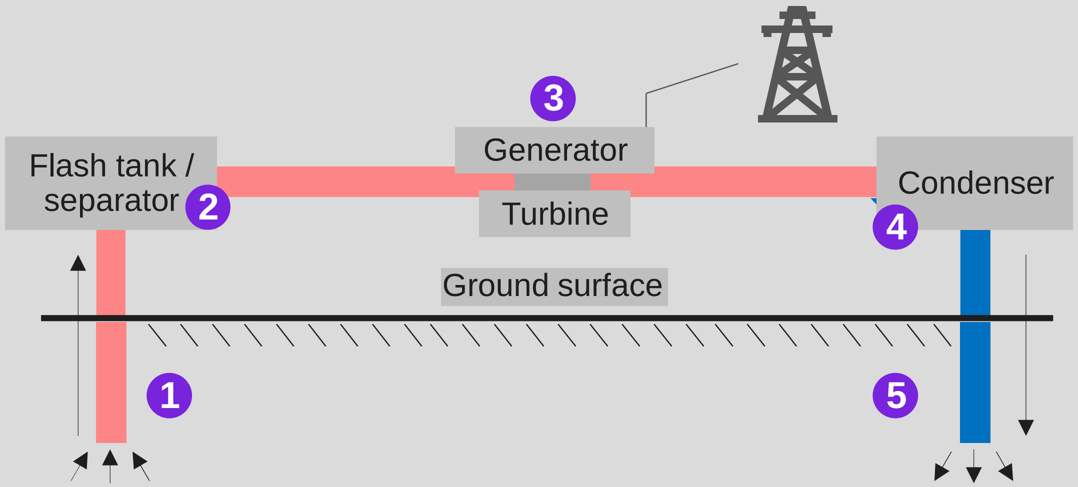
Thermal imbalance	**Continuous extraction or rejection of heat can create thermal imbalances** in the ground, leading to reduced heat exchange efficiency.
Borehole aging	The **thermal resistance of boreholes** may increase due to **changes in the surrounding soil** properties.
System wear and tear	**Mechanical components**, such as compressors and pumps, **experience efficiency loss** due to aging.
Ground thermal recharge	**Lack of seasonal variations** (for example, summer recharge for heating-dominated systems) can **hinder the partial restoration of thermal balance**, potentially reducing long-term efficiency.

Sources: REN21, Global Status Report, 2022; Kearney Energy Transition Institute analysis based on desktop research

2.2 Working principle of geothermal heat and power production

Geothermal power plants use hot water and steam to drive turbines and generate power

Working principle of geothermal power production



1. Deep beneath the Earth's surface, there are reservoirs containing hot water. **When a well is drilled** to access these reservoirs, **the water naturally flows to the surface due to its internal pressure.**[1]
2. As **hot water rises** to the surface, **the pressure decreases**, turning it into steam.
3. **The steam powers a turbine** that is connected to a generator to produce electricity.
4. **Excess steam is cooled and condensed** back into water in the cooling tower.
5. **The condensed water is pumped back** into the Earth to restart the cycle.

Key factors in system efficiency

Reservoir temperature	**Higher reservoir temperatures improve steam production efficiency.** When hot water reaches the surface, the drop in pressure causes it to convert into steam, which is then used to spin turbines.
Well depth	Well depth determines reservoir access, with **deeper wells reaching higher temperature zones**, enhancing steam production for turbine operation.
Flow rate	**Higher geothermal fluid flow rates increase steam generation**, boosting power output for turbines.
Thermal gradient	**A higher thermal gradient means faster temperature rise with depth**, enabling easier access to geothermal energy and reducing deep drilling needs.

Potential risks

Pressure decline	As geothermal fluids are extracted, the reservoir pressure decreases, which can **limit the flow rate and reduce the ability to produce steam effectively. Reinjection** of cooled geothermal fluids **helps to maintain pressure** and sustain long-term reservoir productivity.
Temperature decrease	Over time, **the temperature of the reservoir may decrease due to excessive heat extraction**, lowering the efficiency of power production. **Monitoring thermal gradients and adopting managed extraction rates** are essential to minimize thermal depletion.
Thermal gradient	**High flow rates can accelerate depletion**, leading to reduced fluid availability. Optimal flow rate management, combined with reinjection, can help balance resource extraction with replenishment.

1. This text refers to conventional geothermal technologies. EGS involve injecting high-pressure fluids into hot, impermeable rocks to create fractures, enabling water to circulate, absorb heat, and then drive turbines for power production, similar to conventional systems. AGS use a closed-loop system where a working fluid transfers heat from subsurface rocks to the surface, driving turbines or providing direct heating.
Sources: Kearney Energy Transition Institute analysis based on desktop research

2.2 Working principle of geothermal heat and power production

As conventional geothermal sources are limited, methods evolve to reach new geothermal sources

Conventional geothermal relies on naturally occurring geothermal reservoirs…

Conventional sources are found where water heated by the Earth's temperature is found at a **depth in reach of established drilling technologies.** Conventional sources are defined by the following characteristics:

Sufficient thermal gradient
Source must be of **sufficient temperature to provide the thermal energy required** for the intended application.

Occurrence of natural fluid
Naturally occurring **water or steam reservoirs serve as the working fluid** for heat transfer.

Good reservoir permeability
Reservoir permeability allows sufficient amount of water or steam to travel to the well, then being transported to the surface.

…while new geothermal sources require specific operations to improve reservoir conditions …

Intervention via unconventional methods, such as advanced or engineered/enhanced geothermal systems (AGS and EGS), **unlocks the use of new heat sources previously deemed out of reach or unsuitable.**

Deeper drilling for higher temperatures
Innovative drilling technologies to reach **greater depths and higher temperature** sources.

Injected working fluid for heat transfer
Introduce **artificial working fluids in a closed-loop system** where naturally occurring working fluids are unavailable.

Geological fracking to create permeability
Leverage fracking techniques from the oil and gas industry to create **artificial permeability.**

Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; US DOE Geothermal Technologies Office, 2024, Hydrothermal Resources; Kearney Energy Transition Institute analysis.

A geothermal system is characterized by three different elements

I Exploitation system

The characteristics (temperature, occurrence of natural porosity and permeability) of the reservoir determine the technologies used to exploit the geothermal resource

Conventional geothermal exploits reservoirs with satisfying and pre-existing porosity and permeability conditions.

Unconventional methods (i.e. AGS, EGS, and hybrid) focus on reaching reservoirs with higher temperatures, and on creating artificially hot fluid flow conditions.

- Geothermal heat pumps
- Conventional direct use and power generation
- AGS[1]
- EGS[2]
- Hybrid AGS/EGS

II Drainage systems

Drainage systems are key to manage the heat exchange with the geothermal reservoir.

– The type of loop is defined by the presence of fluids in the geothermal reservoir, the land availability, and local regulations.

– The loop type has an impact on costs, environmental footprint, maintenance, and durability.

Open loop

Natural fluids:
– Geothermal brine
– Steam

Closed loop

Artificial fluids:
– CO_2
– Advanced fluids

III Well design

Well design and drilling process have great impact on the overall thermal efficiency and cost of geothermal projects.

– The definition well design (e.g., the drilled geometry) depends on multiple parameters and results from the economic optimization of the well cost and economic return of the geothermal project.

– Horizontal and directional wells generally increase the contact with (horizontal) geological formations but are generally more expensive.

- Vertical
- Directional
- Horizontal[3]

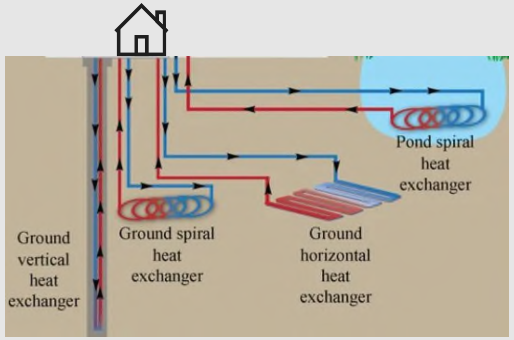
1. Advanced geothermal system; 2. Enhanced or engineered geothermal system; 3. Horizontal drilling is a sub-category of directional drilling.
Sources: Kearney Energy Transition Institute analysis based on desktop research

Emerging geothermal exploitation systems modify the geologic setting to harness energy

Geothermal heat pumps (GHPs)

GHPs use the **temperature of the shallow earth**, providing **heating** in the winter and **cooling** in the summer.

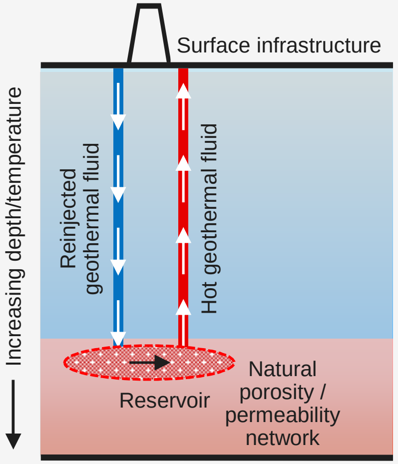
- GHPs utilize a closed-loop system of underground pipes to exchange heat with the ground.
- A heat transfer fluid circulates through the loop, absorbing heat from the earth in winter for heating and releasing heat back into the ground in summer for cooling.



Conventional direct use and power generation

Conventional geothermal technologies **rely on naturally occurring geothermal resources.**

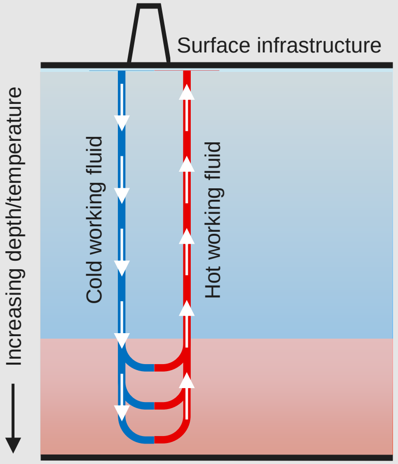
- Conventional geothermal systems **leverage readily available geothermal resources;** e.g., hot water or steam in permeable rock formations.
- Conventional geothermal typically occurs in sedimentary formations.



AGS[1]

AGS enables geothermal **energy extraction in nontraditional areas.**

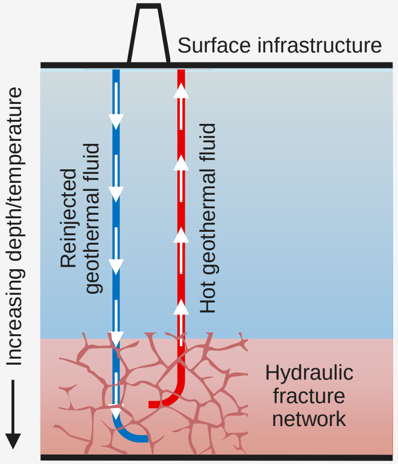
- AGS circulates a heat transfer fluid through a **closed-loop** network of underground pipes.
- Fluid absorbs heat from surrounding rocks before returning to surface with **no direct contact with a geothermal reservoir.**



EGS[2]

EGS enhances rock permeability to **unlock new geothermal sources.**

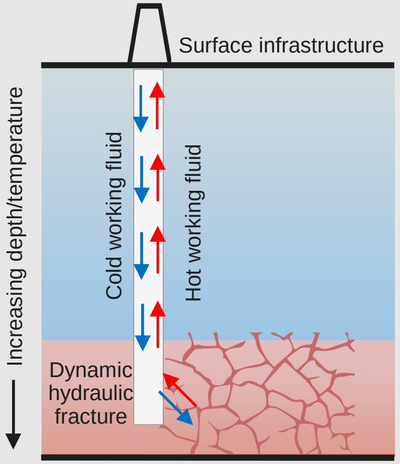
- EGS creates or enhances geothermal reservoirs in hot rock formations that **lack natural permeability or fluid.**
- Fluid is injected into the subsurface to **create new fractures or reopen existing fractures,** thus increasing permeability, in an open loop.



Hybrid AGS/EGS

Hybrid systems combine **existing fracked oil wells and close-loop fluid circulation.**

- Hybrid systems use a single well, repurposing disused oil wells.
- A fluid is pumped with high pressure in the well, **expanding the fractures** and then recovered back later, by deflating the fractures and **obtaining a fluid at higher pressure and temperature**.

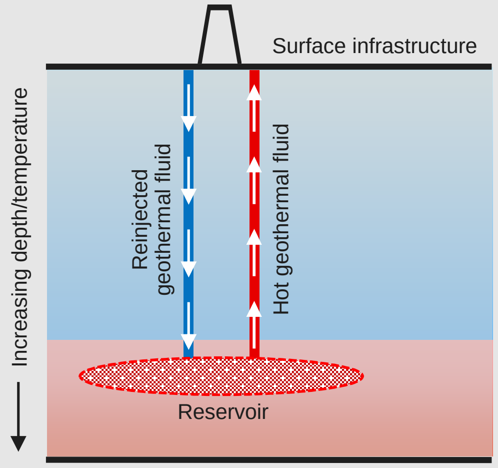


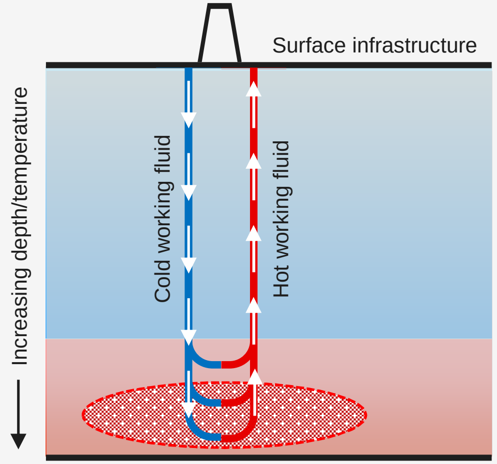
1. Advanced geothermal system; 2. Enhanced or engineered geothermal system

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 based on desktop research

Geothermal systems can extract energy via an open or closed loop, which determines the extent of direct interaction with the geothermal energy source

		Extraction	Heat exchange	Discharge
Open loop	Natural reservoir[2]	Hot geothermal fluid is pumped from the reservoir to surface infrastructure.	Hot geothermal fluid exchanges heat to working fluid by **convection**.	Cooled geothermal fluid is reinjected to the reservoir or discharged into a suitable body of the same fluid.
Open loop	No natural reservoir[1]	Fluid pumped from alternative natural or artificial source and injected into geothermal system.	Hot geothermal fluid exchanges heat to working fluid by **conduction**.	Cooled geothermal fluid is reinjected to the artificial reservoir or discharged into a suitable body (e.g., fractures) with the same fluid.
Closed loop	Reservoir	Cool working fluid circulates through pipe network.	Geothermal fluid exchanges heat to working fluid by **convection**.	Cooled working fluid recirculates through system.
Closed loop	No reservoir	Cool working fluid circulates through pipe network.	Working fluid exchanges heat with surrounding ground by **conduction.**	Cooled working fluid recirculates through system.





1. Natural underground formation containing geothermal fluid, usually water or steam, called hydroreservoir; 2. No geothermal fluid but underground landscape still heated by geothermal gradient, requiring injection of fluid to harness energy.
Sources: Kearney Energy Transition Institute analysis

II Drainage pattern

2.3 Geothermal exploitation systems

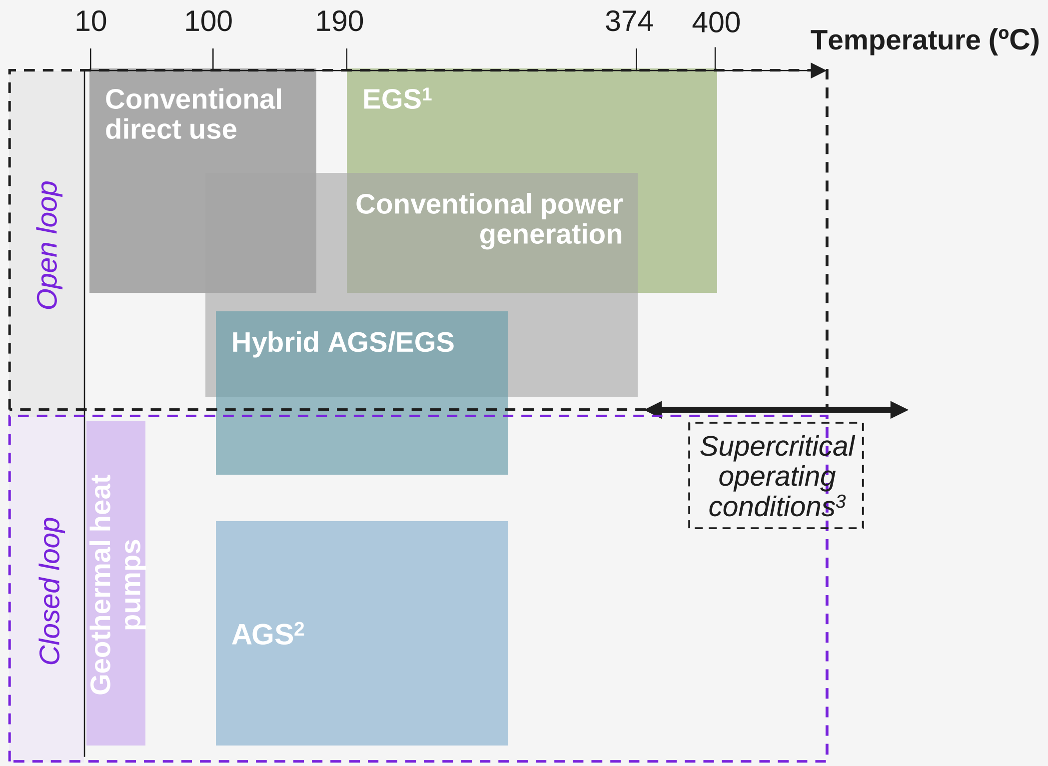
Each geothermal application offers specific advantages and disadvantages

	Advantages	Disadvantages
Geothermal heat pumps	– **Established and mature technology** – **Highly energy-efficient,** with reductions in heating and cooling costs compared to conventional systems – Applicable in a **wide range of locations** – **Sustainable heating** solution	– **High upfront investment** for installation – **Limited to shallow** geothermal resources – **Efficiency and performance** can be affected by **improper system design or maintenance**
Conventional direct use	– **Established technology** used for millennia – **Sustainable and cost-effective** for heating applications – Provide **significant energy savings** compared to fossil-fuel based systems – Suitable for **large-scale applications**	– **High upfront investment** for infrastructure – **Limited to low-medium** temperature geothermal resources – **Requires careful management** of geothermal resources **to prevent depletion** and maintain sustainability over time
Conventional power generation[1]	– **Continuous and unaffected** by seasonal or weather changes, unlike other renewable – **Cost competitive** with other generation technologies – **Smaller land requirement** than other generation technologies	– **High upfront investment** – **Limited to specific geographies** with suitable and accessible geothermal resources – **Depletion of geothermal resource** over time if geothermal fluid is not reinjected – Potential for **induced seismicity**
AGS[2]	– Applicable to a **wide range of locations** – Lower risk of induced seismicity	– Relies on **heat conduction** through **low-conductivity rock** – **Yet to be delivered** at scale – **Ongoing high development costs**
EGS[3]	– **Unlocks geothermal potential** in less permeable locations	– Prone to **short-circuiting between injection and production wells** and **circulating water loss** – **Yet to be delivered** at scale – **Ongoing high development costs** – Higher risk for **induced seismicity**
Hybrid AGS/EGS	– **Leverage the closed-loop design of AGS with the enhanced permeability techniques of EGS**, maximizing efficiency by increasing heat transfer from the surrounding rock to the working fluid – **Unlock geothermal potential** in a wider range of geological settings	– **Yet to be delivered** at scale – **Ongoing high development costs**

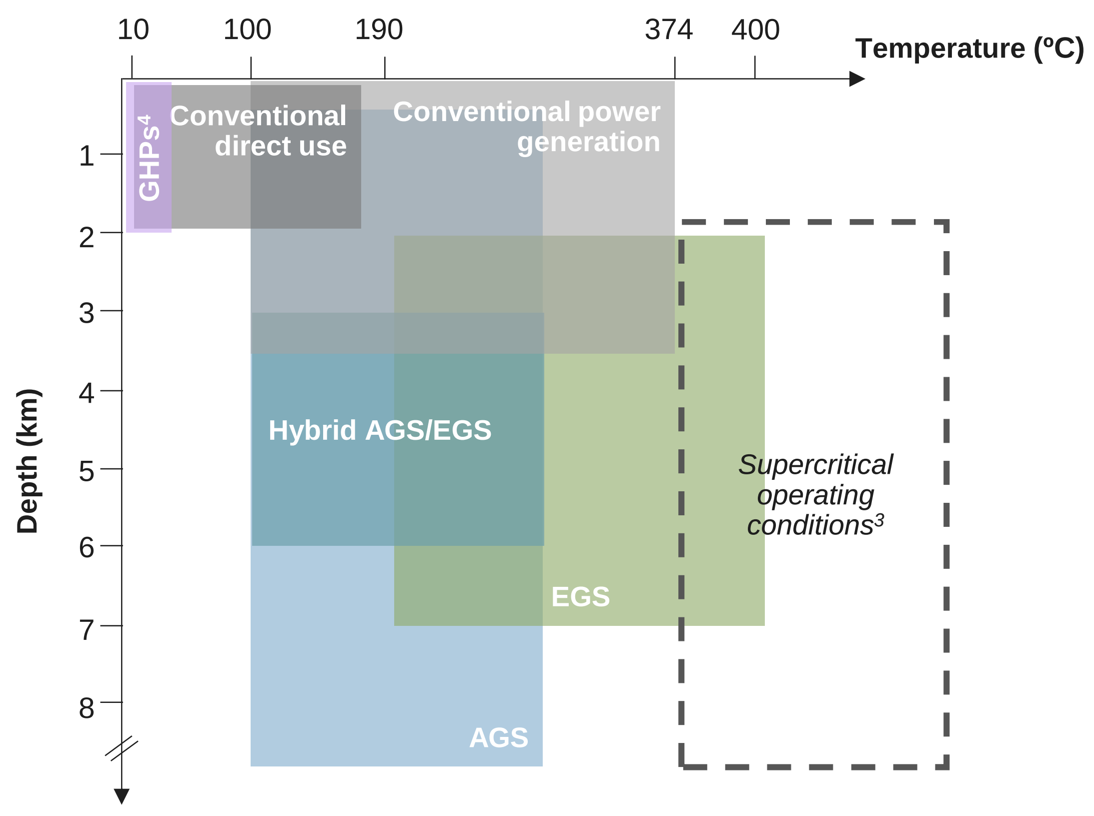
1. Includes dry steam, flash steam, binary cycle, combined cycle, and wellhead generator; 2. Advanced geothermal system; 3. Enhanced or engineered geothermal system.
Sources: Kearney Energy Transition Institute analysis based on desktop research

Geothermal exploitation systems have different operating temperatures, depth, and specific drainage patterns

Geothermal exploitation systems by temperature and drainage pattern



Geothermal exploitation systems by temperature and source depth range



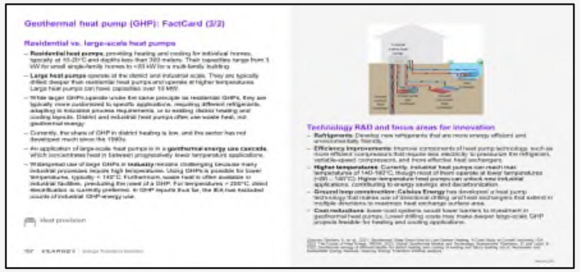
1. Enhanced or engineered geothermal system; 2. Advanced geothermal system; 3. For example, pure water at temperatures exceeding 374°C and pressures exceeding 221 bar.; 4. Geothermal heat pumps.
Sources: Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal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

Geothermal exploitation systems use conventional, AGS, and EGS technologies

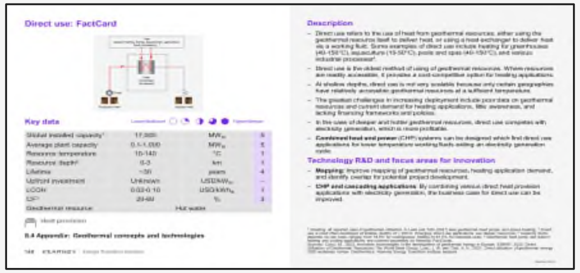
Press Ctrl and click the image to navigate to the details in the Appendix.

Overview of geothermal exploitation systems

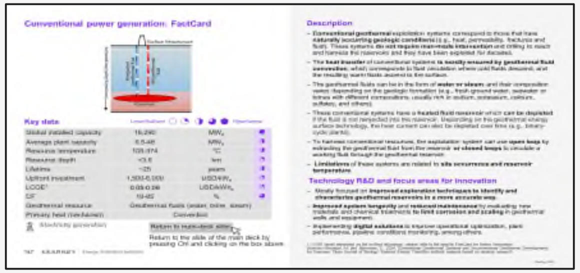
Geothermal heat pump[1]



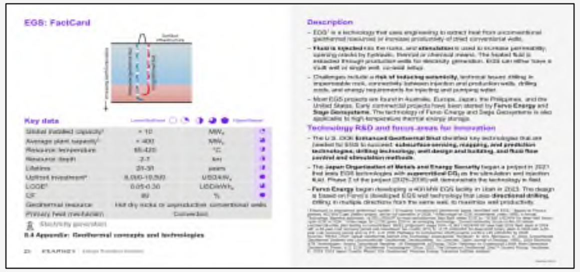
Conventional direct use



Conventional power generation

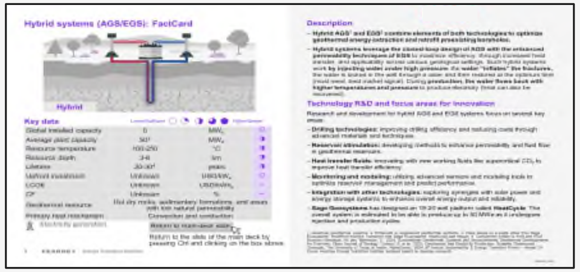


EGS[2]

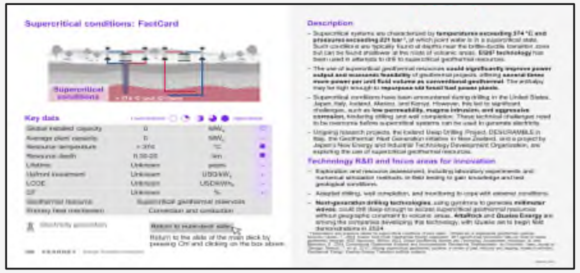


AGS[3]

Hybrid AGS/EGS



Supercritical operating conditions



Heat provision | Electricity generation | Heat provision / electricity generation

1. GHP; 2. Enhanced or engineered geothermal system; 3. Advanced geothermal system
Sources: Kearney Energy Transition Institute analysis based on desktop research

Open loops are cheaper to install, but raise concerns of durability and environmental safety, which are mitigated by closed loops

	Open loop		Closed loop	
Cost	– **Cheaper to install** given lesser complexity	Better	– **Costlier to install** given greater complexity	Poor
	– **Costlier maintenance** due to reliance on quality of external water sources and subsequent disposal in absence of reservoir	Poor	– **Cheaper maintenance** due to recirculation of same working fluid	Better
Feasibility	– **Require reliable and clean alternative fluid** if no geothermal reservoir, which may not be available everywhere	Poor	– **Suitable to broader range of locations** given no reliance on fluid flow through rock	Better
	– **Require permeable rock** for fluid flow	Poor	– **Does not require permeable rock**	Better
Durability	– **Degraded performance over time** due to poor fluid quality, e.g., sediment build-up, mineral content reactions, reduced supply, etc.	Poor	– **Higher durability**, performing for up to 100 years with minimal maintenance	Better
Environment	– **Depletion of geothermal fluid or alternative fluid**	Poor	– **Environmentally safer given closed circulation of fluid** for minimal contamination	Better
	– **Risk of induced seismicity** by fluid injection (and fracking when used)	Intermediate	– **Risk of induced seismicity** in case of fracking (hybrid AGS/EGS)	Intermediate
Efficiency	– **More efficient** given high thermal conductivity of fluid in direct contact with geothermal resource	Better	– **Highly efficient**, although to lesser extent given heat exchange losses through piping to working fluid	Intermediate

Better

Intermediate

Poor

Sources: Ahmed, S.F. et al., 2021, Physical and hybrid modelling techniques for earth-air heat exchangers in reducing building energy consumption: Performance, applications, progress, and challenges, Solar Energy; Eavor, 2022, Existential risks and solutions for geothermal energy production; Dandelion Energy, 2020, Open Loop vs Closed Loop Geothermal Systems; Kearney Energy Transition Institute analysis based on desktop research

The well pattern has performance and cost implications for the geothermal installation

The **well pattern** is dictated by the purpose of the well, the surface or shallow hole conditions, the reservoir conditions, the casing requirements, and other logistical requirements, such as financing or project time constraints.

The **well pattern and spacing** are key to **maximizing heat recovery.** Design depends on the convection and conduction profiles of the rock.

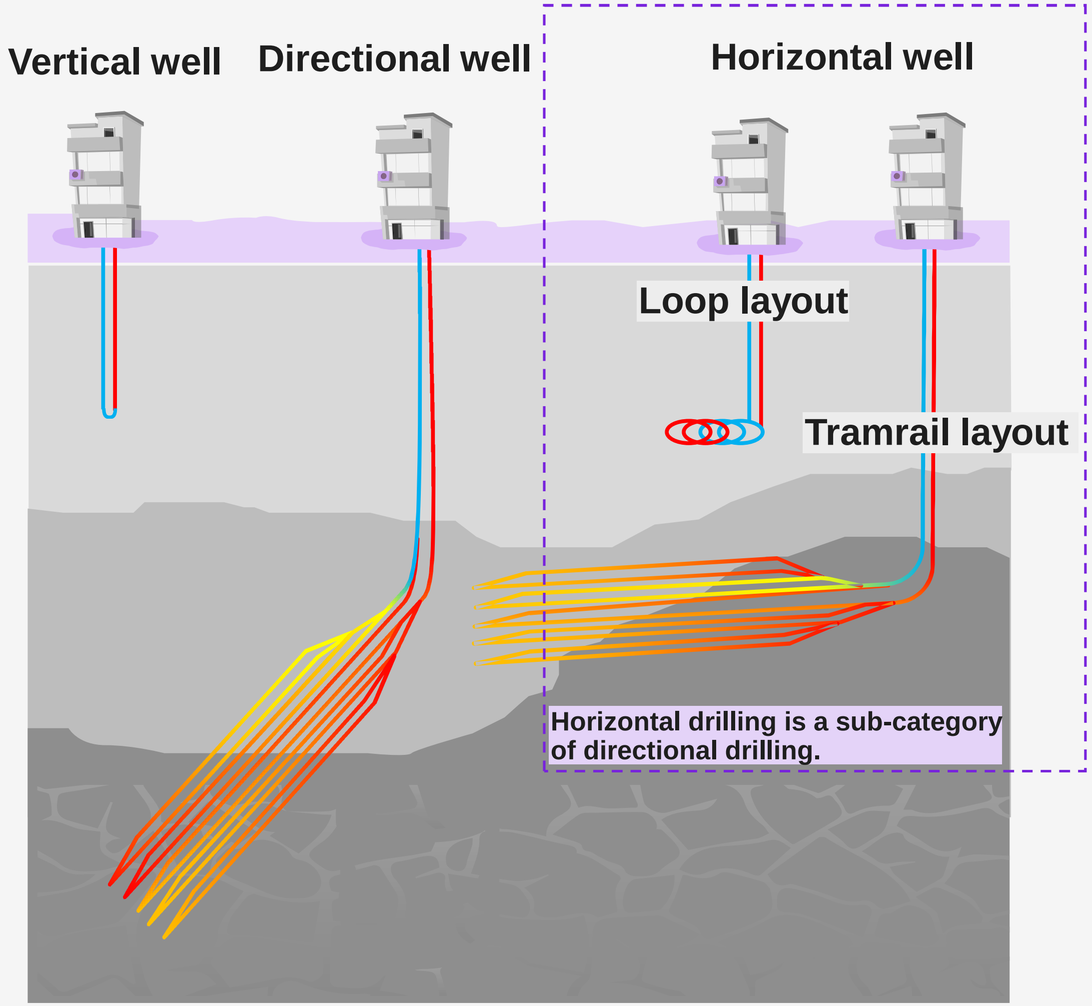
- **Vertical well:** Minimal surface disruption and lesser surface area requirement compared to horizontal systems.
- **Horizontal well:** Maximum contact surface with reservoir and lower power requirements for pumping working fluid.
- **Directional well:** Maximum intersection of existing vertical fractures at desired depth.

Well pattern

2.3 Geothermal exploitation systems

Geothermal well patterns

Non-exhaustive



Sources: Sandia National Laboratories, 2010, Handbook of best practices for geothermal drilling; Kearney Energy Transition Institute analysis

Research on geothermal exploitation systems centers around reservoir management, while research into nascent technology also considers well design and fracture control

Non-exhaustive

Exploitation system	Well design and planning Research aims at effectively **designing wells based on natural subsurface characteristics.**	Fracture control Research focuses on **developing and understanding optimum fracture network.**	Reservoir management Research aims at **maintaining long-term heat exchange efficiency.**
Geothermal heat pumps	– Developing technologies like **directional drilling and extending heat exchangers in multiple directions**, maximizing heat exchange surface area.		– **Innovation in working fluids** for utilization of lower temperature resources.
Conventional direct use			– **Cascading applications** to optimize use of effluent heat and integrate hybrid systems.
Conventional power generation			– **Injecting additional wastewater** to maintain reservoir productivity. – **Efficiency improvements** via exergy analysis and specific steam consumption. – **Efficiency improvements** via combined heat and power applications to reduce exergy loss during reinjection.
AGS[1]	– **Reduced drilling cost and increased speed** for faster development. – **Increased heat transfer rates** via enhanced well designs, such as **Eavor-Loop.**	– **Improvement to accuracy** of seismicity predictions, despite the very low risk of induced seismicity (no fracking operations)	– **Retrofit of old wells** and maximized heat extraction via systems such as **GreenFire's GreenLoop** co-axial heat exchangers. – **Use of treated wastewater** for heat transfer fluid replenishment.
EGS[2]	– **Subsurface sensing and mapping technologies.** – **Drilling and well design.**	– **Fluid flow control and stimulation methods** to optimize fracturing and resource recovery. – **Improvement to accuracy** of seismicity predictions.	
Hybrid AGS/EGS	– Similar research to AGS and EGS well design.	– Similar research to EGS stimulation methods. – **Improvement to accuracy** of seismicity predictions.	– **Enhanced reservoir management** via improved well productivity, cycling systems for sustained energy production, such as **HeatCycle by Sage Ecosystems.**
Supercritical conditions	– **Exploration, resource assessment, and laboratory simulations** to target extreme geothermal environments.	– **Adapted drilling and well completion technologies** for high-temperature, high-pressure conditions.	– **Next-gen drilling technologies (e.g., gyrotrons for deep geothermal access)** and resource sustainability in extreme environments

Research and innovation **around more mature technologies focus on reservoir management** rather than stimulation planning, well design and fracture control.

1. Advanced geothermal system; 2. Enhanced or engineered geothermal system
Sources: Hamm, S.G. et al., 2021, Geothermal Energy R&D: An Overview of the US Department of Energy's Geothermal Technologies Office, Journal of Energy Resources Technology; Kearney Energy Transition Institute analysis based on desktop research

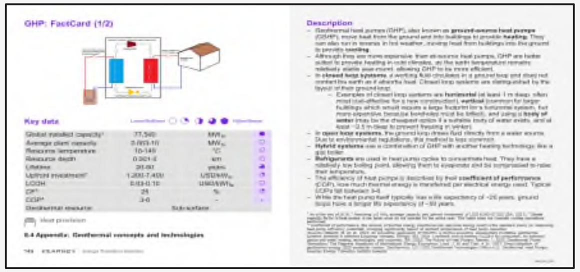
Geothermal energy surface technologies follow common engineering principles, but are nuanced by infrastructure and operating conditions

Press Ctrl and click the image to navigate to the details in the Appendix.

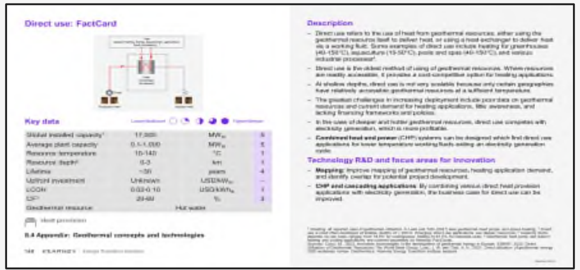
2.4 Geothermal energy surface technologies

Overview of geothermal energy surface technologies

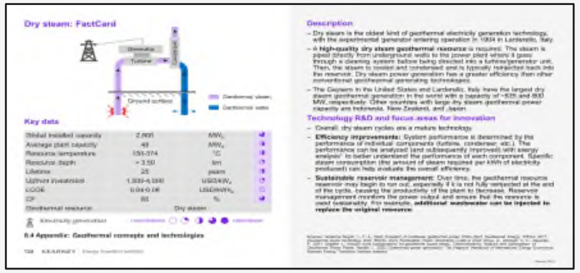
Geothermal heat pump[1]



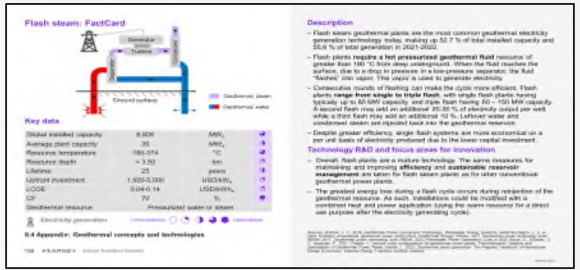
Conventional direct use



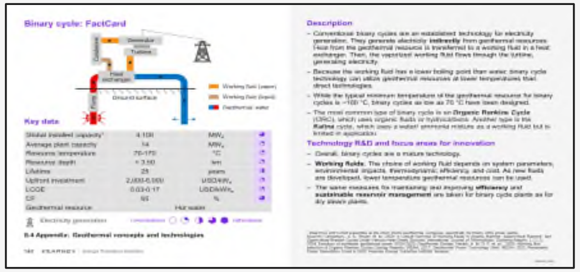
Dry steam



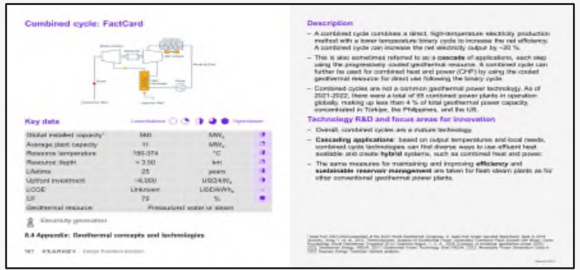
Flash steam



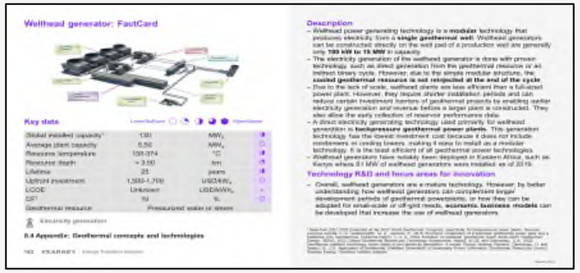
Binary cycle



Combined cycle



Wellhead generator



Heat provision | Electricity generation

1. GHP
Sources: Kearney Energy Transition Institute analysis based on desktop research

Research for geothermal energy technologies has been mostly focused on heat provision

Non-exhaustive

2.4 Geothermal energy surface technologies

Heat provision

Geothermal heat pump[1]

- **Refrigerants:** New energy-efficient and eco-friendly refrigerants.
- **Efficiency:** Improve components, such as efficient compressors requiring less electricity, variable-speed compressors, and more effective heat exchangers, for higher COP[2] up to 5.2.
- **Higher temperatures:** Development of higher temperature heat pumps (140-160°C) for industrial applications.
- **Ground loop construction:** Development of technology that uses directional drilling and multi-directional heat exchangers to maximize heat exchange surface area, e.g., *Celsius Energy.*
- **Cost:** Reduction of drilling costs to improve feasibility of deeper large-scale GHP projects for heating and cooling applications.

Direct use

- **Mapping:** Improved mapping of geothermal resources and heating application demand.
- **Cascading applications:** by combining various direct heat provision applications with electricity generation, the business case for direct use can be improved.

District heating

- **Efficiency:** Use of distributed heat pumps for cooler distribution grids.
- **Depth:** Tapping deeper geothermal resources, e.g., *Eden Geothermal Energy Project.*

1. GHP; 2. Coefficient of performance.
Sources: Kearney Energy Transition Institute analysis based on desktop research

Electricity generation

As electricity technologies are broadly used with other thermal generation technologies, such as natural gas or biomass, innovation is limited to **efficiency improvements**.

Summary of technical features and financial performance per geothermal exploitation system for electricity generation

Non-exhaustive

Application	Global installed capacity	Average plant capacity	Resource temperature	Operating depth	Lifetime	Upfront investment	Levelized cost of electricity (LCOE)	Capacity factor	Geothermal resource
	(MW_e)	(MW_e)	(°C)	(km)	(years)	(USD/kW_e)	(USD/kW_e)	(%)	-
Conventional power generation	16,290	5.5-48	100-374	0-3.5	25	1,500-6,000	0.03-0.17	10-75	Hot water or steam
AGS[1]	0-5	1-10	100-250	0.30-5.5	30	2,300-14,500[3]	0.13-0.32	Unknown	Hot reservoir or hot dry rocks
EGS[2]	0-10	0-400	150-400	2-7	20-30	8,000-19,500[3]	0.13-0.32	80	Hot dry rocks or unproductive conventional wells
Hybrid AGS/EGS	0	50	100-250	3-6	20-30	Unknown	Unknown	Unknown	Hot dry rock with created reservoir

Note: Hybrid AGS/EGS systems have not been deployed, only one single project has been developed to date, some of these indicators are extrapolated from AGS and EGS performance.
1. Advanced geothermal system; 2. Enhanced or engineered geothermal system; 3. The upfront investment estimates for AGS and EGS are based on first-of-a-kind projects and should be considered indicative rather than definitive.
Sources: Kearney Energy Transition Institute analysis based on desktop research

Summary of technical features and financial performance per technology for key applications in conventional geothermal systems

LCOE(H) and CF discussed in 5. Cost of geothermal energy

Non-exhaustive

Application	Technology	Global installed capacity	Average plant capacity	Resource temperature	Operating depth	Lifetime	Upfront investment	LCOE(H)[1]	Capacity factor	Geothermal resource
	-	($MW_{e(th)}$)	($MW_{e(th)}$)	(°C)	(km)	(years)	($USD/kW_{e(th)}$)	($USD/kW_{e(t)}$)	(%)	-
Heat provision	Direct use	17,000	0.10-1,000	10-170	0-3	30	Unknown	0.02-0.10	19-61[3]	Hot water or steam
Heat provision	GHP[2]	77,500	0.003-10	4.5-21	0.001-2	20-50	1,200-7,400	0.03-0.10	25[3]	Subsurface
Electricity generation	Dry steam	2,900	48	180-374	0-3.5	25	1,500-4,000	0.04-0.08	60	Dry steam
Electricity generation	Flash steam	8,600	35	180-374	0-3.5	25	1,500-5,000	0.04-0.14	70	Pressurized water or steam
Electricity generation	Binary cycle	4,100	14	100-180	0-3.5	25	2,000-6,000	0.03-0.17	65	Hot water or steam
Electricity generation	Combined cycle	560	11	150-374	0-3.5	25	6,000	Unknown	75	Pressurized water or steam
Electricity generation	Wellhead generator	130	5.50	150-374	0-3.5	25	1,500-1,700	Unknown	10	Pressurized water or steam

Lower temperature resources are not suitable for electricity production and **are used** primarily **for heat provision**. Sufficiently **hot resources** are mostly commercialized for **electricity generation** given it is often the most efficient use.

1. LCOE and LCOH denote levelized cost of electricity and levelized cost of heat, respectively; 2. Geothermal heat pump; 3. The capacity factor, as defined by J. Lund and A. Toth, is calculated as follows: [(energy use in TJ/yr)/(installed capacity in MWth)] x 0.0317. This number reflects the equivalent percentage of equivalent full load operating hours per year (i.e., if the CF=0.70 then this is equivalent to 6,132 full load operating hours per year (8,760 x 0.70)).
Sources: Kearney Energy Transition Institute analysis based on desktop research

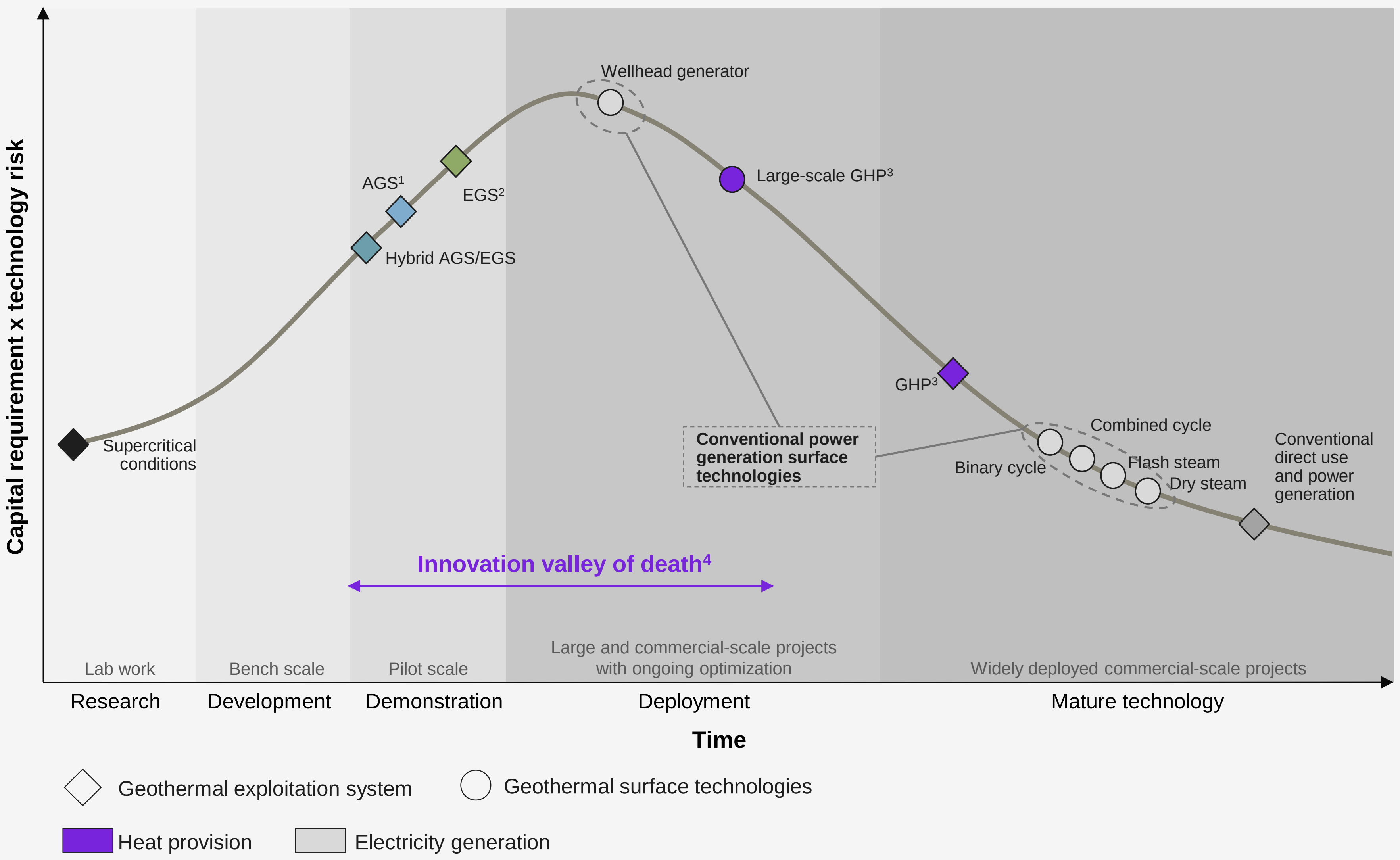
Most emerging technologies remain immature, requiring a stronger business case to reach commercialization

Non-exhaustive

Most geothermal surface technologies are mature and widely developed; however, among exploitation systems, only conventional geothermal is well established and emerging technologies for new ways of exploiting the reservoir are at earlier maturity stages.

2.6 Maturity curve

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

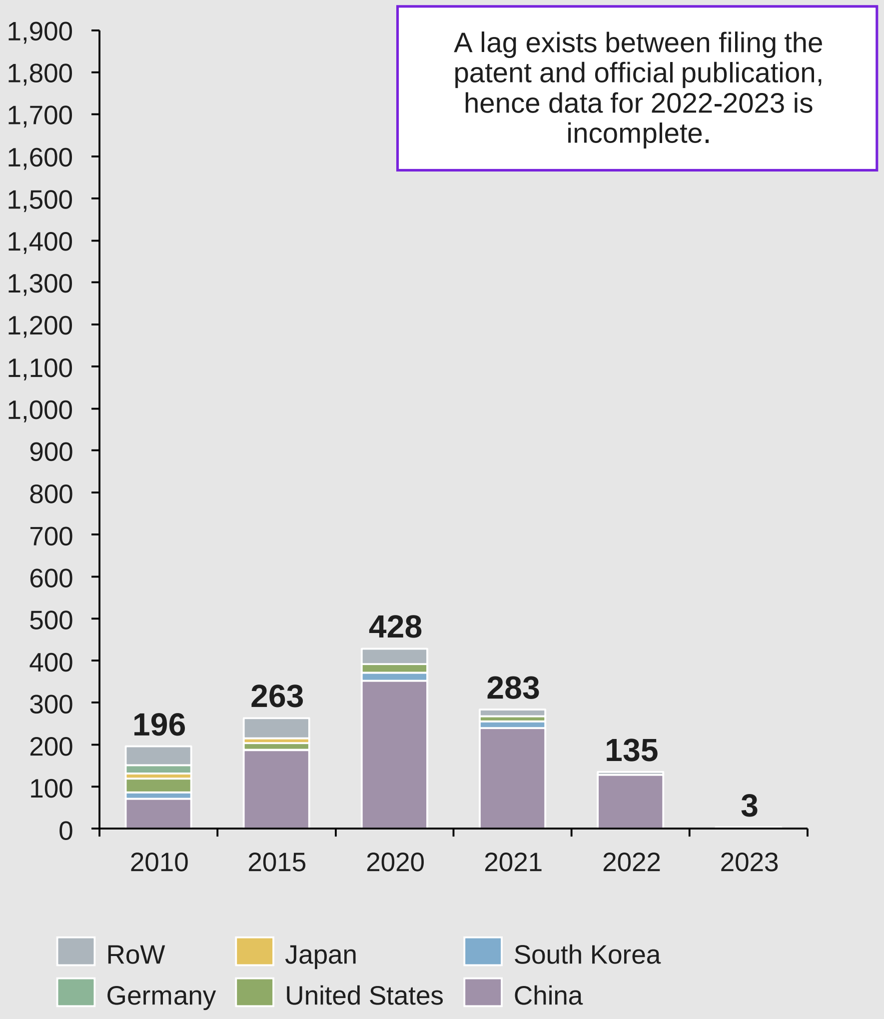
Geothermal energy innovation has focused on reaching deeper and higher temperature sources, reflected by an increased number of patents

Non-exhaustive

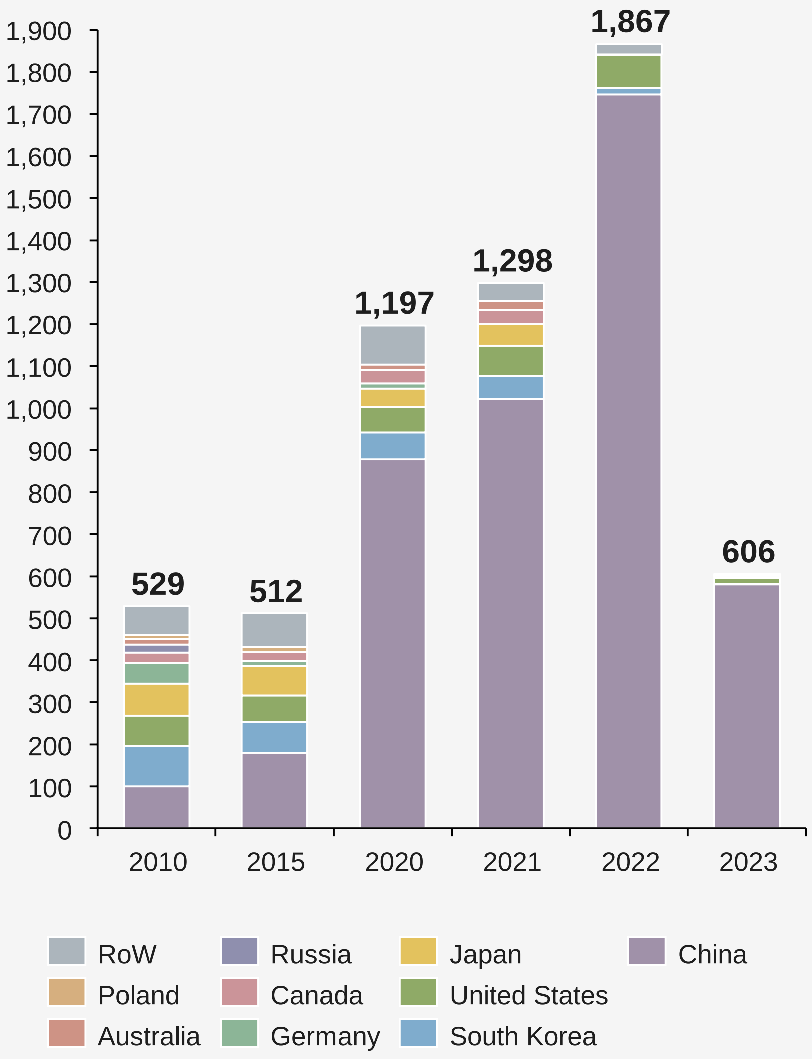
Although China has little geothermal electricity deployed, today it accounts for 75% of filed patents in geothermal electricity production and heat pumps, followed by the United States and South Korea with a combined share of 11%.

2.7 Geothermal R&D

Annual patents for geothermal heat pumps
2023



Annual filed patents for geothermal electricity generation
2023



Note: RoW is rest of world.
Sources: IRENA, 2023, Renewable Energy Patents Evolution; Kearney Energy Transition Institute analysis

3. Current and emerging geothermal energy uses

Geothermal energy uses

Geothermal energy uses

– With geothermal technology advances to leverage higher-temperature resources, applications have expanded to include more energy-intensive uses. Emerging and synergistic uses are less deployed.

Traditional uses

– For **heat provision in relatively low energy-intensive industrial and domestic settings,** such as space heating and cooling, bathing and recreation, and pulp and paper processing, as well as electricity generation to a lesser extent

– The **minimum required temperature of the geothermal energy source for heat provision is ~10°C, rising above 100°C for electricity generation**

Emerging uses

– **Data center** power and cooling

– **Green hydrogen** production via several pathways – hydrogen from geothermal fluid, electrolysis driven by geothermal power, thermochemical processes, and high temperature steam electrolysis.

– Geothermal **co-location with other renewable energy sources**, allowing complementary generation profiles to ensure a stable supply, increased dispatchability, and reduced expenditure via shared grid infrastructure. Most commonly hybridize with solar PV.

Synergistic uses

– **Mining:** some geothermal brines are rich in minerals and precious metals, which can be extracted as a by-product of electricity generation. Some projects are currently producing lithium.

– **Oil and gas:** abandoned wells can be repurposed for geothermal energy, in operating wells fluids co-extraction allow hydrocarbon and water (steam) extraction, with steam used for electricity generation.

– **Carbon capture and storage:** geothermal for the dual benefit of renewable electricity or resource extraction and carbon sequestration.

Geothermal energy use is expanding through new services and leveraging synergies with fossil-driven industries

● Existing
● Not applied

Non-exhaustive

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

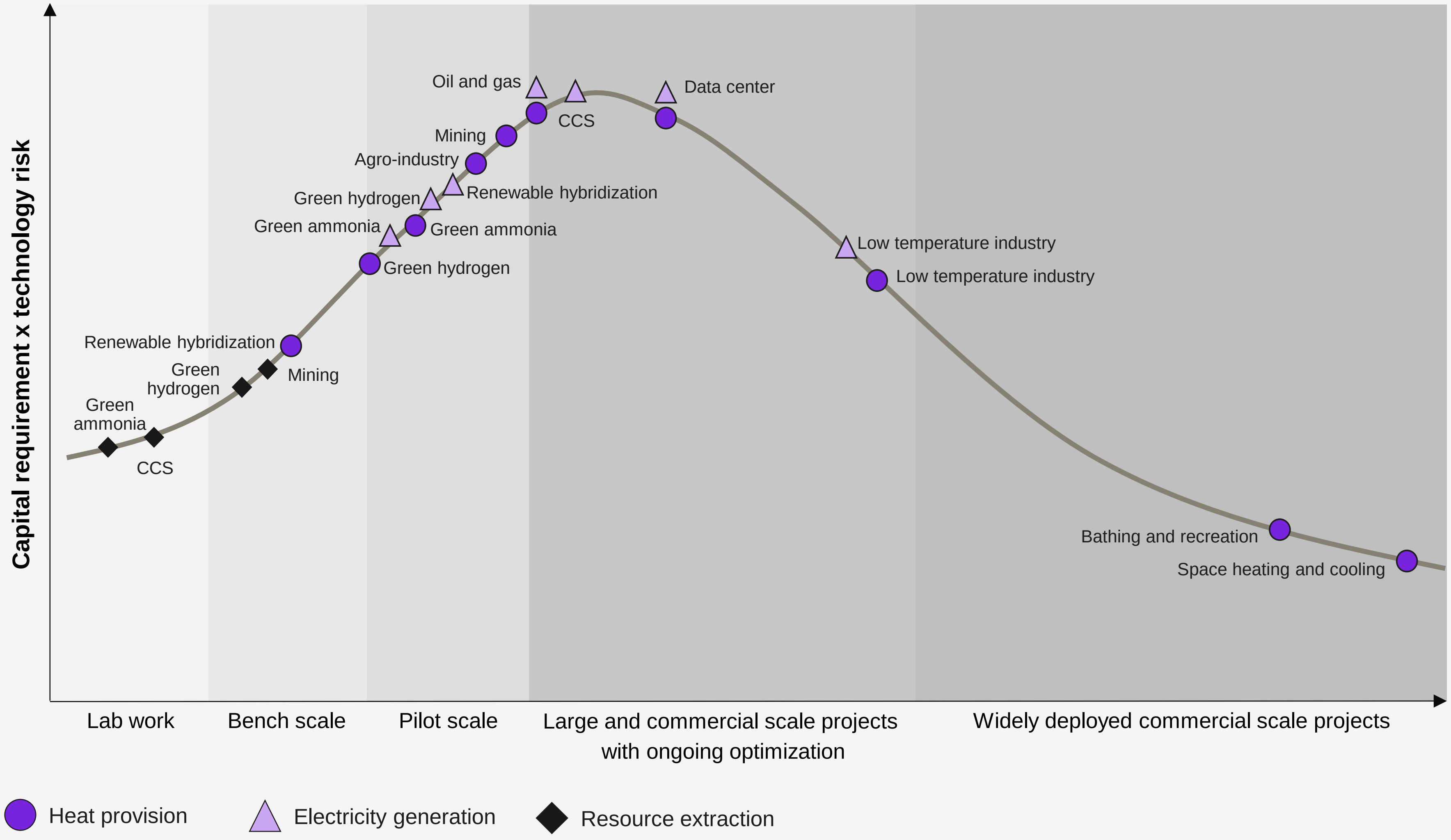
1. Pulp and paper processes, textile washing and dying, leather and fur treatment, etc.; 2. Carbon capture and storage
Sources: Kearney Energy Transition Institute analysis

3.1 Geothermal energy uses

Geothermal energy applications remain at bench and pilot scale; only traditional uses of heat provision have reached wide deployment

Non-exhaustive; illustrative

Maturity curve for geothermal energy applications

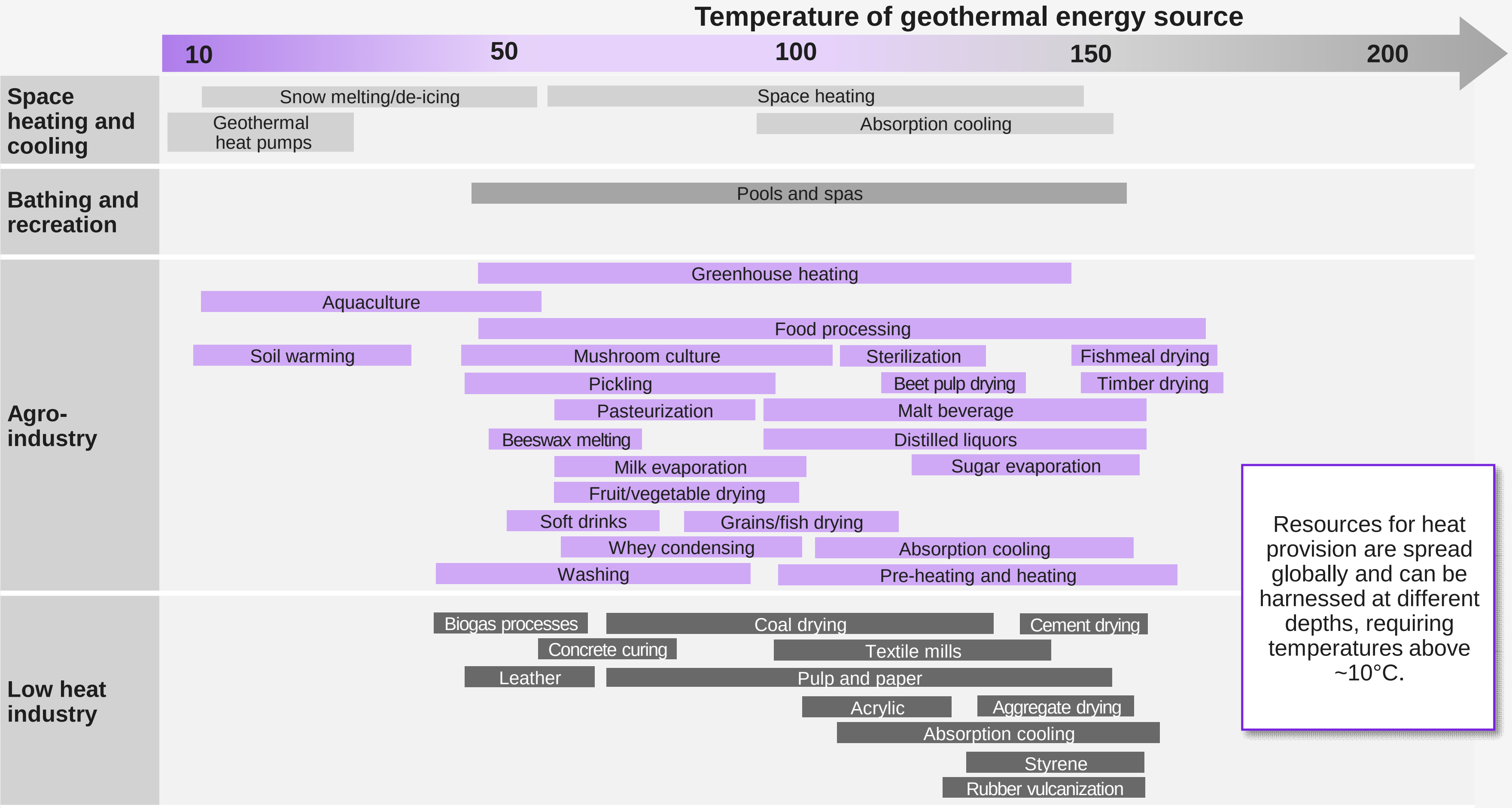


Note: CCS is carbon capture and storage.
Sources: Kearney Energy Transition Institute analysis

3.2 Maturity curve of geothermal energy uses

Geothermal energy covers a range of temperatures and can thus be used for a variety of heating applications, as well as electricity generation and thermal storage

Non-exhaustive



Resources for heat provision are spread globally and can be harnessed at different depths, requiring temperatures above ~10°C.

- Most of the **direct uses** for space heating and cooling, bathing and recreation, and agro-industry are **mature applications**.
- Current **novel industrial applications** include geothermal direct use for cement and concrete production, and desalination by heating seawater or providing electricity to the desalination plant.
- In some cases, geothermal energy can **simultaneously provide steam** for **industrial processes and** for the **electricity production.** For electricity production, the geothermal fluid must be above 100°C.

Sources: ESMAP, 2022, Direct Utilization of Geothermal Resources, The World Bank Group; IRENA, 2023, Global Geothermal Market and Technology Assessment; Kearney Energy Transition Institute analysis.

Emerging uses of geothermal increasingly address energy-intensive and hard-to-abate sectors

As data center deployment accelerates, geothermal energy is increasingly relevant

Providing round-the-clock cooling and power

Cooling

- To remove heat generated by data center equipment**, geothermal closed-loop systems** transfer heat into shallow underground heat exchangers.
- **The systems are not limited to specific locations**.
- Among major benefits identified, geothermal cooling systems **reduce energy and water consumption**.
- They have been deployed for more than a decade.
- Operational projects include:
  - Verne Global, Iceland
  - Iron Mountain, US

Electricity

- Powering data centers with unconventional geothermal technologies decarbonizes energy demand while maintaining baseload electricity.
- Most applications are in the United States, with recent uptake driven by **rise of geothermal PPA.**
- **Recent announcements of data centers** using geothermal electricity include:
  - Microsoft and G42, Kenya
  - Google data centers and Fervo Energy, US
  - Meta platforms and Sage Geosystems, US

A Traditional

B Emerging

C Synergies

Illustrative

3.4 Emerging uses

Sources: US DOE Better Buildings, 2019, Iron Mountain data centers: geothermal cooling systems; BloombergNEF, 2023, Next-generation geothermal technologies are heating up; Kearney Energy Transition Institute analysis

Hybridization increases energy production by combining geothermal with another renewable energy technology

A Traditional

B Emerging

C Synergies

Benefits include:

- Shared grid infrastructure
- Generation profile complementarity
- Increased dispatchability
- Potential reduction of environmental impact

Non-exhaustive

3.4 Emerging uses

Hybrid geothermal systems operate with the same stand-alone principles as renewables

Working with another renewable energy generation system to increase energy yield

Solar

- **Geothermal-solar PV** where solar PV **complements** the geothermal output, when **the production decreases from geothermal** binary power plants (air-cooled) due to hot weather conditions. Several projects with such hybrid systems exist in the United States.
- **Geothermal-CSP power plants where** the **heat from the collectors** is **combined to the geothermal brine** increasing efficiency and the energy utilization rate, thus **increasing power output**. This combination also allows creation of **seasonal storage** of the heat produced during the summer.

Only projects combining solar technologies have been implemented to date:

- CyrqEnergy, Patua: 48 MW geothermal and 10M W solar PV
- Ormat, Tungsten mountain: 27 MW geothermal and 7MW solar PV
- ENEL, Stillwater: 33 MW geothermal, 26.4 MW solar PV, and 2 MW CSP

Other renewables

Other synergies are possible with **wind and biomass,** although no such hybrid installations are currently at a **conceptual stage**.

These hybrid installations may incur increased maintenance and equipment constraints.

Sources: SLB, 2023, Better Together: New Synergies and Opportunities From Hybrid Geothermal Projects; Geothermal rising, accessed 2024, Geothermal in hybrid renewable systems; Kearney Energy Transition Institute analysis.

Geothermal energy provides renewable-based pathways for green hydrogen and ammonia production

A Traditional

B Emerging

C Synergies

Companies active in the sector leading research and pilot projects include:
- CeraPhi Energy, US
- KEPCO, Korea
- Whitebark Energy, Australia
- Mercury Energy, New Zealand
- PT PLN, Indonesia

3.4 Emerging uses

Geothermal can play different roles in the production of green hydrogen and ammonia

Most of which are at early stages of research or pilot projects.

Hydrogen from geothermal fluid
It is theoretically possible to extract hydrogen from hydrogen sulfide in geothermal fluid. Application is limited to locations where geothermal fluid contains hydrogen sulfide, methane, and carbon dioxide, usually in tectonic and volcanic regions.

Electrolysis driven by geothermal power
Hydrogen production through electrolysis using geothermal power is possible depending on geothermal reservoir characteristics and electrolysis operating conditions. Geothermal-based hydrogen systems might not be viable due to exergy limitations in some conversion pathways.

Thermochemical process with geothermal
Limited processes, such as the copper-chlorine cycle at 350-550°C, can be compatible with geothermal energy.

High-temperature steam electrolysis with geothermal
In the high temperature steam process to produce hydrogen, geothermal heat and power can be used (e.g., solid oxide electrolysis cell). The steam is used to directly heat the water to the geothermal temperature range, then water is overheated as needed to reach the optimal temperature. The geothermal electricity is then used to power the electrolysis and split hydrogen and oxygen.

Sources: Hamlehdar, M., Beardsmore, G. and Narsilio, G.A., 2024, Hydrogen production from low-temperature geothermal energy – A review of opportunities, challenges, and mitigating solutions; Kearney Energy Transition Institute analysis

As subsurface activities, there are potential synergies between geothermal energy and the mining industry (1/3)

Operating mines and geothermal

Mines are energy-intensive installations designed to operate all year round, requiring a baseload electricity source which matches with geothermal generation profile. **The co-location of geothermal power generation is increasingly relevant for off-grid mines**, where other variable renewable generation options do not provide constant supply.

In Papua New Guinea, Newcrest mining developed more than 15-year ago a 56 MW geothermal power plant to supply less than 1% of the power needed by the Lihir gold mine, the rest being supplied by fossil fuels.

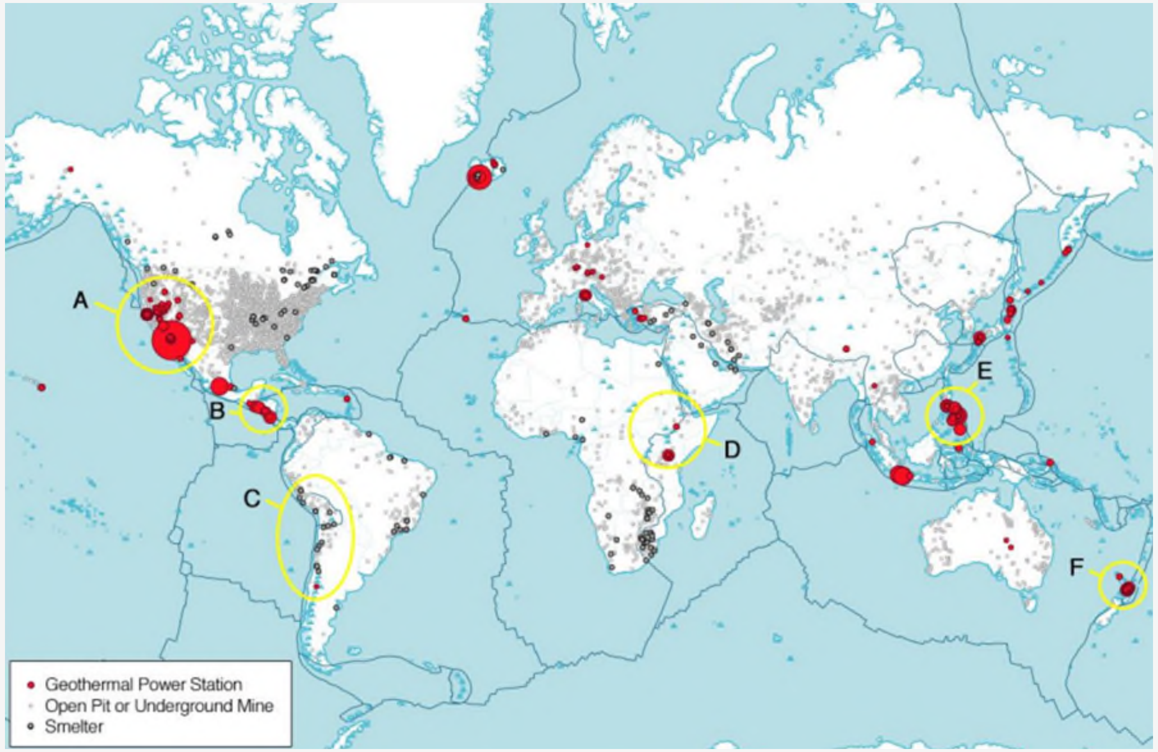
Geothermal is also used for enhanced heap leaching, a chemical process for recovering low-grade metal ores through the application of an aqueous leachate solution. In such cases, the geothermal fluid is used to heat the aqueous leach solution to improve leaching performance.

Mine prospection and exploration for geothermal

Collected data during mineral resource exploration by the mining industry contains information relevant to geothermal exploration and development. Leveraging these databases helps identifying undiscovered geothermal resources and reduce geothermal exploration costs and risks.

In the United States, geothermal sites have been discovered thanks to mining datasets, in particular in the state of Nevada where three power plants were developed.

Location of geothermal power plants and mining sites



A Traditional B Emerging C Synergies

Sources: NREL, 2022, Mining G.O.L.D. (Geothermal Opportunities Leveraged Through Data): Exploring Synergies Between the Geothermal and Mining Industries; Patsa, E. et al., 2015, Geothermal Energy in Mining Developments: Synergies and Opportunities Throughout a Mine's Operational Life Cycle; Newcrest Mining Limited, 2023, 2023 Sustainability report; Kearney Energy Transition Institute analysis

As subsurface activities, there are potential synergies between geothermal energy and the mining industry (2/3)

A Traditional

B Emerging

C Synergies

Abandoned mines can be used to **generate energy.** These types of installations have **reduced upfront costs** as the excavation expenses are limited **by reusing existing** disused mine **sites**.

3.5 Synergistic uses

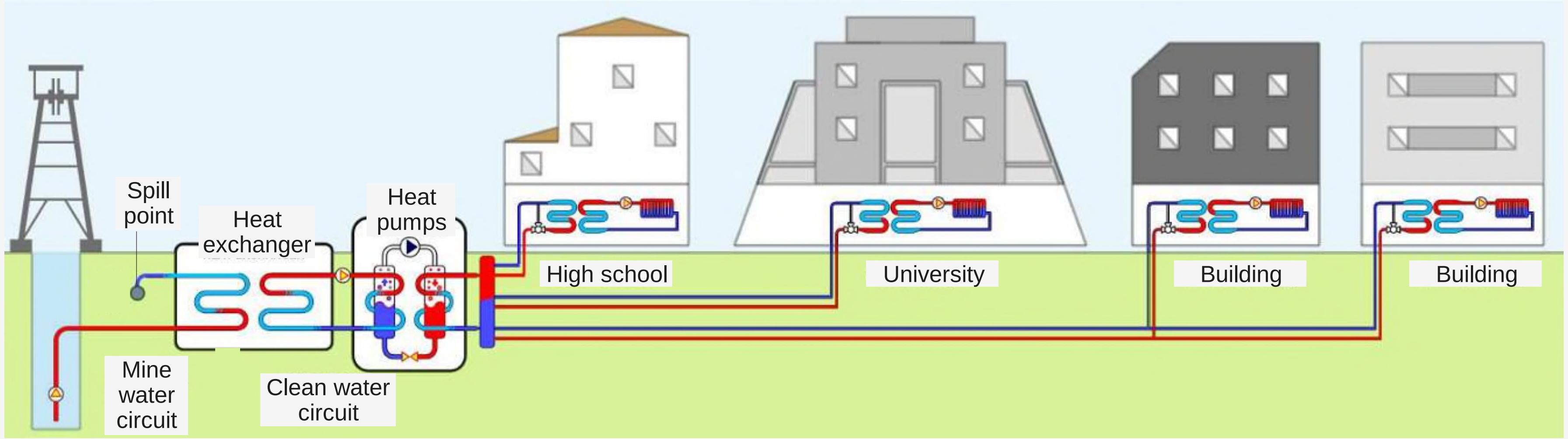
Repurposing closed mines for heat provision

Mine water geothermal installations are those **using subsurface heat from flooded (or partially flooded) mines**.

The **post-mining** use of **geothermal can provide a sustainable solution,** helping to keep water levels safe; repurposing the shaft, voids, and pumping installations; and reducing the long-term economic burden.

These installations can be **open-loop** which has an **efficient heat recovery** or **closed-loop** which **limits water contamination** and has a low cost.
Depending on the temperature reached in the reservoir, additional booster heat pumps might be needed to reach end users required temperature (usually ranging from 45° to 60°C).

Geothermal district heating with coal mine water



Sources: Menéndez, J. et al., 2019, Energy from closed mines: Underground energy storage and geothermal applications; Global District Energy Climate Awards, visited September 2024, "Barredo Colliery" District Heating | Mieres, Asturias, Spain. Part 1: Selection criteria and equipment of the experimental site; Kearney Energy Transition Institute analysis from desk research.

As subsurface activities, there are potential synergies between geothermal energy and the mining industry (3/3)

A Traditional

B Emerging

C Synergies

Geothermal brine has become a **new source of mineral extraction**, especially for critical resources of the energy transition. Across the globe, few combined facilities are operating, and several projects are in the pipeline.

3.5 Synergistic uses

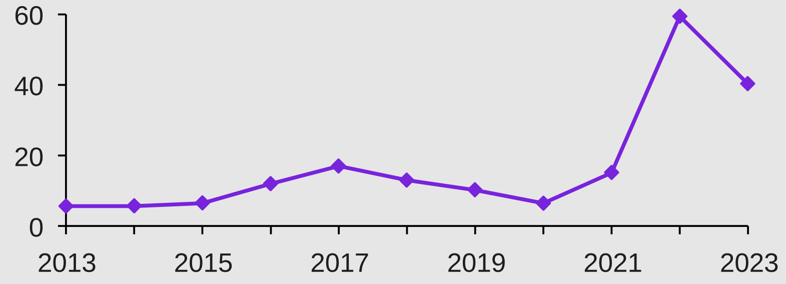
Mineral extraction combining geothermal

Geothermal brines differ between reservoirs, depending on geological conditions. Some brines are rich in minerals and precious metals, which can be exploited as a **byproduct of the primary power generation.**

- The most common minerals that could be extracted from geothermal brine are **silica, lithium, rare earths, manganese, and precious metals** among others.
- There is a broad range of extraction methods (adsorption, ion exchange, membrane separation, solvent extraction, precipitation…) with challenges and advantages; research is being focused on optimizing the processes.
- Some research has also been done to **extract drinking water** from geothermal springs by using geothermal energy as the energy source to water extraction. A demonstration plant BrineMine is exploring this in Chile with the support of the Fraunhofer ISE.
- Mineral extraction allows combining **two revenue streams** based on the sales of heat or electricity and complemented by the sale of minerals. The **profitability** of this model is **subject to price volatility of minerals**.

Global weighted average lithium carbonate sale price

Thousand USD/t



Lithium extraction from geothermal brine

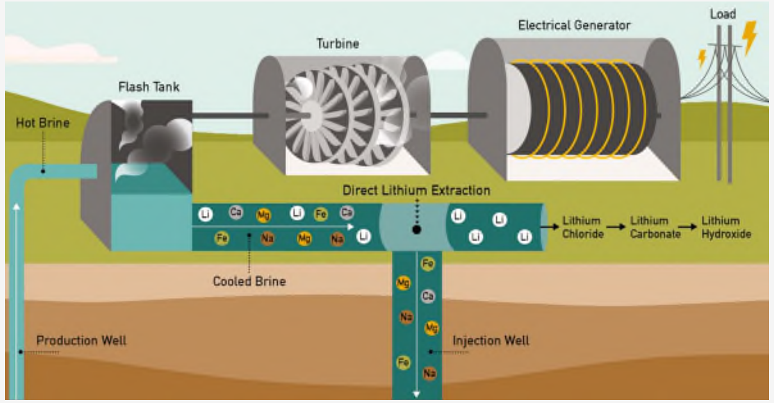
Projects of lithium and other minerals recovery have been deployed **in few countries**, motivated by increasing demand, the possibility to secure domestic supply, and ensuring a more sustainable extracting method.

Lithium extraction **concentration and brine conditions** are very different from site to site:

- Salton Sea in California, US (400 mg/l at 200-330°C)
- Upper Rhine valley, Germany (210 mg/l at 200°C)
- Alsace, France (162 mg/l at 205°C)
- Wairakei, New Zealand (13 mg/l at 60-80°C)

Today, few projects aiming to extract lithium from the geothermal brine exist. In Germany and France, battery-grade lithium has been achieved in 2024, while in Italy and the United States, projects are at different development stages.

Schematic view of lithium extraction with geothermal



Sources: NREL, 2021, Techno-Economic Analysis of Lithium Extraction from Geothermal Brines; Berkeley Lab, 2021, Sizing Up the Challenges in Extracting Lithium from Geothermal Brine; Sengun, R. et al., 2024, Mineral Extraction from Geothermal Reservoirs: A Case Study from Western Anatolia; Energy Institute, 2024, Statistical Review of World Energy; Kearney Energy Transition Institute analysis form desk research.

Geothermal energy can also benefit from synergies with the oil and gas industry (1/3)

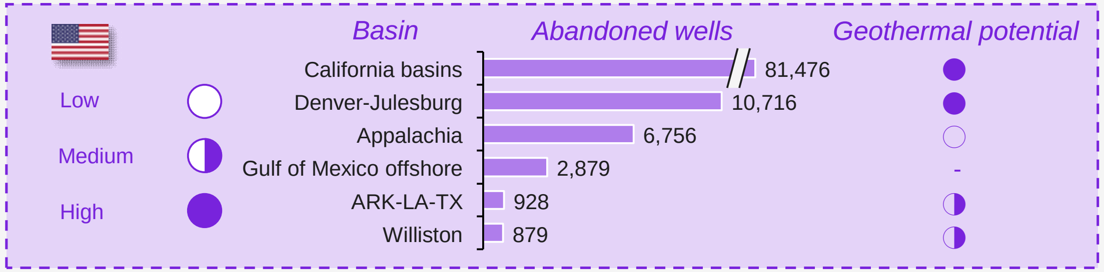
Heat recovery from hydrocarbon wells and reservoirs

Similar to mining, geothermal projects can take **advantage of exploration data from oil and gas** exploration to identify the low-temperature geothermal **resources in sedimentary basins**.

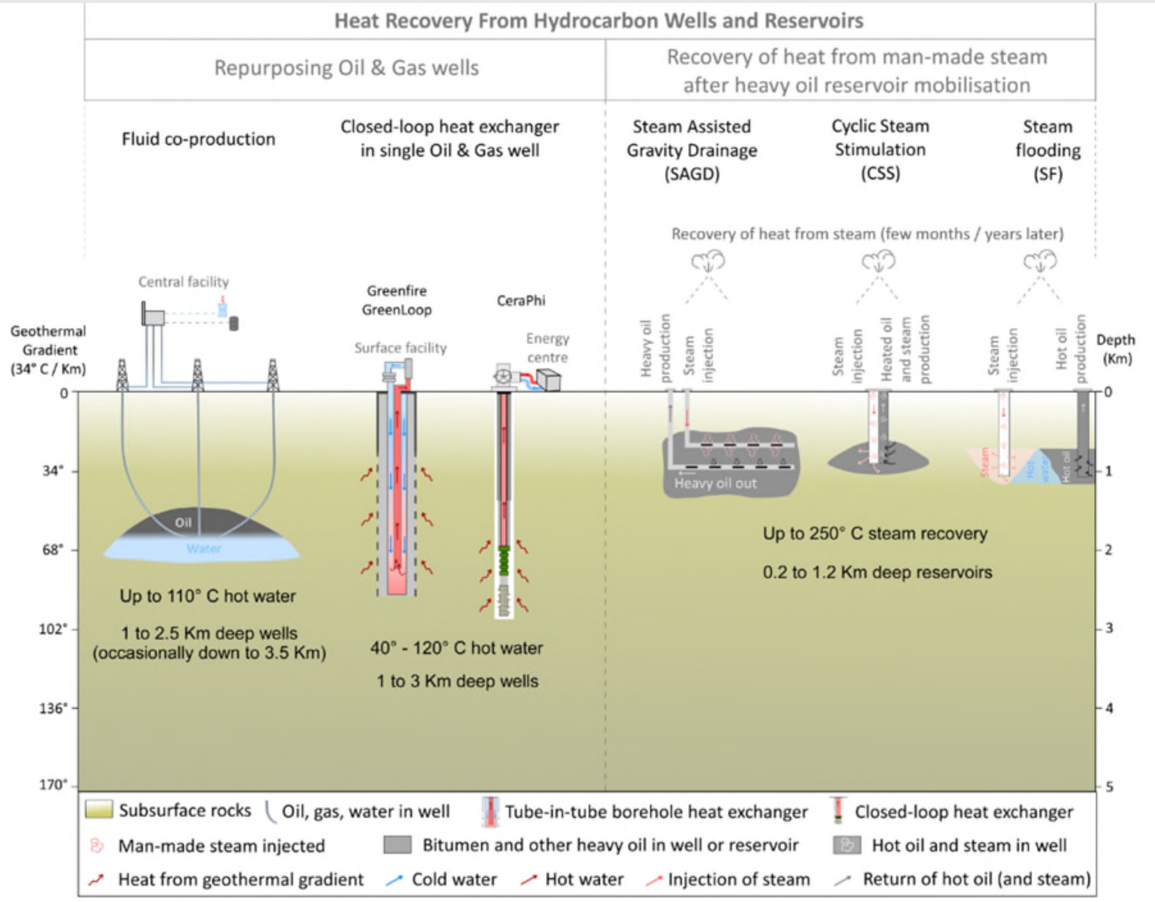
The benefits of repurposing onshore hydrocarbon wells include reduced investment cost through the reutilization of existing assets, as it limits drilling activities needed for the geothermal systems. The disadvantages include, reservoir pressure decline in the case of fluids co-production and low power output of closed-loops.

– A large number of oil and gas wells exist; some are producing hydrocarbons and others are not suitable for heat recovery.
– Regulation does not always allow repurposing wells, requiring adjustments of subsurface rights or ownership depending on the country.

These projects can exploit geothermal resources by operating in parallel with oil and gas extraction, repurposing depleted or abandoned oil and gas wells and, from heavy oil reservoirs.



Geothermal installations in oil and gas wells and reservoirs



Sources: Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; AlphaSense, 2024, 9th Annual Sustainability & Energy Transition Primer – Ahead Of Curve; Kearney Energy Transition Institute analysis

Geothermal energy can also benefit from synergies with the oil and gas industry (2/3)

A Traditional

B Emerging

C Synergies

Hydrocarbon well repurposing or use for geothermal energy are in theory possible, but their feasibility, efficiency, and scalability are still to be demonstrated.

Repurposing hydrocarbon wells

The **warm fluids from oil and gas wells** can be used to produce electricity or heat through geothermal installations in lieu of ditching the wells.

Schematic configuration in next slide

Co-production of fluids in same field wells

Corresponds to the parallel production of hydrocarbons and water extraction in multiple wells from the same field. The (warm) water is pumped out mixed with the hydrocarbon, separated, and then goes into a binary cycle turbine to produce electricity or into a heat exchanger to recover heat. Once the water is cooled down, it is then reinjected into the underground reservoir to avoid contaminating ground water sources.

– Few projects have proven the repurposing of these wells. Small pilot plants in China, the United States and France have operated in such manner, with usually low electricity or heat output.

Closed loop in single hydrocarbon well

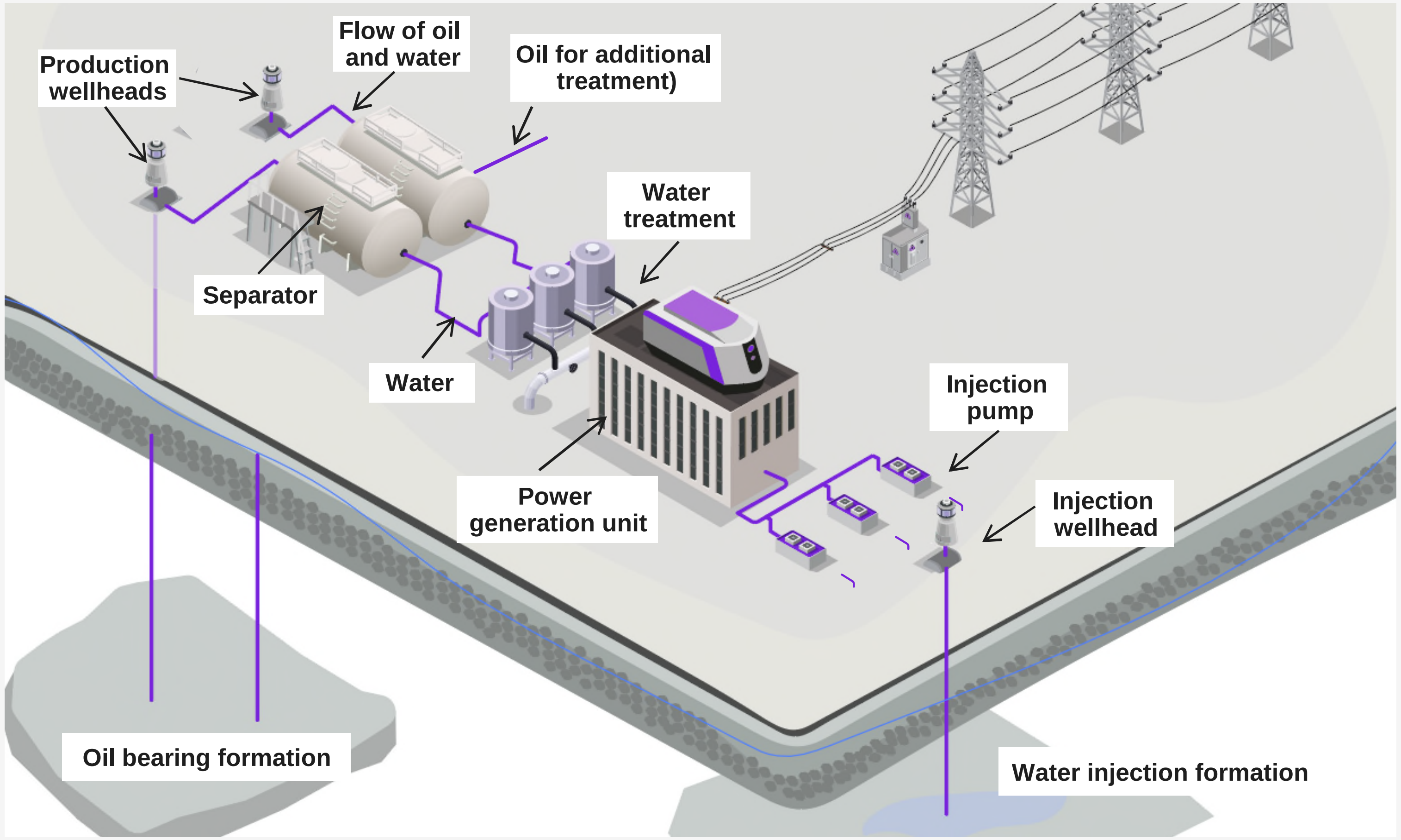
Similar to a conventional shallow or deep closed-loop system, this closed loop allows a fluid to recover the heat beneath the surface through a borehole heat exchanger and avoids water extraction and reinjection into the reservoir.

– Few projects are trying closed loop borehole heat exchangers; CeraPhi is developing a project in North Yorkshire in the UK in a 3-km deep abandoned gas well.

Sources: Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; Kearney Energy Transition Institute analysis

Geothermal energy can also benefit from synergies with the oil and gas industry (3/3)

Binary cycle oil field power generation unit schematic



Effective separation and treatment of the co-extracted fluids (hydrocarbon and water) are crucial for the efficient operation of the binary cycle unit. Improved fluid separation and treatment help minimize issues with heat exchangers, such as hydrocarbon build-up or scale, which can reduce the overall efficiency.
Binary cycle systems are the most widely used technology for generating electricity from geothermal resources in the 100-180°C range.

A Traditional
B Emerging
C Synergies

3.5 Synergistic uses

Sources: Céspedes, S. et al., 2022, Technical and Environmental Feasibility Study of the Co-Production of Crude Oil and Electrical Energy from Geothermal Resources: First Field Trial in Colombia, Processes; Kearney Energy Transition Institute analysis

CCS offers synergies with geothermal energy for the dual benefit of renewable electricity or resource extraction and carbon sequestration

Non-exhaustive

A Traditional

B Emerging

C Synergies

3.5 Synergistic uses

Electricity generation: CO_2-EGS[1]

- CO_2-EGS **couples geological carbon storage and geothermal electricity generation.**
- Conventional EGS uses water as the working fluid but incurs a 10-20% loss during operation due to fracture leakage, evaporation, rock absorption, etc.
- CO_2 is a promising alternative; **loss is conducive to greenhouse gas reduction in a closed loop.**
- **CO_2 is injected into a geothermal reservoir,** absorbing hot rock heat and returning to generate electricity by driving turbines.
- Water remains the fluid for hydraulic fracking.

Electricity generation: Utilization of sedimentary basins

- Sedimentary basins, often used for geothermal energy extraction via lower temperature resources, **offer large volumetric storage capabilities for CO_2.**
- Integrate geological carbon storage and geothermal electricity generation in these basins by leveraging CO_2 as working fluid in a closed loop.
- Closed loop required **to contain CO_2 and maintain pressure** for efficient heat exchange with geothermal resource and electricity generation

E.g., **Carbfix and ON Power, Iceland, are** developing a process to capture CO_2 from ON Power's emissions, which it will pump into basalt rock layers to react and store.

Electricity generation: Hybridization with bioenergy

- Combined bioenergy production and geothermal energy by injecting emissions from biogenic fuel combustion into geothermal wells.
- **Potential for overall negative emissions** if, e.g., forestry residue is used given forests already remove CO_2 from atmosphere.

Resource extraction: Mineralization

- In certain geothermal systems, **CO_2 is injected into a geothermal reservoir where it dissolves in water to form carbonic acid** (if no naturally occurring water, CO_2 is dissolved in water prior to injection)**.**
- **Carbonic acid reacts with minerals in the host rock to form stable carbonates,** locking away CO_2 permanently, preventing emission to the atmosphere.
- **Stable carbonates, such as $CaCO_3$ and $MgCO_3$, can be extracted** for use in production of construction materials, paints, coatings, etc., as well as neutralizing acidic soils and treating wastewater.

1. EGS is enhanced or engineered geothermal system.
Note: CCS is carbon capture and storage.
Sources: Cariaga, C., 2022, Geothermal and carbon capture – a natural synergy; Littlefield, A. and Stauterg, E., 2022, Synergies Between Carbon Capture, Utilization and Sequestration and Geothermal Power in Sedimentary Basins; Wu, Y. and Li, P., 2020, The potential of coupled carbon storage and geothermal extraction in a CO2-enhanced geothermal system: a review; Kearney Energy Transition Institute analysis

4. Past and projected geothermal energy market growth

Past and projected geothermal energy market growth

Geothermal technical potential

- **Geothermal energy has the second-largest global technical electricity potential** following solar (596 TW vs. 2,221 TW, respectively); however, <0.01% of its potential is currently exploited (focused on easily accessible sites), reaching 0.2% by 2050 under the Net Zero Emissions by 2050 scenario (supported by broadened scope of accessible sites via emerging technologies).
- **Similarly, <0.01% of global technical geothermal heat potential is harnessed** at present.

Geothermal heat provision

- **Geothermal heat pumps dominate heating**, with China leading at 51% of total capacity (99 GW_{th}) in 2023.
- **Geothermal heat serves diverse end-user applications;** direct use is set to account for 6.1% of renewable heat in buildings by 2028.

Geothermal electricity generation

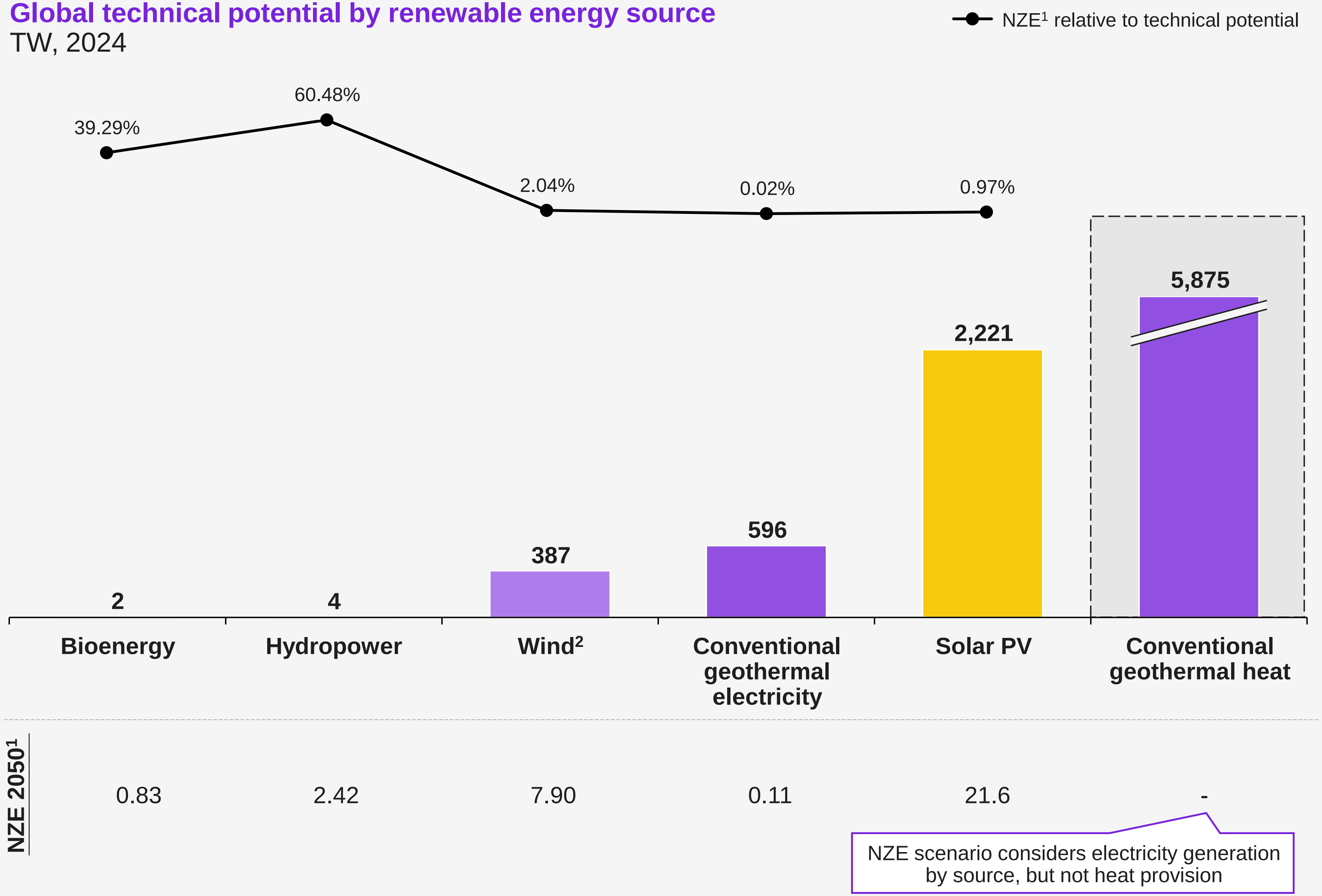
- **Geothermal electricity accounts for 0.3% of the global mix**, with potential to triple by 2030.
- **Top ten countries by installed geothermal electricity generation capacity** account for 82% of global total, led by the US.
- **Indonesia leads development with 38% of pipeline**, followed by the US, Kenya, and the Philippines.
- **Annual geothermal well drilling, averaging 200 between 2015–2020, is expected to rise to 500 by 2025,** driven by EGS and AGS technologies, with over 10,000 active wells projected by 2030.

Investment in geothermal energy

- **In 2023, geothermal heat and power investments exceeded USD 47 billion**, over 5% of global renewable energy spending, with China contributing 70%.
- **Unlocking potential of emerging geothermal electricity and heat requires over USD 1 trillion by 2035 and USD 2.8 trillion by 2050,** respectively.
- **Start-ups are driving EGS and AGS development,** reflected by rising VC investments from USD 368 million in 2022 and to over USD 420 million annually in 2023.

Geothermal energy has the second-largest technical electricity generation potential behind solar

Global technical potential by renewable energy source
TW, 2024



1. Net zero emissions scenario by 2050; 2. Combined onshore and offshore global technical potential (274 TW and and 113 TW, respectively).
Sources: IEA, 2024, The Future of Geothermal Energy; IEA, 2024, World Energy Outlook 2024; Kearney Energy Transition Institute analysis

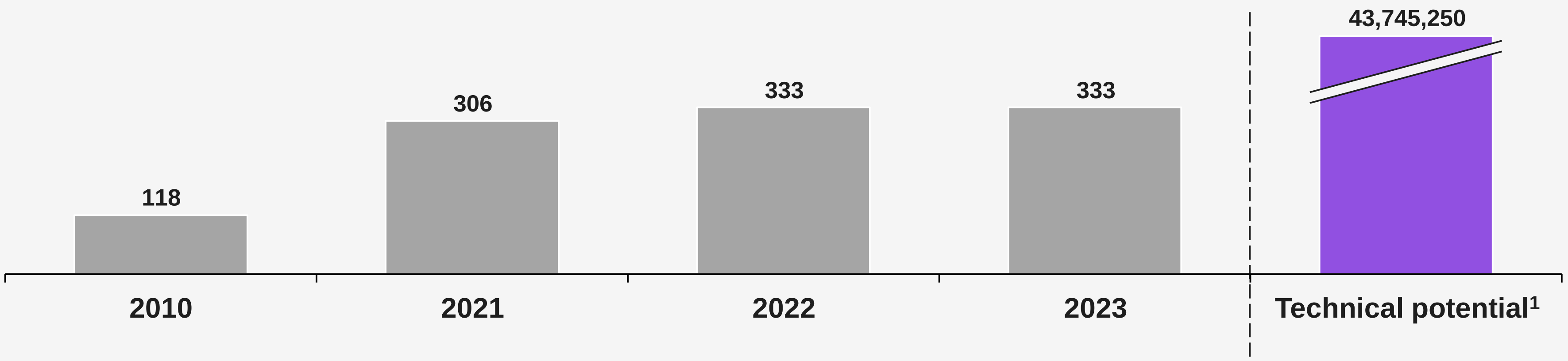
4.1 Geothermal technical potential

Today, about 333 TWh/year of geothermal energy is utilized for heat provision and about 100 TWh/year for electricity generation

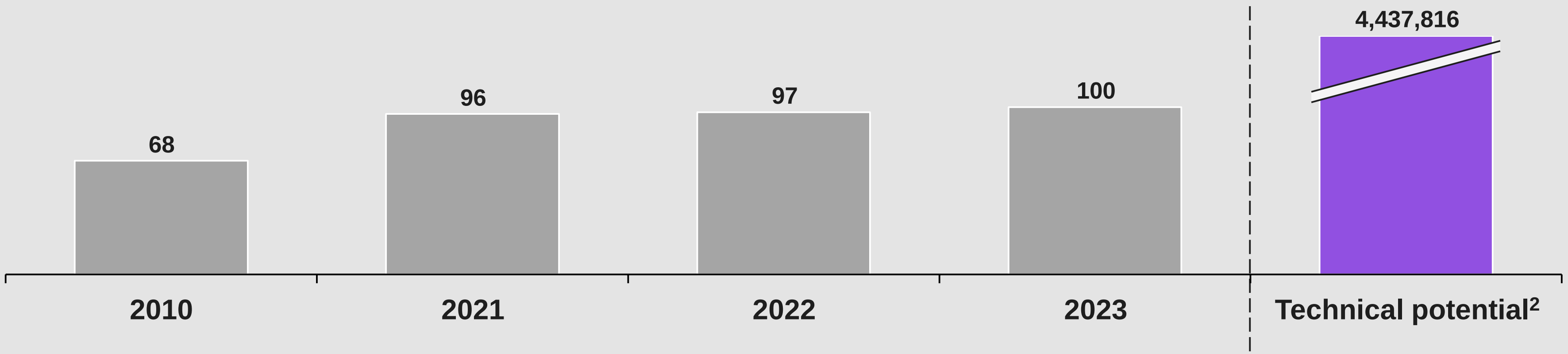
Current use of geothermal energy for heat and electricity **represents <0.01% of global energy potential** for each application.

4.1 Geothermal technical potential

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



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

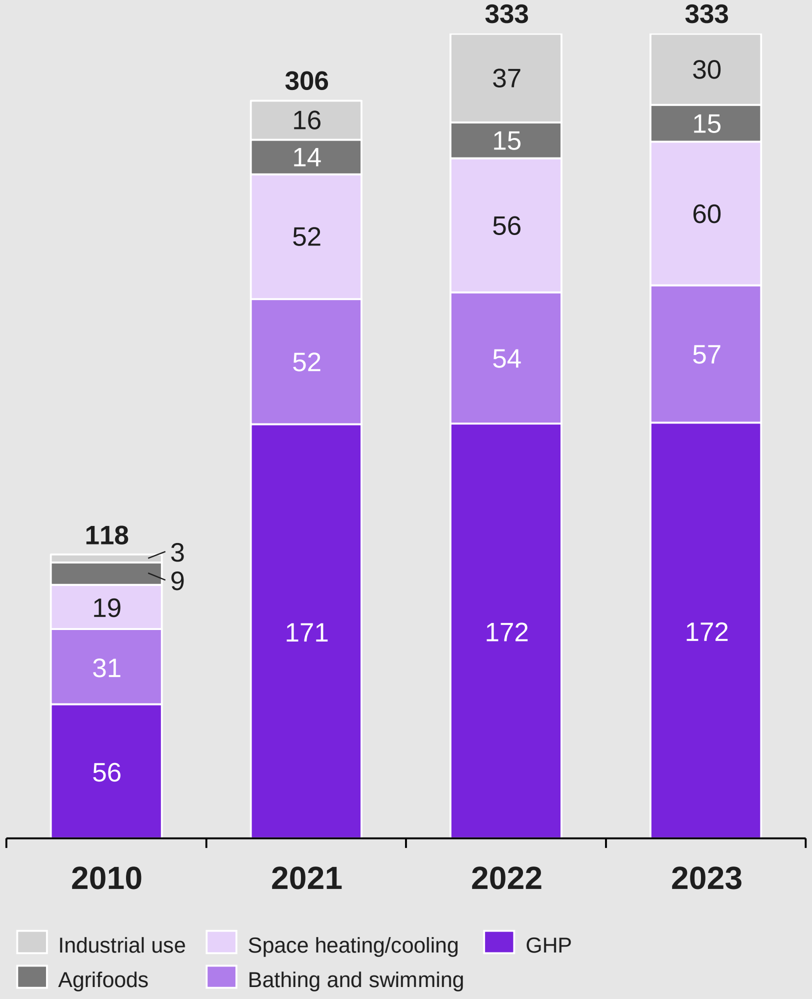


Note: Heat provision in this study is divided into direct use (industrial use, agrifoods, bathing and swimming and space heating), district heating and cooling (space heating and cooling) and geothermal heat pumps.
1. Considering a capacity factor of 40%; 2. Considering a capacity factor of 85%.
Sources: 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

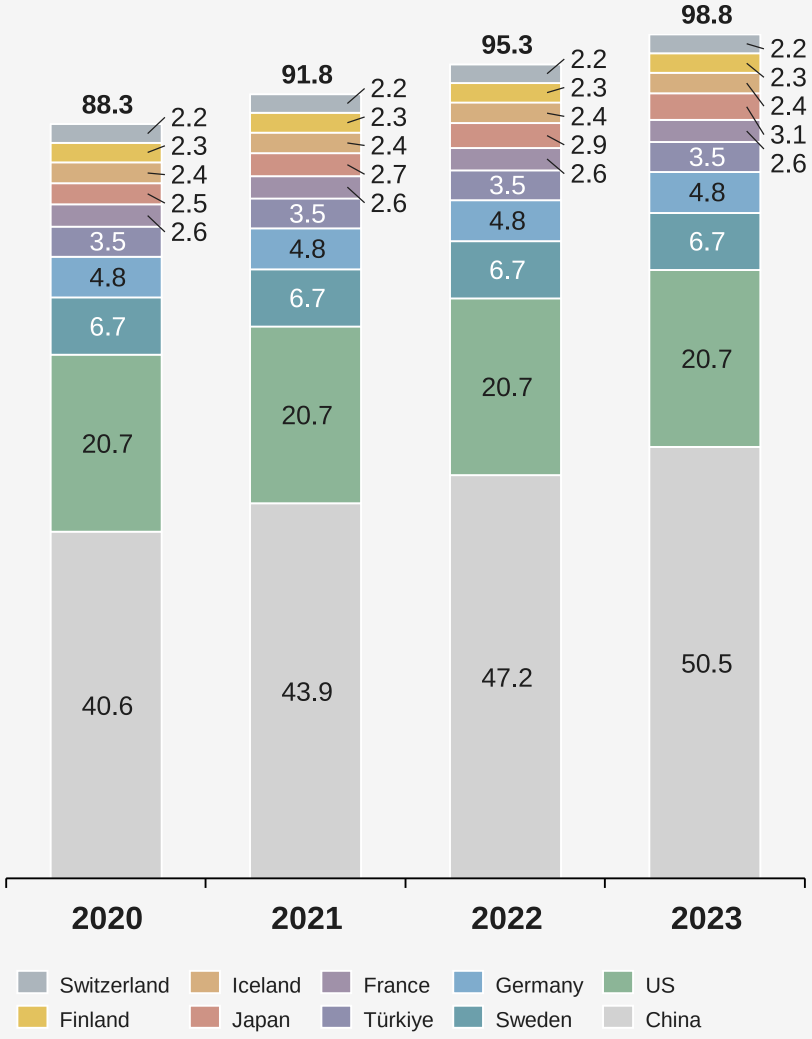
GHPs[1] are the dominant application of geothermal energy in the heating and cooling industry

In 2020, the top 10 countries for heating and cooling represented ~82% of global thermal capacity.

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



Top ten countries by geothermal heating installed capacity
GW_{th}, 2020-2023



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

Heat provision

4.2 Geothermal heat provision

Geothermal (direct use) in heat consumption is expected to accelerate slightly during 2023-2028

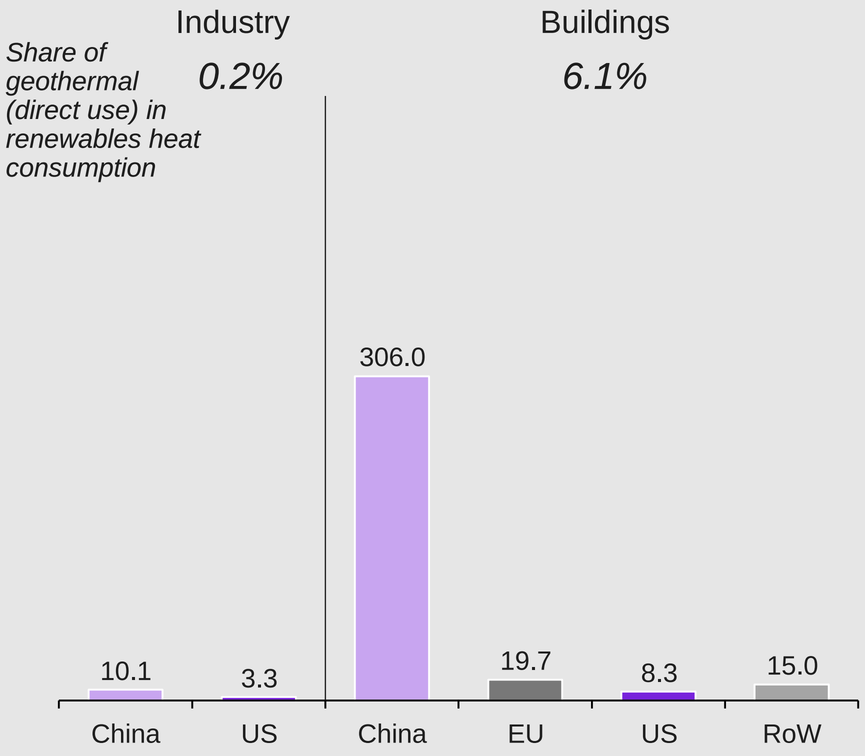
Geothermal (direct use) will significantly contribute to buildings' heat consumption, accounting for up to 6.1% of renewables heat consumption between 2023 and 2028.

Heat provision

4.2 Geothermal heat provision

Projected use of geothermal (direct use) in heat consumption in selected regions

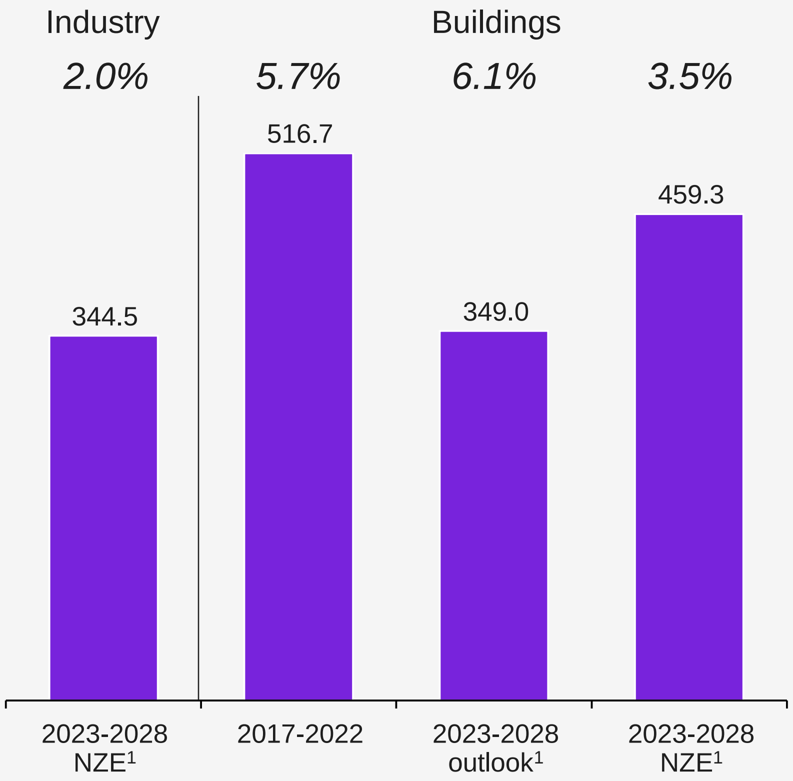
PJ, 2023-2028



Geothermal (direct use) in renewable heat consumption is expected to accelerate slightly over the outlook period, rising about 362 PJ globally during 2023-2028.[1]

Projected use of geothermal (direct use) in heat consumption in various scenarios

PJ, 2017-2028



Overall, the share of renewables in heat consumption rises to 22% in industry and 34% in buildings by 2028 in the Net Zero Scenario, with geothermal accelerating slightly.

1. The 2023-2028 outlook forecasts that almost 3,700 GW of new renewable capacity will become operational worldwide over the next five years. The 2023-2028 NZE forecasts that almost 4,500 GW of new renewable capacity will become operational worldwide over the next five years.
Note: RoW is rest of world. The projections for heat provision from geothermal sources focus on geothermal (direct use), as data on geothermal heat pumps and district heating and cooling are not available.
Sources: IEA, 2024, Renewables 2023; Kearney Energy Transition Institute analysis

Geothermal utilization for heating and cooling covers a wide range of end-user applications

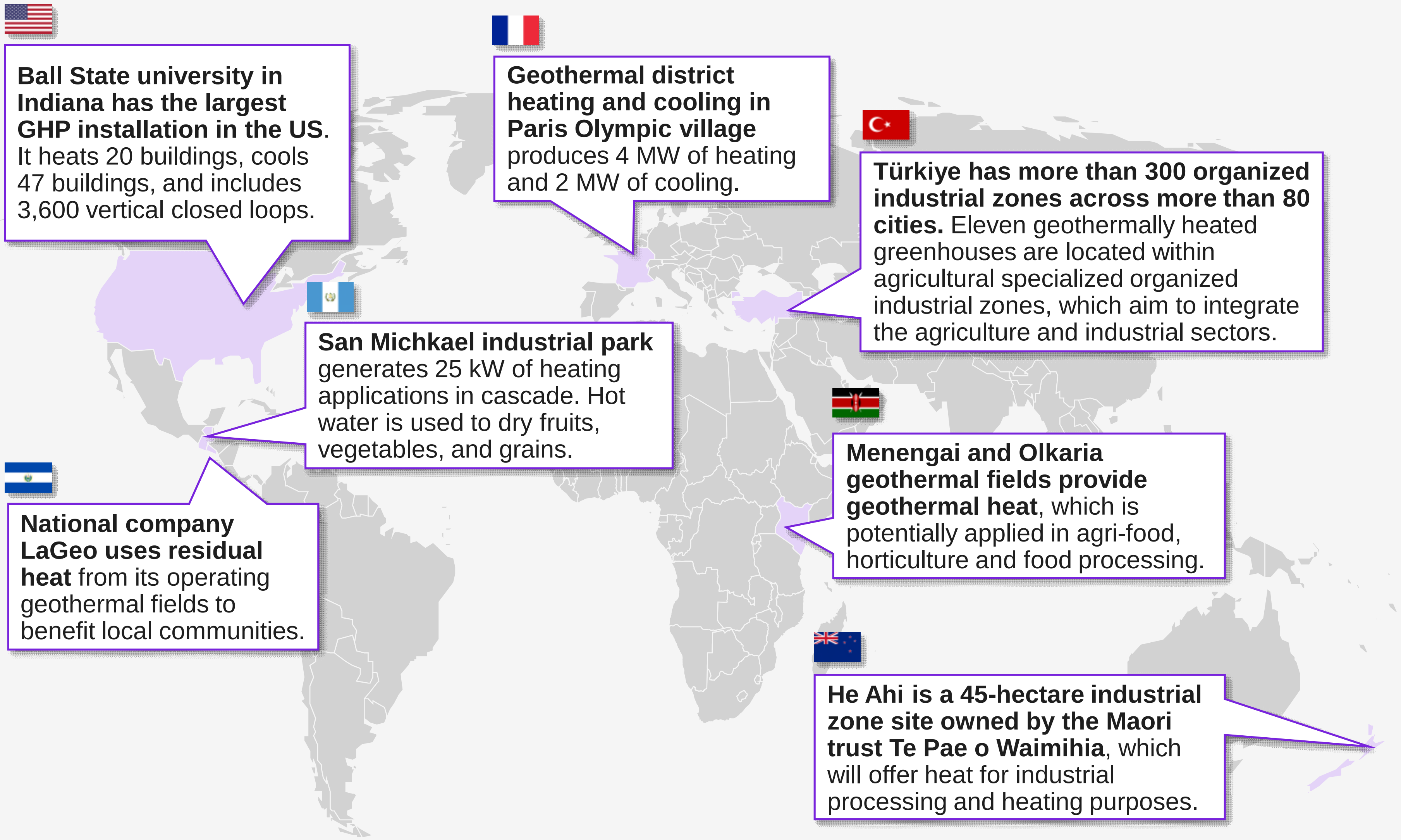
Non-exhaustive

Heat provision

4.2 Geothermal heat provision

Geothermal heat provision projects

2023

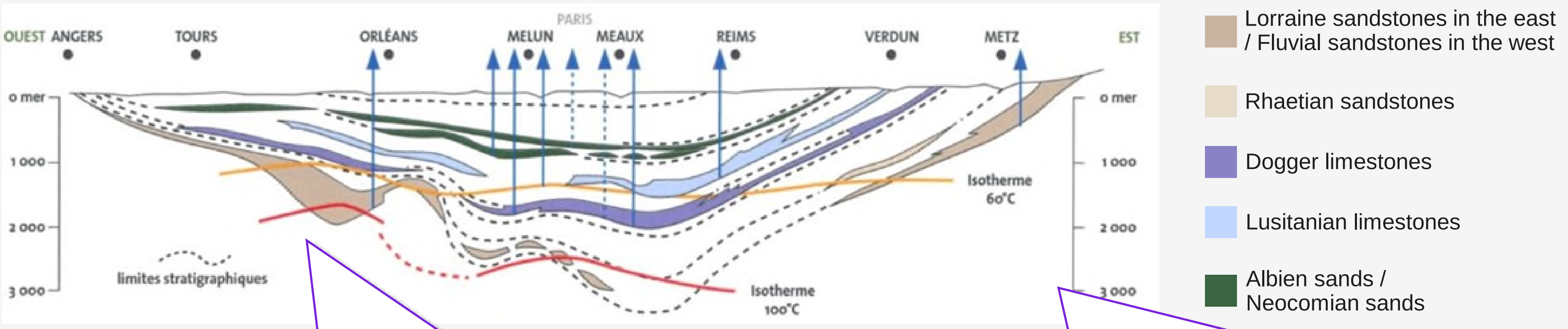


Sources: IRENA and IGA, 2023, Global geothermal market and technology assessment; European Geothermal Energy Council, 2023, Geothermal stories; Kearney Energy Transition Institute analysis

Near-surface geothermal energy could cover up to 29.75 TWh/year, which is approximately 58% of the current thermal energy consumption in the Greater Paris region

1. A geothermal doublet system consists of two wells: a production well, which extracts hot water or steam, and an injection well, which reinjects the cooled water. 2. A geothermal triplet system consists of three wells: one production well, which extracts hot water or steam, and two injection wells, which reinject the cooled water.
Sources: BRGM, 2022, Cartographie du potentiel de la géothermie de surface sur le territoire de la Métropole du Grand Paris; EGEC, 2023, Lessons learnt from successful project development: the case of the Paris basin GDH; BRGM, Les grands aquifères géothermaux du Bassin Parisien; Veloso, F.M.L. et al., 2021, Target area of Paris Basin Region – FR: Data inventory, seismic target and GAP analysis, EU H2020 PilotSTRATEGY; Kearney Energy Transition Institute analysis

Greater Paris region basin geothermal potential



Western Ile-de-France basin:
- Fluvial and deltaic geological settings, with **shallow sedimentary deposits** like the Neocomian and Albian sands
- **Lower thermal gradients**
- **Shallow** aquifers make this region suitable for **small-scale geothermal projects**, such as residential heating.

Eastern Ile-de-France Basin:
- **Deeper reservoirs**, including the Dogger limestone, which has been extensively used for **geothermal district heating**
- **Contains high-quality aquifers** with significant porosity and permeability, such as the Lorraine sandstones and Dogger aquifers.
- **Higher geothermal gradients**
- High **potential for** large-scale geothermal applications, such as **district heating networks**

Ile-de-France basin geothermal district heating learning curve

1 — 1969–1980
- First geothermal district heating doublet installed at Melun l'Almont.
- Five doublets completed.[1]
- Wells were largely vertical and single-well operations dominated.

2 — 1980–1990
- Fifty doublets completed.
- Challenges such as scaling, corrosion, and limited operational efficiency

3 — 1990–2000
- Introduction of anticorrosion well materials to address chemical challenges within the geothermal reservoir.

4 — 2000–2010
- 34 geothermal district heating systems online
- Directional well architectures were introduced, allowing better access to reservoir layers, maximizing flow and energy extraction.
- 4 new doublets / triplets[2]

5 — 2010–Present
- 36 new doublets / triplets

Perspectives 2030
- *30 more doublets*
- *Exploration of deeper aquifers*

Kearney XX/ID

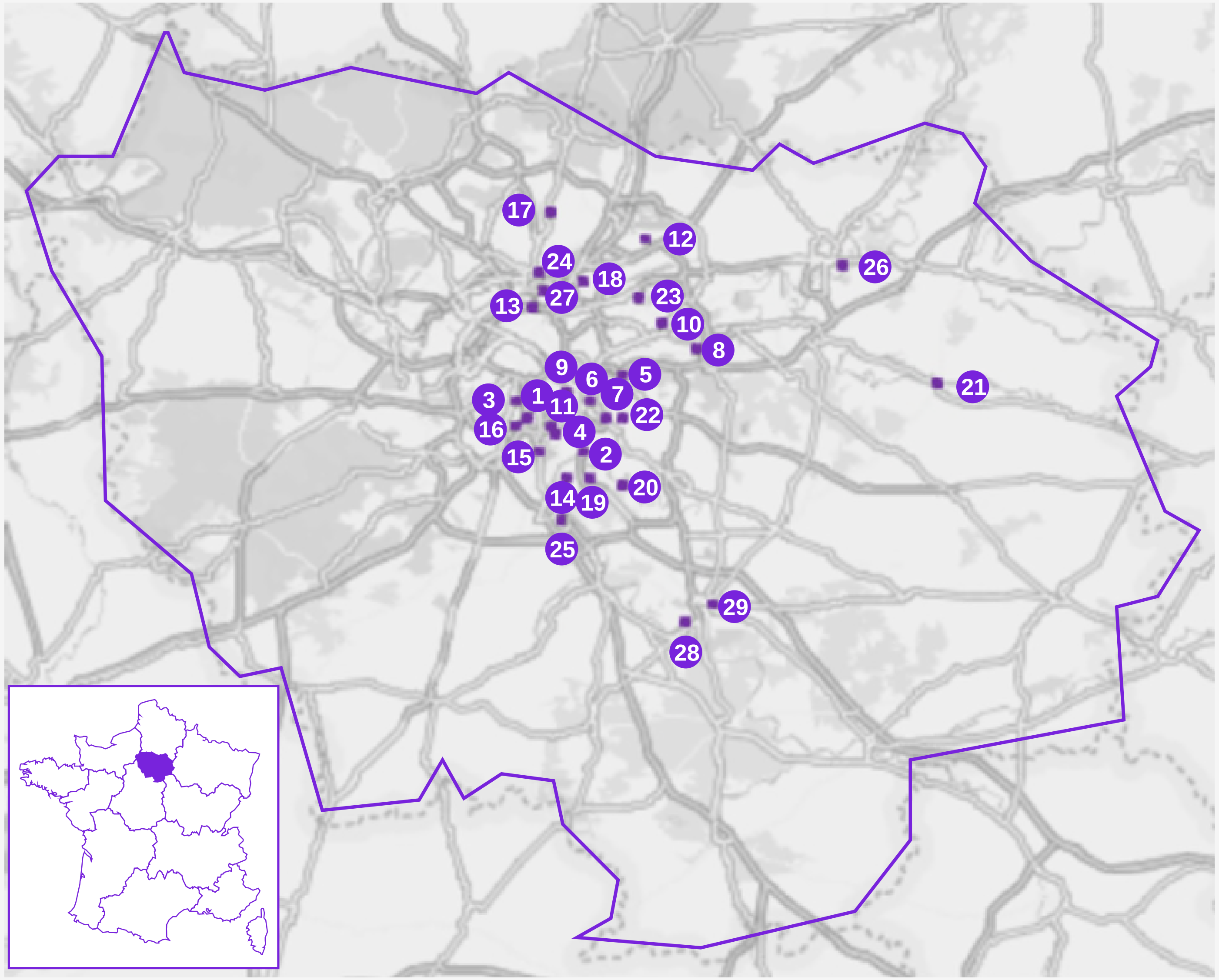
France's geothermal district heating accounts for 232 MWth (280 GWh/year), with 29 out of 30 projects located in Île-de-France

Non-exhaustive

France's geothermal district heating accounts for 45% of the installed capacity and 36% of the annual energy consumption of geothermal district heating in Europe.

4.2 Geothermal heat provision

Geothermal district heating systems in Ile-de-France region



#	Locality	Capacity (MWth)
1	Chevilly Larue / L'Hay-les-Roses	19
2	Villeneuve Saint Georges	13
3	Cachan Nord-Sud	12
4	Orly 2 & 3	11
5	Champigny sur Marne	11
6	Créteil	10
7	Bonneuil sur Marne	10
8	Torcy	10
9	Alfortville	9.5
10	Chelles	9.5
11	Thiais	8.8
12	Tremblay en France	8.6
13	Paris- Porte de la Chapelle	8.5
14	Vigneux sur Seine	8.2
15	Orly airport	8
16	Fresnes	7.9
17	Villiers le Bel	7.2
18	Le Blanc Mesnil	7
19	Montgeron	7
20	Epinay sous Sénart	6.7
21	Coulommiers	6.4
22	Sucy en Brie	6.2
23	Clichy sous Bois	5.6
24	La Courneuve Nord	4.1
25	Ris Orangis	4.1
26	Meaux Hôpital	3.8
27	La Courneuve Sud	3.3
28	La Mée sur Seine	3.2
29	Melun l'Almont	3.2

Sources: EGEC et al., 2014, GeoDH Geographical Information System; Kearney Energy Transition Institute analysis based on desktop research

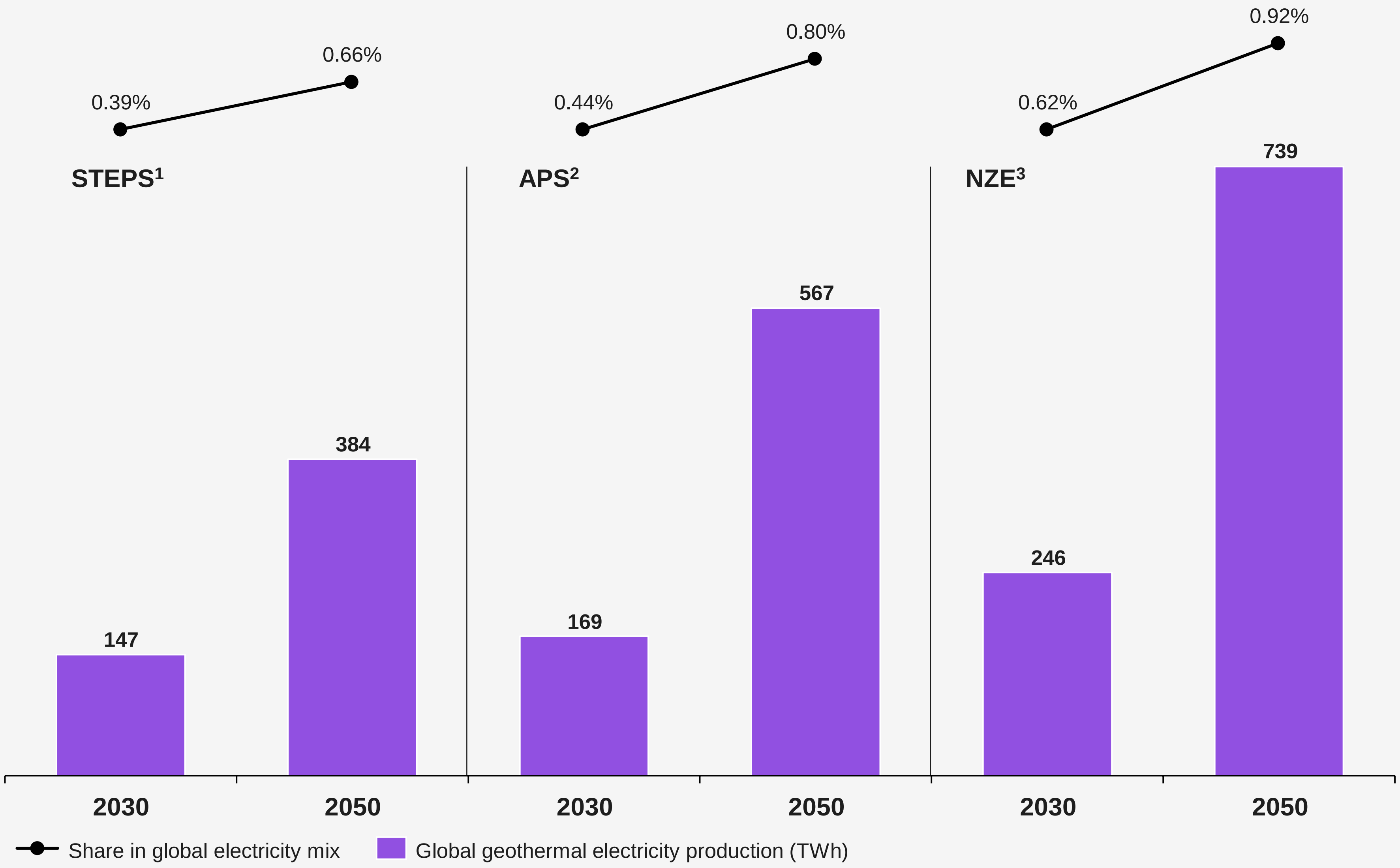
Geothermal share of global electricity output is expected to remain limited in future energy scenarios for 2050, despite its large global technical potential

The geothermal share in the global electricity mix **stands at 0.3%; it is expected to remain <1.00%** given the nascency of emerging technologies required to explore new geographies.

Electricity generation

4.3 Geothermal electricity generation

Geothermal energy in global electricity mix by future development scenario
TWh, 2030-2050



1. Stated policies scenario; 2. Announced pledges scenario; 3. Net zero emissions by 2050 scenario
Sources: IEA, 2024, World Energy Outlook 2024; Kearney Energy Transition Institute analysis

Installed geothermal electricity capacity has grown at 2% CAGR since 2020, slowing from growth observed in earlier 2000s

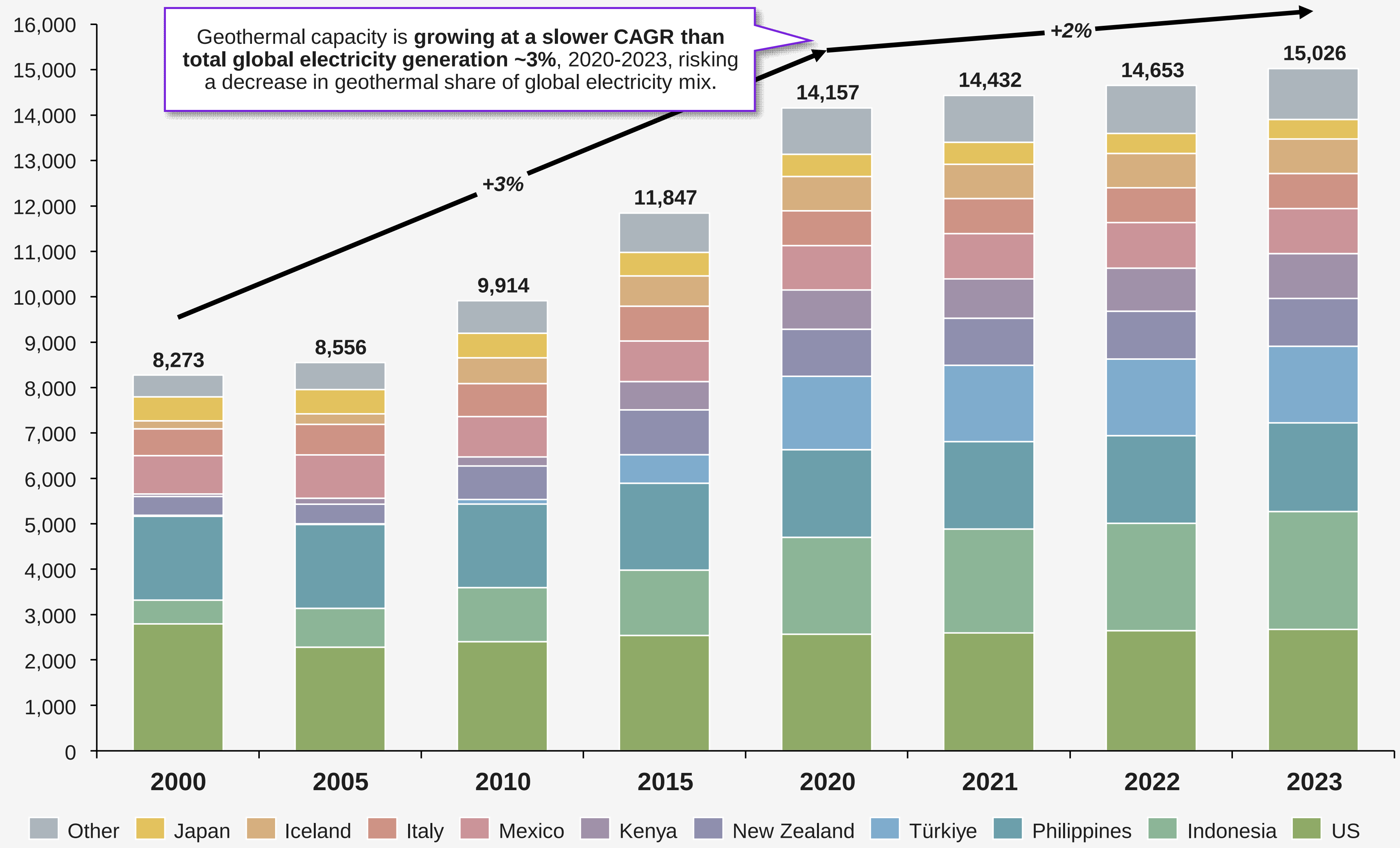
In 2023, the 10 largest countries by installed geothermal electricity capacity represented **~92% of global total,** while 20 other countries accounted for the remaining 8%.

Electricity generation

4.3 Geothermal electricity generation

Installed geothermal electricity capacity by country

MW_e, 2000-2023

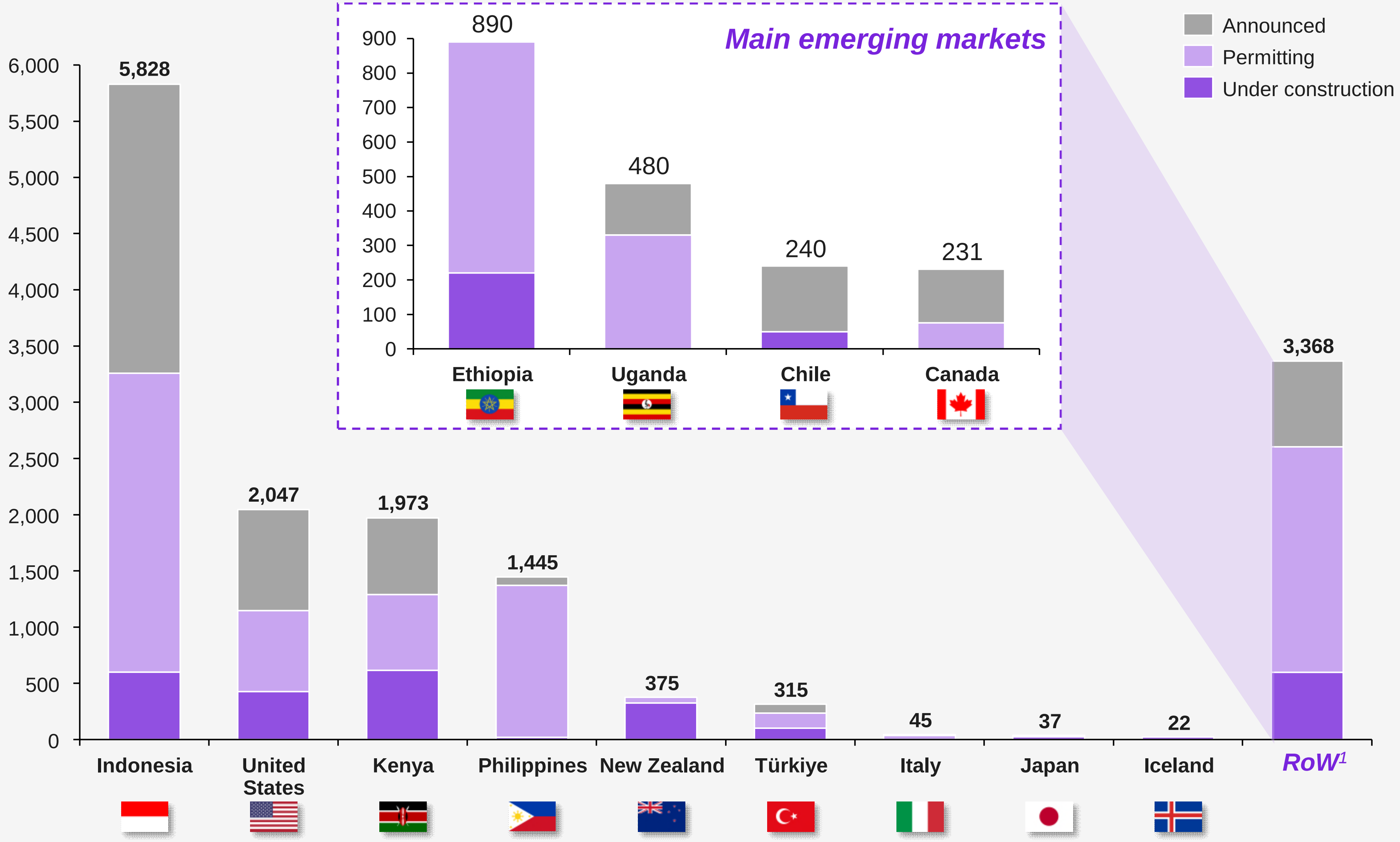


Sources: IRENA, 2024, IRENASTAT Online Data Query Tool; IRENA and IGA, 2023, Global geothermal market and technology assessment; ThinkGeoEnergy, 2024, Top 10 Geothermal Countries 2023 – Power generation capacity; REN21, 2023, Renewables 2023 Global Status Report collection, Renewables in Energy Supply; Gutiérrez-Negrin, L.C.A., 2024, Evolution of worldwide geothermal power 2020-2023, Geothermal Energy; Kearney Energy Transition Institute analysis

Indonesia is the most prominent market for geothermal development, with the United States and Kenya also presenting significant potential

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: GlobalData, 2024, Geothermal Capacity by Power Plant data; Kearney Energy Transition Institute analysis

Electricity generation

4.3 Geothermal electricity generation

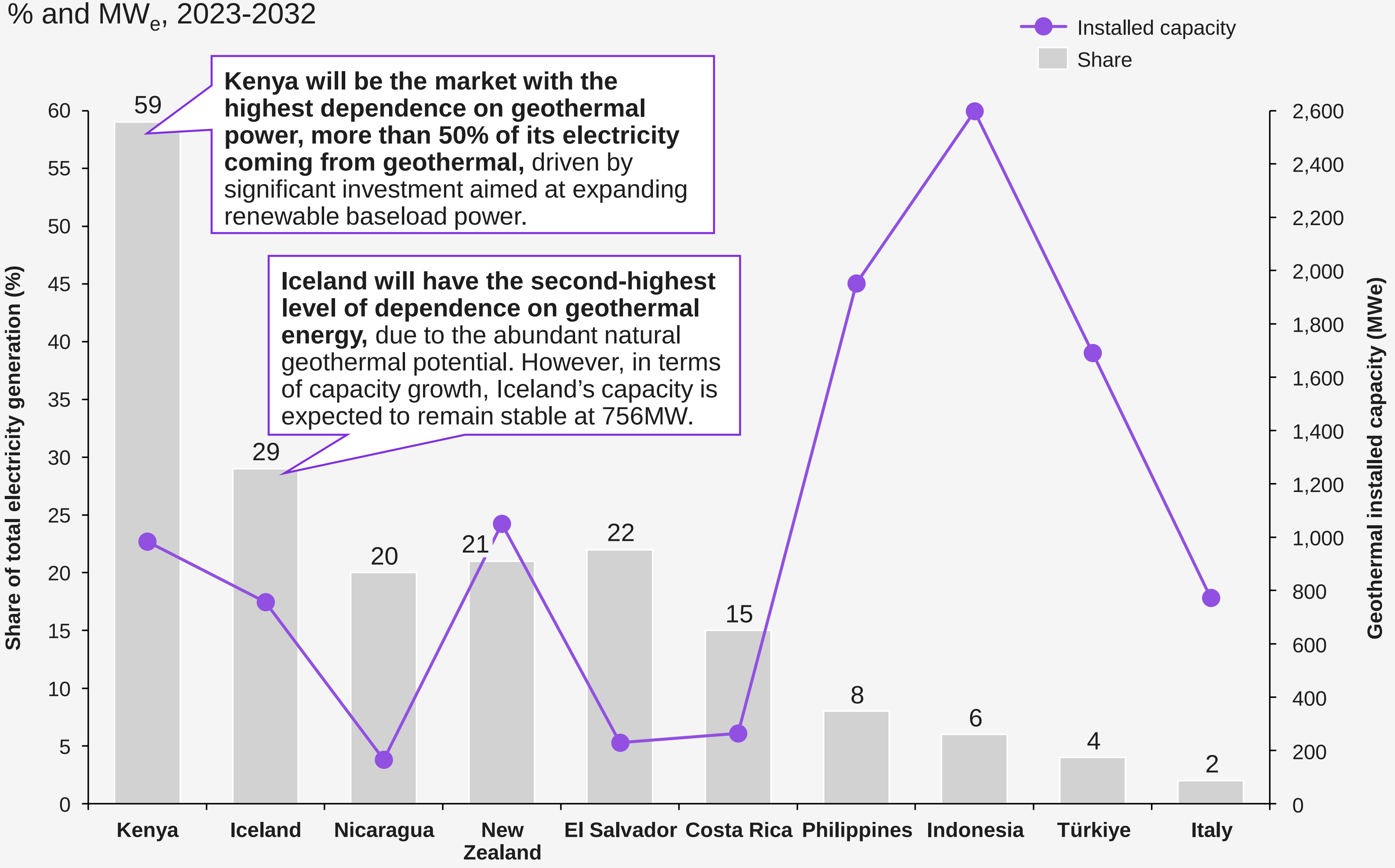
Six markets are expected to generate more than 10% of their power from geothermal sources

Electricity generation

4.3 Geothermal electricity generation

Top 10 markets by geothermal share of total electricity generation

% and MW_e, 2023-2032

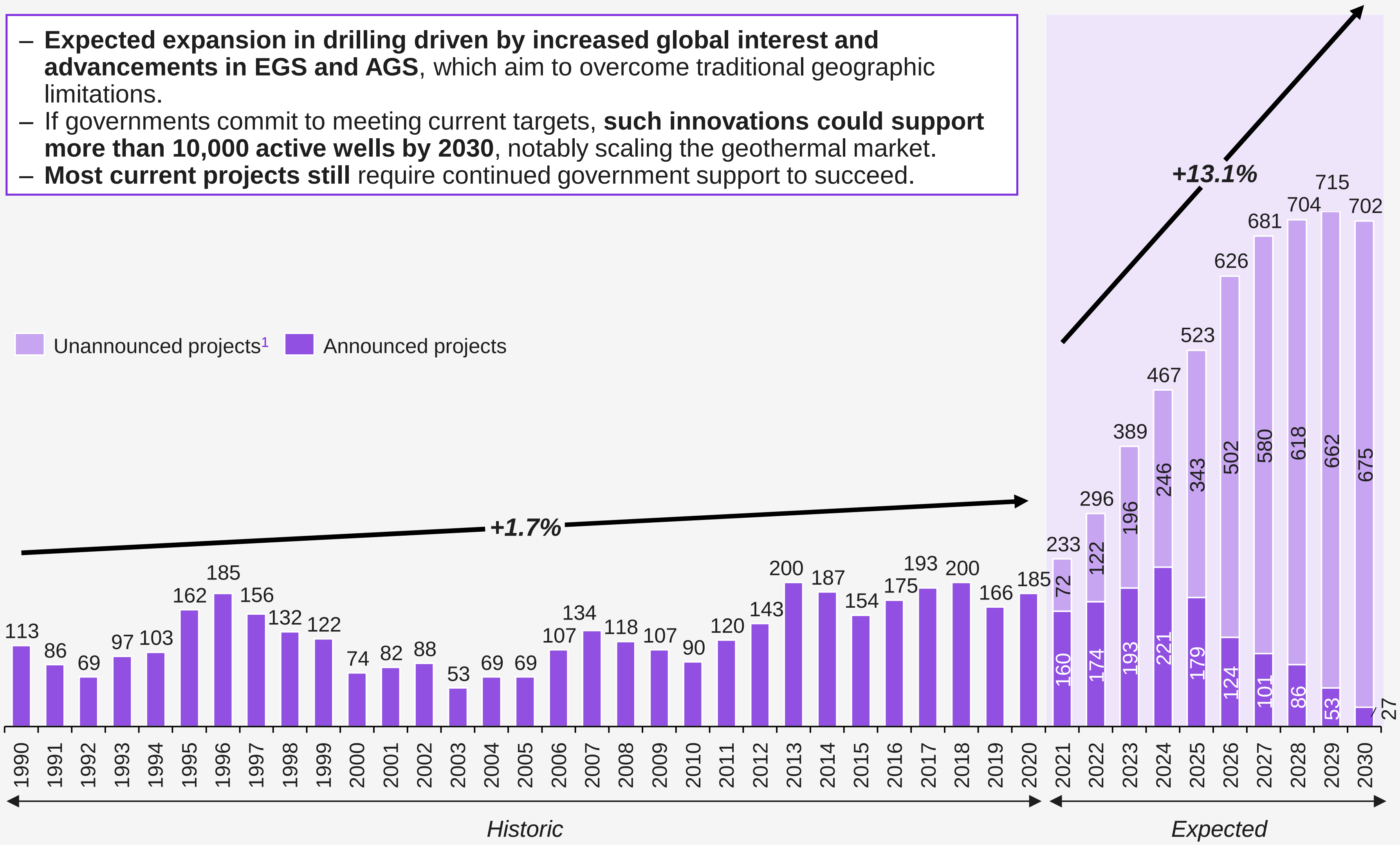


Sources: IRENA, 2024, Renewable Energy Statistics 2024; Kearney Energy Transition Institute analysis based on desktop research

About 200 wells for geothermal electricity have been drilled annually from 2015-2020, which is expected to increase to 500 by 2025

Projected wells drilled globally for geothermal electricity generation
Total wells, 1990-2030

- **Expected expansion in drilling driven by increased global interest and advancements in EGS and AGS**, which aim to overcome traditional geographic limitations.
- If governments commit to meeting current targets, **such innovations could support more than 10,000 active wells by 2030**, notably scaling the geothermal market.
- **Most current projects still** require continued government support to succeed.



1. Unannounced projects contain an estimated number of wells to be drilled to meet government targets on capacity additions toward 2030.
Sources: Rystad Energy, 2021, Geothermal analysis dashboard; Kearney Energy Transition Institute analysis

Electricity generation

4.3 Geothermal electricity generation

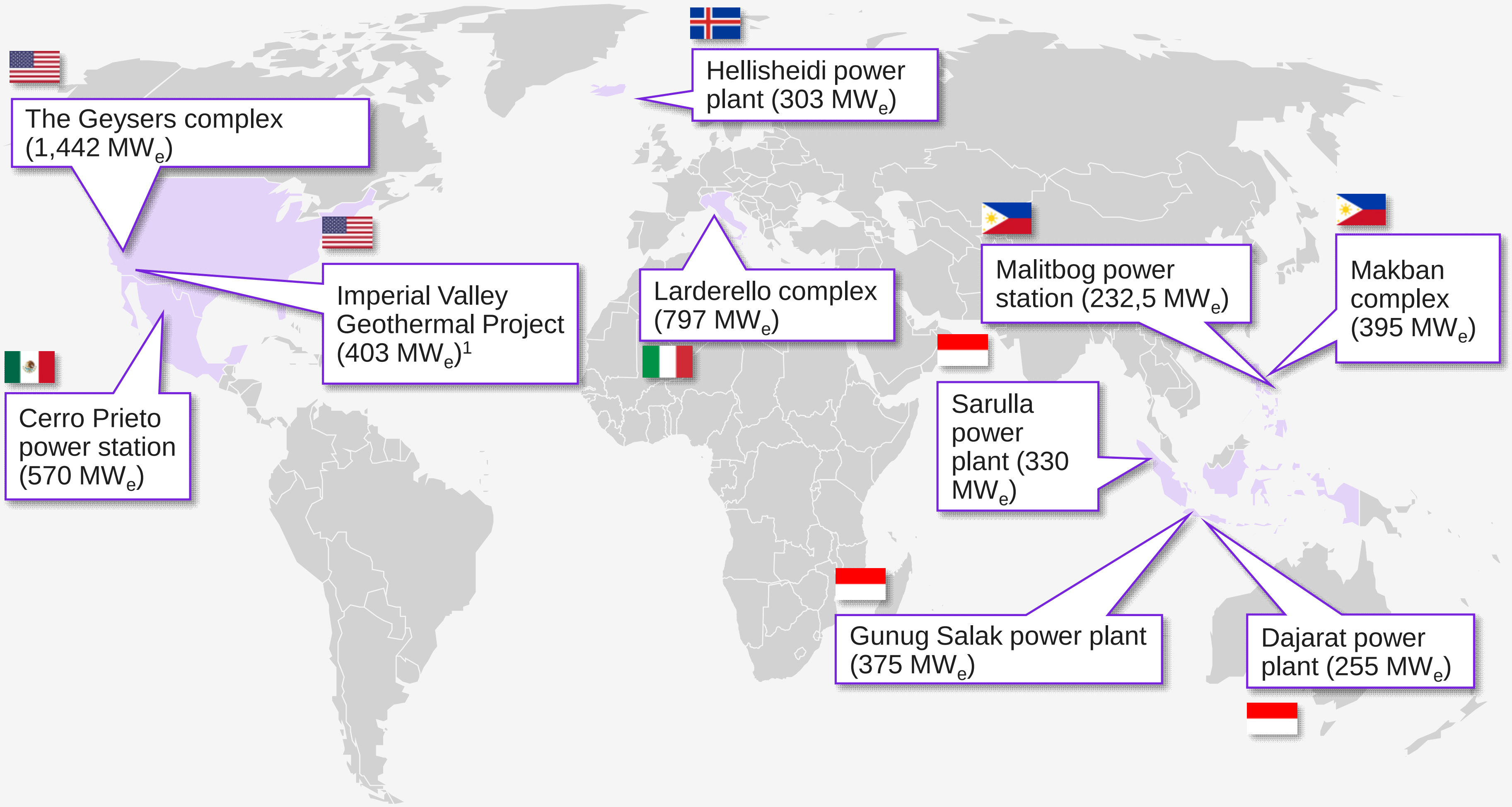
Indonesia hosts three of the world's 10 largest geothermal power plants, with the United States and the Philippines each having two

Electricity generation

4.3 Geothermal electricity generation

Top 10 largest geothermal electricity generation projects

MW_e, 2024

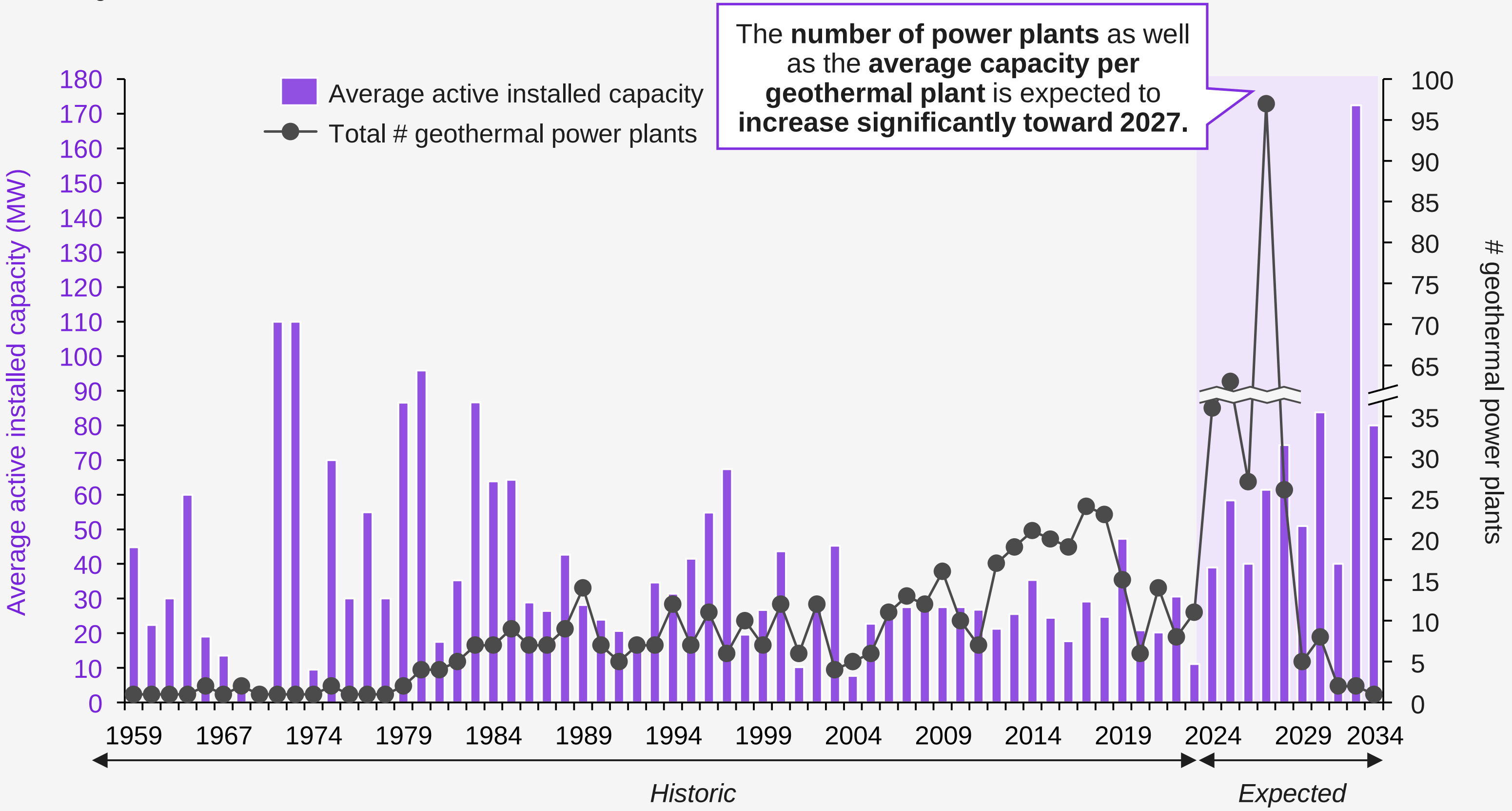


Note: The moment of data analysis, the Tiwi geothermal complex is under rehabilitation and modernization and not considered active.
1. Estimated potential of 2,950 MW_e, 2,250 MW_e of which is currently considered developable.
Sources: GlobalData, 2024, Geothermal Capacity by Power Plant data; Kearney Energy Transition Institute analysis

The number of geothermal projects commissioned each year is stable, with projects typically figuring small capacities

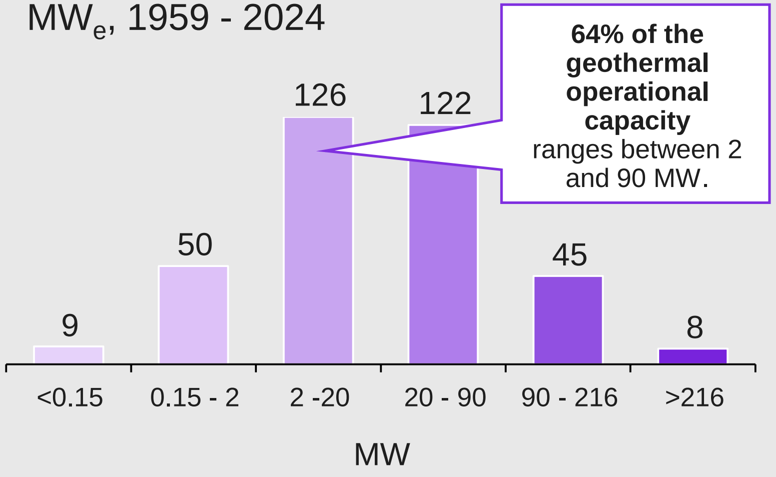
Number of electricity-generating geothermal power plants and average generating capacity per commissioning year

MW_e, 1959-2034



Histogram of electricity-generating geothermal projects

MW_e, 1959 - 2024



The smallest geothermal plant consists of a 30 kW unit in Zhiben, Taidong a geothermal hot spring area in the Southwest of Taiwan.

The largest geothermal plant consists of a 379.6 MW unit in Laguna and Batangas, Philippines. The plant was developed to harness the geothermal resources of the Bulalo field.

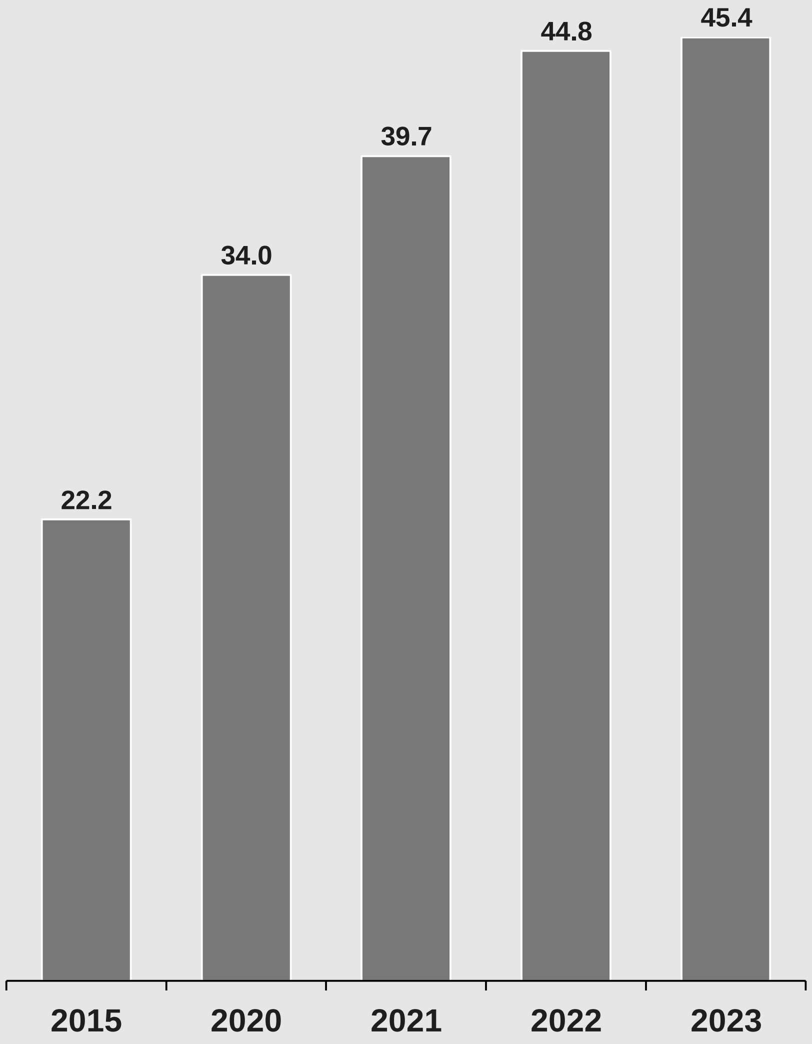
Sources: GlobalData, 2024, Geothermal Capacity by Power Plant data; Kearney Energy Transition Institute analysis

In 2023, geothermal heat and power investments surpassed USD 47 billion, comprising over 5% of total renewable energy spending

Residential and commercial heating, including ground-source heat pumps, accounted for more than 95% of these investments. China accounted for over 70% of total geothermal investments.

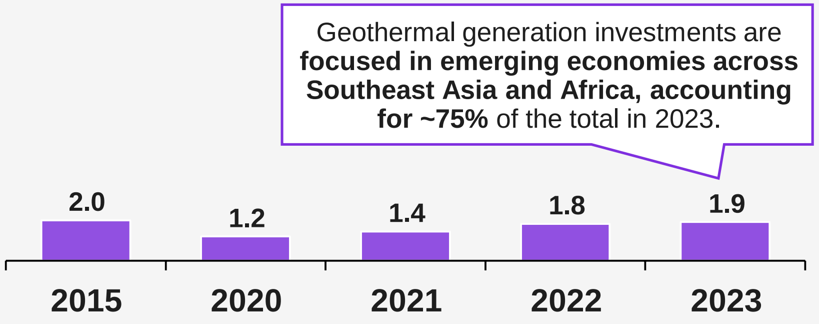
4.4 Investment in geothermal energy

Investment in direct use of geothermal
USD billion, 2015-2023



Geothermal power generation investment
USD billion, 2015-2023

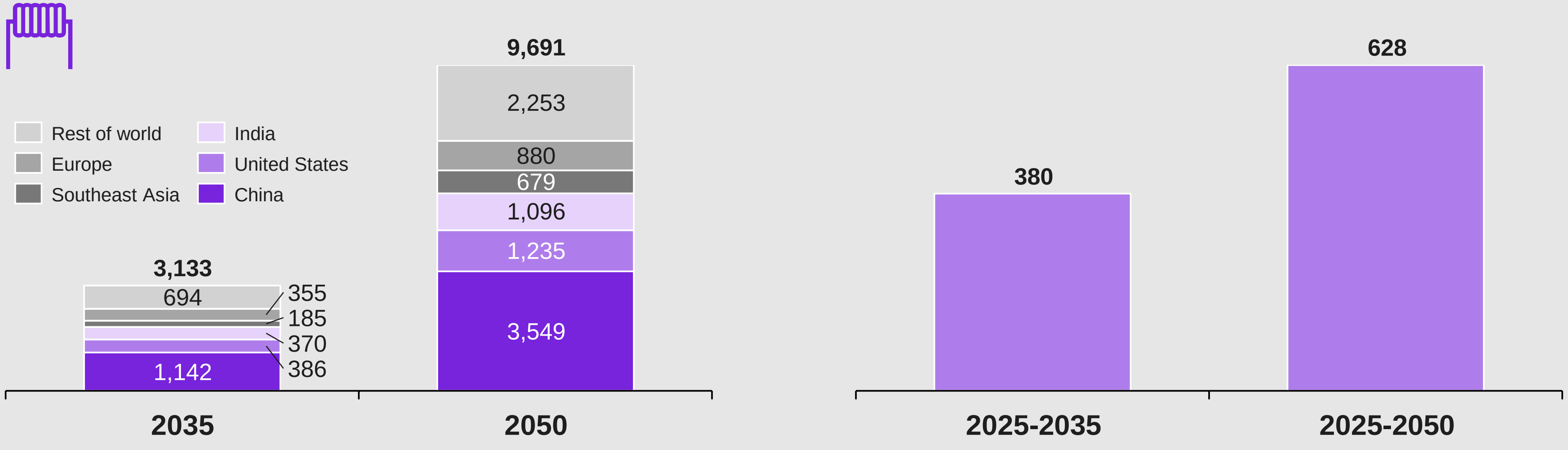
Between 2015 and 2019, investments in geothermal energy for both electric power and direct-use applications were distributed as follows: Oceania (0.5%), Africa (6.3%), Europe (8.5%), the Americas (10.3%), and Asia (74.4%).



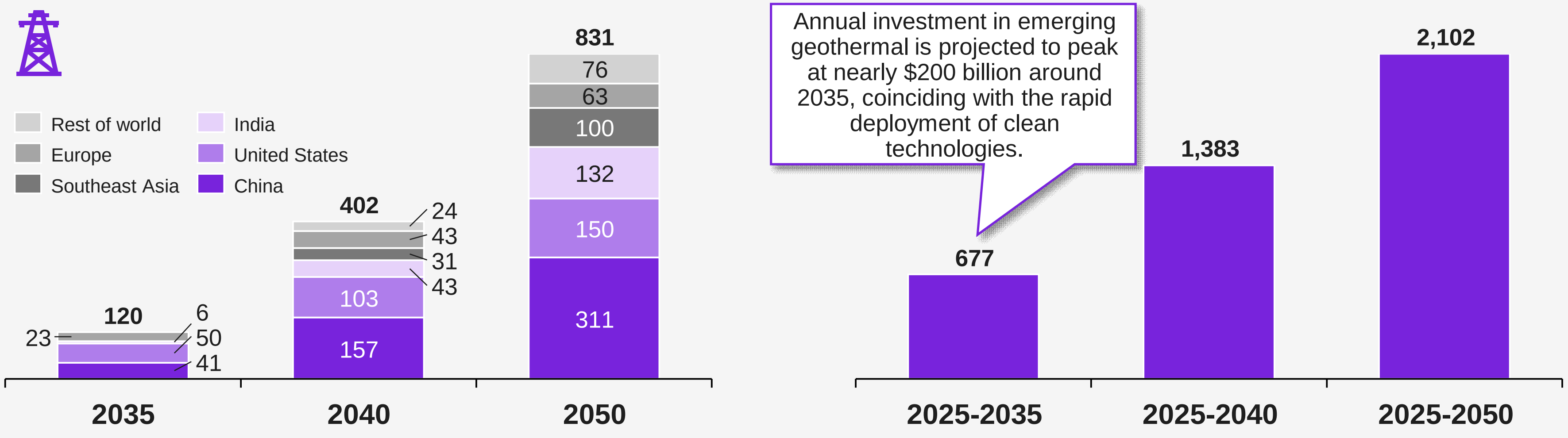
Sources: IEA, 2024, The Future of Geothermal Energy; Kearney Energy Transition Institute analysis

To unlock the full potential of emerging geothermal technologies, global investment must exceed USD 1 trillion by 2035 and reach ~USD 3 trillion by 2050

Market potential and cumulative investment for emerging geothermal industrial heat
PJ - USD billion, 2035-2050



Market potential and cumulative investment for emerging electricity capacity
GW - USD billion, 2035-2050

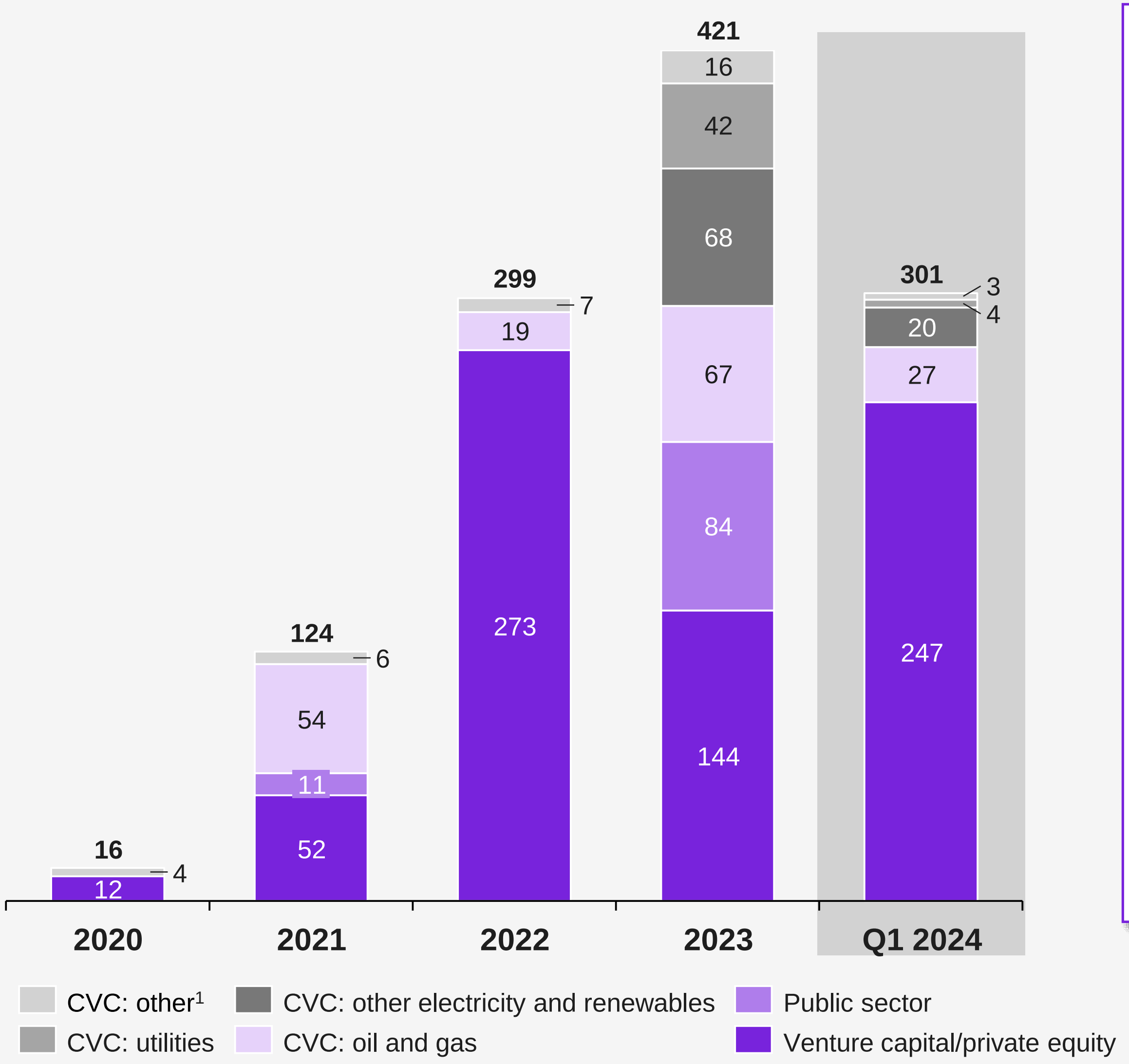


Sources: IEA, 2024, The Future of Geothermal Energy; Kearney Energy Transition Institute analysis

4.4 Investment in geothermal energy

Since 2020, geothermal investment growth has been led by private investors

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



- **Investments in emerging geothermal technologies surpassed USD 420 million annually in 2023,** driven by venture capital, public funding, and corporate backing.
- **Nearly 75% of global funding in the past five years went to power generation projects,** with the remainder supporting heat production, including district heating and shallow-heat applications.
- Oil and gas companies, leveraging synergies with geothermal, invested USD 140 million in EGS and AGS advancements.
- For heat, Singapore's GIC invested USD 240 million in Arctic Green Energy to develop district heating in Europe and Asia.

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

4.4 Investment in geothermal energy

Start-ups play a significant role in the development of geothermal solutions

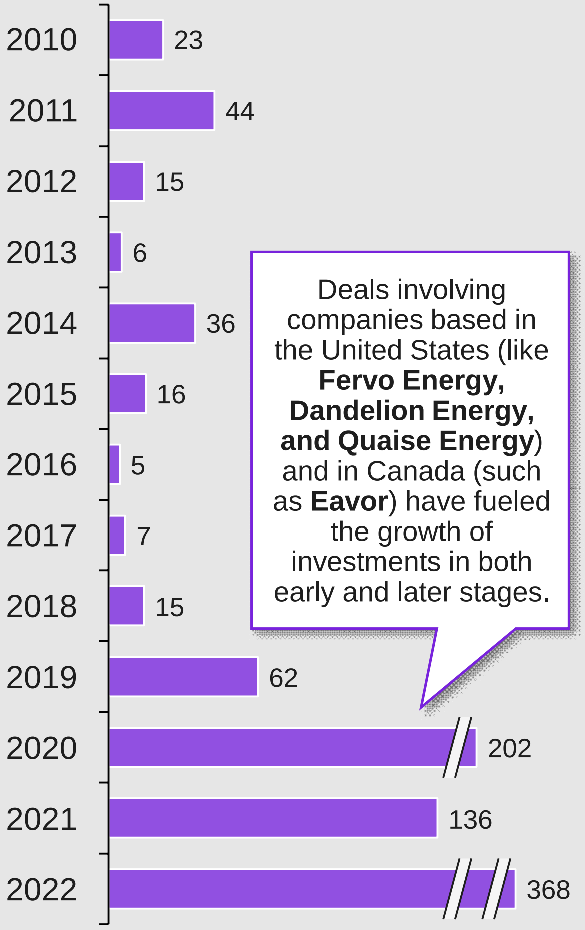
Illustrative

Global venture capital investment has increased sharply since 2019, reaching an all-time high of EUR 368 million in 2022, doubling the average investment seen in 2020 and 2021.

4.4 Investment in geothermal energy

Total venture capital and corporate companies by selected country
2017-2022

Global venture capital investments
EUR million, 2010-2022



Start-ups driving geothermal innovation and investment growth

- **In the United States**, emerging geothermal developer **Fervo Energy** has raised **$244 million** in 2024, in a round by shale oil and gas company Devon Energy.
- **Zanskar** has closed a **$30 million** funding round in 2024 to scale their AI-led discovery and development platform to identify new greenfield geothermal sites.
- In 2024, **Eavor Technologies** has received financing of more than **EUR 130 million** to support the commercial-scale Eavor-Loop geothermal project in Bavaria, Germany.
- **Dandelion** raised **$70 million** in 2022 to grow its operations in geothermal heat pumps for home heating and cooling applications.

Sources: European Commission Joint Research Centre, 2023, Deep geothermal heat and power in the European Union; Kearney Energy Transition Institute analysis based on desktop research

5. Geothermal value chain and project development

Value chain and project development

Geothermal stakeholders

– **The geothermal energy sector is characterized by a highly fragmented and complex value chain,** which varies significantly depending on specific applications and geographic conditions.

Project development

– Successful **geothermal heat pump and district system projects** rely on precise resource assessment, tailored designs, and efficient operations.
– **Geothermal power project development** is a long-term process, which **can last up to a decade**, from exploration to production.

Value chain players

– **The geothermal heat pump industry is highly competitive**, featuring both global and regional players, while the district systems market is dominated by experienced, established manufacturers.
– **Diverse players**, from technology vendors and established power firms to start-ups, are actively involved in the developing and applying of geothermal heat pumps.
– **The geothermal power sector relies on a broad network of specialized companies at each stage,** but market players are more concentrated in component manufacturing and project development and operation phases.
– **Japanese companies have emerged as key global suppliers of geothermal equipment** (such as Mitsubishi), providing 67% of total equipment supplier capacity needed for electricity production.
– **The geothermal power industry has traditionally been dominated by operators** with significant expertise and technical knowledge. Notably, the top 10 developers account for 57% (13.0 GW) of installed capacity and 39% (12.4 GW) of the pipeline capacity.

Oil and gas players

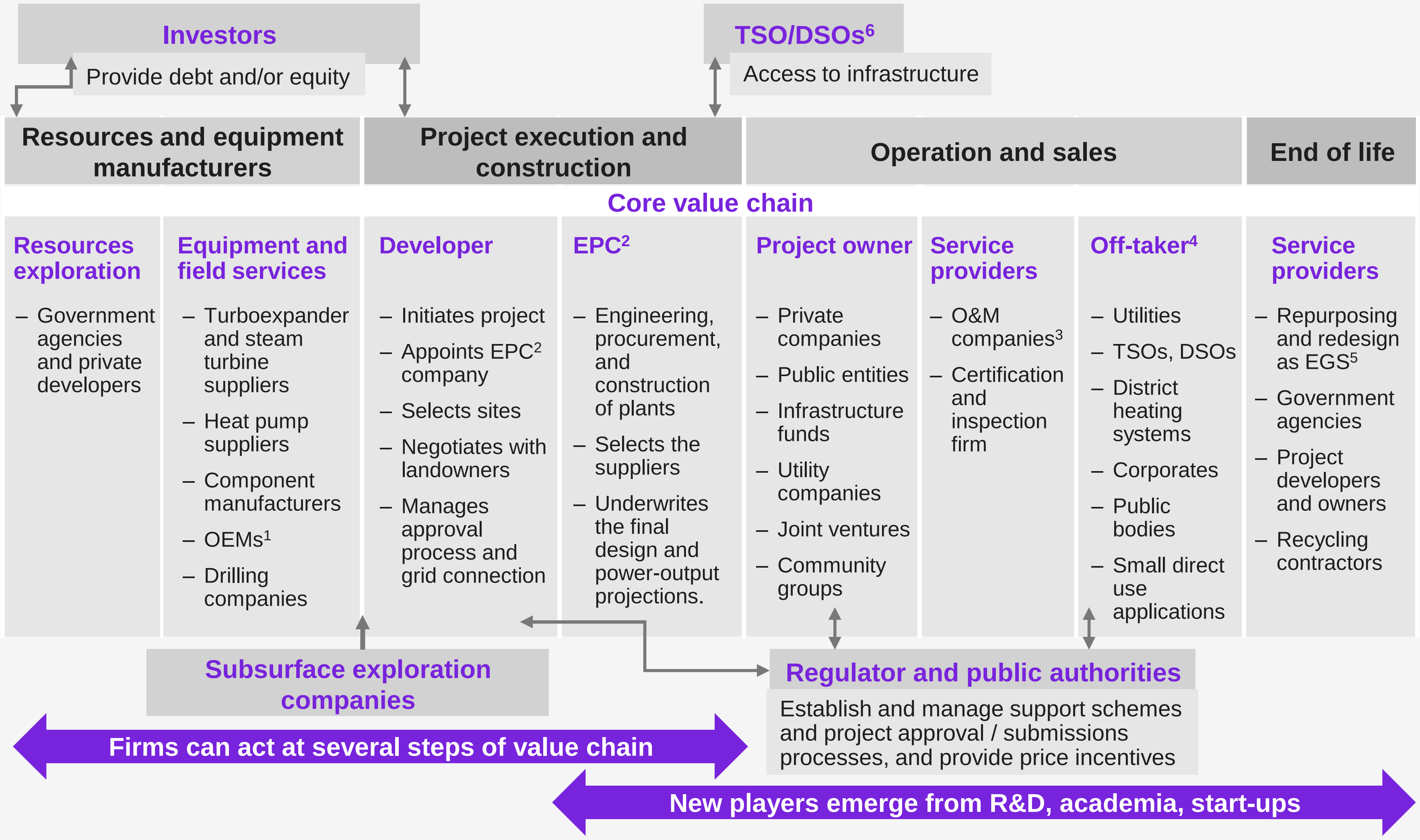
– A growing trend is the increasing participation of traditional oil and gas companies in geothermal energy deployment, offering various revenue opportunities for these players. The **oil and gas industry's expertise in engineering, location identification, well repurposing, and regulatory frameworks can significantly benefit the development of geothermal energy.**

The geothermal value chain is highly fragmented and depends on the varying conditions encountered across different geothermal applications

Illustrative

The geothermal business ecosystem highly depends on the type of technology used, the local regulations, and the business model.

Geothermal ecosystem



1. Original equipment manufacturers; 2. Engineering, procurement, and construction; 3. Operations and maintenance; 4. Off-takers are the ones purchasing the electricity, often in bulk and at a set price. They take on the risk of price fluctuations.; 5. Enhanced or engineered geothermal system; 6. Transmission system operator and distribution system operator

Sources: European Commission Joint Research Centre, 2023, Deep geothermal heat and power in the European Union; EHPA, 2023, Heat Pumps in the Net Zero Industry Act; NREL, 2018, Global Value Chain and Manufacturing Analysis on Geothermal Power Plant Turbines; US DOE, 2024, Pathways to Commercial Liftoff: Next-Generation Geothermal Power; ESMAP, 2012, Geothermal handbook: planning and financing power generation; Kearney Energy Transition Institute analysis

Geothermal district system projects rely on precise resource assessment, tailored designs, and efficient operation

Illustrative

Heat provision

5.2 Project development

Geothermal district system project development

Exploration phase

Preliminary study
- Site identification & reconnaissance
- Surface investigations
- Geoscientific studies
- Pre-feasibility report

Detailed assessment
- Exploration drilling
- Feasibility studies

Operation phase

Commissioning
- System testing and adjustment
- Integration into local heating systems

Operations & maintenance
- Regular monitoring of system performance
- Predictive maintenance for pumps, pipelines, and other equipment

End use
- Heating or cooling distribution for residential, commercial, or industrial use

1 — <7 years — 2 — 2-5 years — >20 years — 3

Project development

Exact timeframe per phase is dependent on the scale of the project.

Development phase

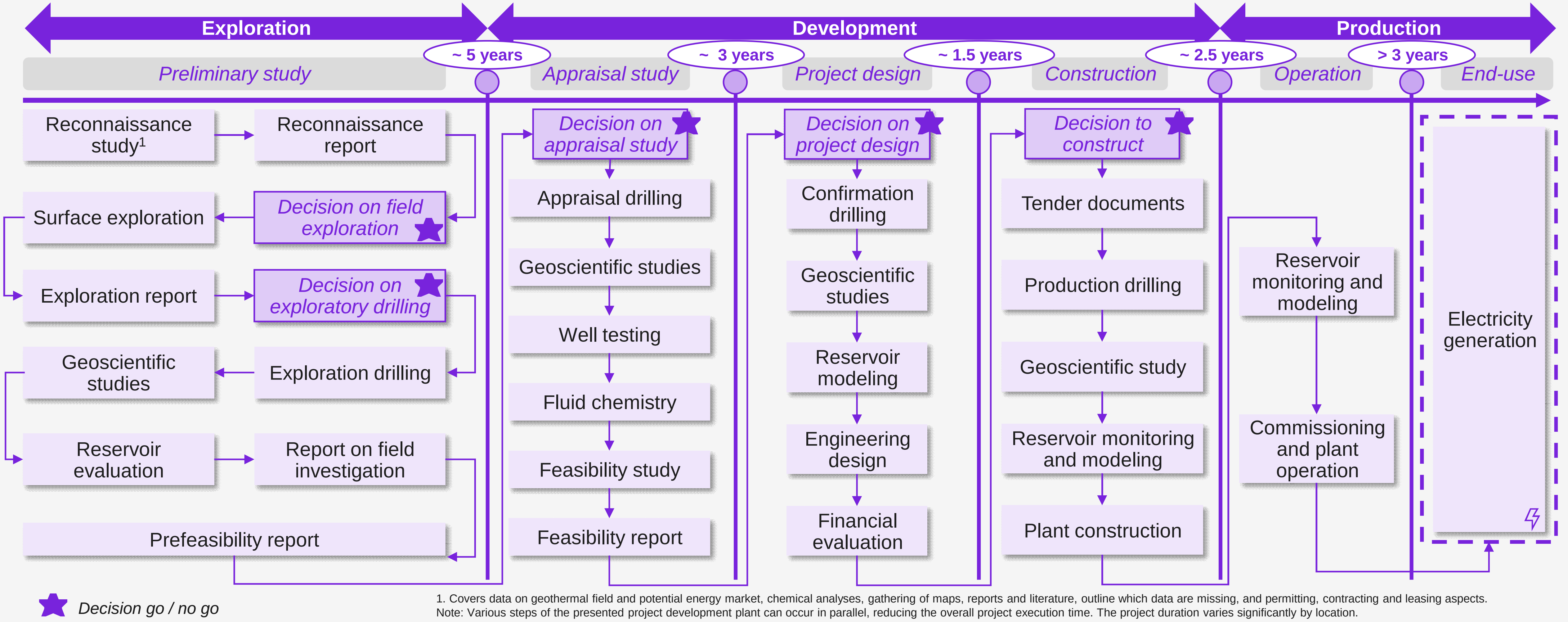
Project design
- Engineering design
- Permitting and approvals
- Financial planning

Infrastructure construction
- Well drilling and completion
- Plant and network construction
- Monitoring systems

Note: Geothermal heat pump projects can be deployed in weeks, but the timeframe highly depends on the drilling time if required.
Sources: Kearney Energy Transition Institute analysis based on desktop research

Conventional geothermal power project development is a complex process, with greenfield project development lasting up to a decade

Illustrative



1. Covers data on geothermal field and potential energy market, chemical analyses, gathering of maps, reports and literature, outline which data are missing, and permitting, contracting and leasing aspects.
Note: Various steps of the presented project development plant can occur in parallel, reducing the overall project execution time. The project duration varies significantly by location.
Sources: ESMAP, 2019, Preparing feasibility studies for the financing of geothermal projects; United Nations University and LaGeo, 2014, Phases of geothermal development in Iceland: from a hot spring to utilization; Kearney Energy Transition Institute analysis

The geothermal heat pump industry is highly competitive, with global and regional players, while the district systems market is led by experienced and established manufacturers

Non-exhaustive

Heat provision

5.3 Value chain players

District systems and geothermal heat pump manufacturers, owners and operators

- Aqua Systems
- Bosch Thermotechnology
- Carrier Corporation
- ClimateMaster
- Coriance
- Daikin Industries
- Dalkia
- Dandelion Energy
- Danfoss Group
- E.ON
- Efficient Energy
- Enertech Global
- ENGIE
- Fortum
- Fujitsu General
- Geo-Flo Products Corporation
- GeoComfort
- GeoSource Energy
- Honeywell
- Lennox International
- Longstor
- Maritime Geothermal Ltd.
- Mitsubishi Electric
- Modine Manufacturing
- NIBE Industrier AB
- Nordic Heat Pumps
- NRG Energy Inc.
- Open Loop Energy Solutions
- OCHSNER Warmepumpen
- Paloma Industries
- Rheem Manufacturing
- SABIC
- SP Group
- Statkraft
- Stiebel Eltron
- Swegon
- Teijin
- Trane Technologies
- Vaillant
- Vattenfall
- Veolia
- Viessmann Group
- WaterFurnace International
- WFI Innovations

Geothermal heat pump systems O&M[1] service providers

- Aire Serv
- All Seasons Heating & AC
- Angi
- AquaGeo Services
- Beco Air & Heat
- Carrier Service Technicians
- ClimateMaster Service
- Ecolution Group
- Evolved Thermal Energy
- Geo Green Power
- Geothermal Professionals
- Jacobs Heating & Cooling
- Modernize
- One Hour Heating & AC
- Partner Heating & Cooling
- Prime Energy Services
- Stiebel Eltron Maintenance
- Trane Service
- Viessmann Maintenance
- WaterFurnace Service

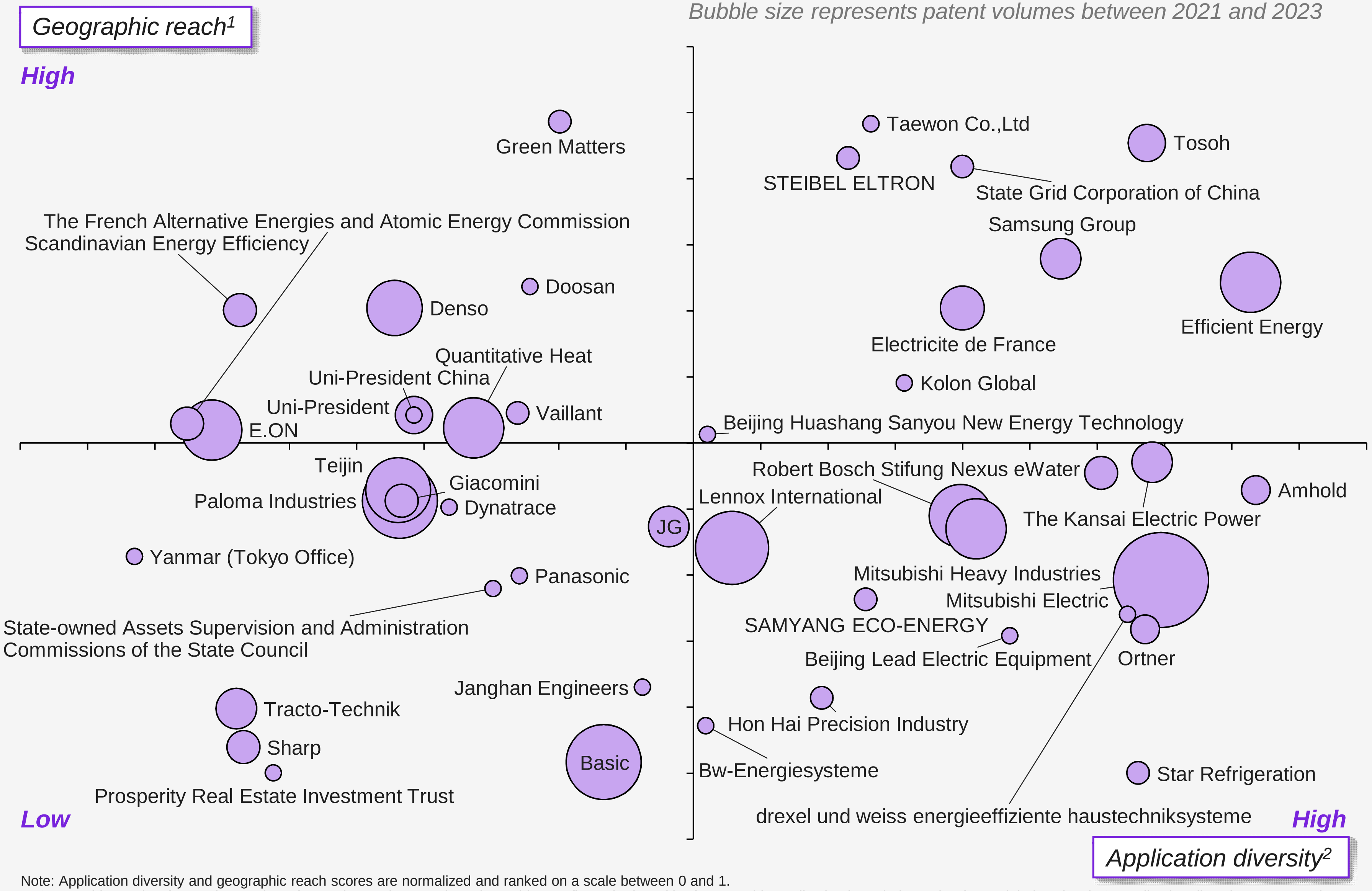
1. Operations and maintenance
Sources: Kearney Energy Transition Institute analysis based on desktop research

A variety of companies, such as technology vendors, established power firms, and emerging start-ups, are active in the development and application of geothermal heat pumps

Heat provision

5.3 Value chain players

Key players in geothermal heat pumps



Note: Application diversity and geographic reach scores are normalized and ranked on a scale between 0 and 1.
1. Geographic reach refers to the number of countries each patent is registered in. It reflects the breadth of geographic application intended, ranging from 'global' to 'local'; 2. Application diversity measures the number of applications identified for each patent. It broadly splits companies into either 'niche' or 'diversified' innovators.
Sources: Power Technology, 2024, Leading innovators in geothermal heat pumps for the power industry; Kearney Energy Transition Institute analysis based on desktop research

The geothermal sector is highly fragmented and consists of a large network of specialized companies at each stage

Non-exhaustive

Resources

- Alcoa Corporation
- BHP Billiton
- Cabot Corporation
- China Molybdenum Co.
- Codelco
- Eurasian Resources Group
- Freeport-McMoRan
- Glencore
- Huntsman Corporation
- Iluka Resources
- Mersen
- Norilsk Nickel
- Olin Corporation
- Orion Engineered Carbons
- Rio Tinto
- Rusal
- Samancor Chrome
- Sinopec
- Tronox
- Vale S.A.
- VSMPO-AVISMA

Drilling service company

- Aker Solutions
- Amec
- Bentec
- Baker Hughes
- Cape Industrial Services
- Drillmec
- Drillstar
- Fnagmann
- Fugro
- Halliburton
- Huisman
- Herrenknecht
- Marathon
- Noble Drilling
- Odjfell Drilling
- SLB
- Welltec
- Scientific Drilling

Component manufacturing

- Alfa Laval AB
- Ansaldo/Tosi
- Atlas Copco-Exergy
- Babcock & Wilcox
- Baker Hughes
- Borets company
- Canadian ESP
- Danfoss & Sondex Holdings A/S
- Dow Chemical company
- Ecolab/Nalco
- ETC Ltd.
- Exergy
- Flowserve
- Fuji
- GE Oil & Gas
- GE Power
- Gunter AG & Co. KG
- Halliburton
- Hamon & Cie international SA
- ITT/Goulds
- Kelvion Holdings Gmbh
- Mitsubishi
- Modine
- Ormat
- SLB
- SPX Corporation
- SWEP international
- Toshiba
- Turboden
- Weatherford International
- Xylem Inc.

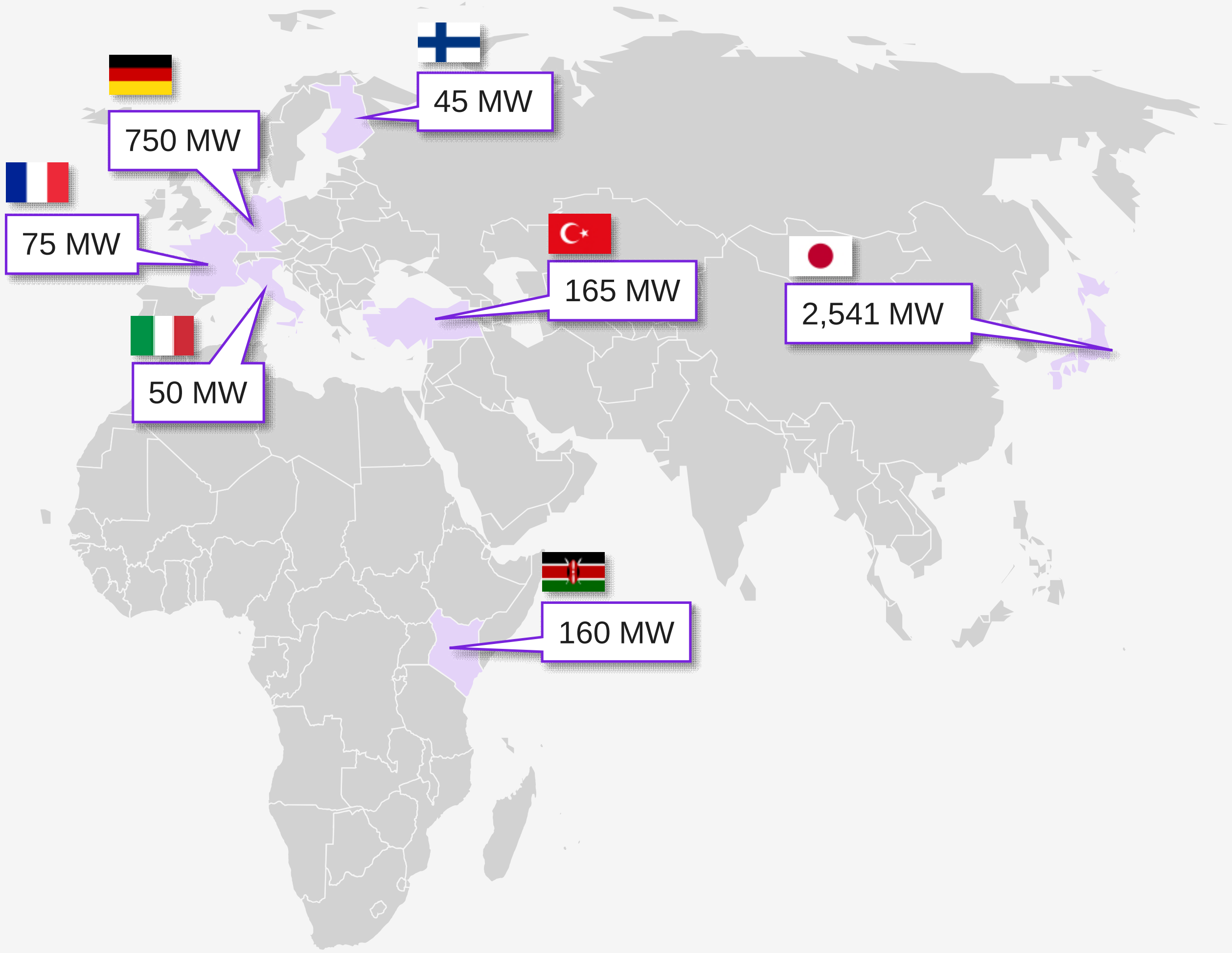
Operators

- Altarock
- Bedrock energy
- Berkshire Hathaway Inc
- Calpine
- CFE
- Contact Energy Ltd
- Coso
- Cyrq energy
- Dandelion
- Darcy
- Eavor
- Eden
- Enel SpA
- Energy Source
- Fervo energy
- KenGen
- Lopez Inc
- Orkuveita Reykjavikur
- Ormat
- PT Pertamina
- Qheat
- Quaise energy
- Sage Geosystems
- Terrapin

Sources: NREL, 2018, Global Value Chain and Manufacturing Analysis on Geothermal Power Plant Turbines; ETIP-Deep Geothermal, 2019, Competitiveness of the geothermal industry; Vonsée, B., Crijns-Graus, W., and Liu, W., 2019, Energy technology dependence - A value chain analysis of geothermal power in the EU; Kearney Energy Transition Institute analysis based on desktop research

Japanese companies dominate the global supply of equipment for geothermal electricity generation

Geothermal electricity equipment suppliers by country
MW_e, 2023



- Japan's significant role in geothermal projects is highlighted by the presence of two leading Japan-based companies, particularly in the supply of geothermal equipment, with **Japanese firms accounting for 67% of total capacity across seven key markets.**
- **Toshiba Corporation and Fuji Electric Company** are key players in this market, supplying equipment for **1,281 MW and 945 MW** of geothermal capacity, respectively.

Electricity generation

5.3 Value chain players

Sources: BMI, 2023, Global Geothermal Power Report; Kearney Energy Transition Institute analysis

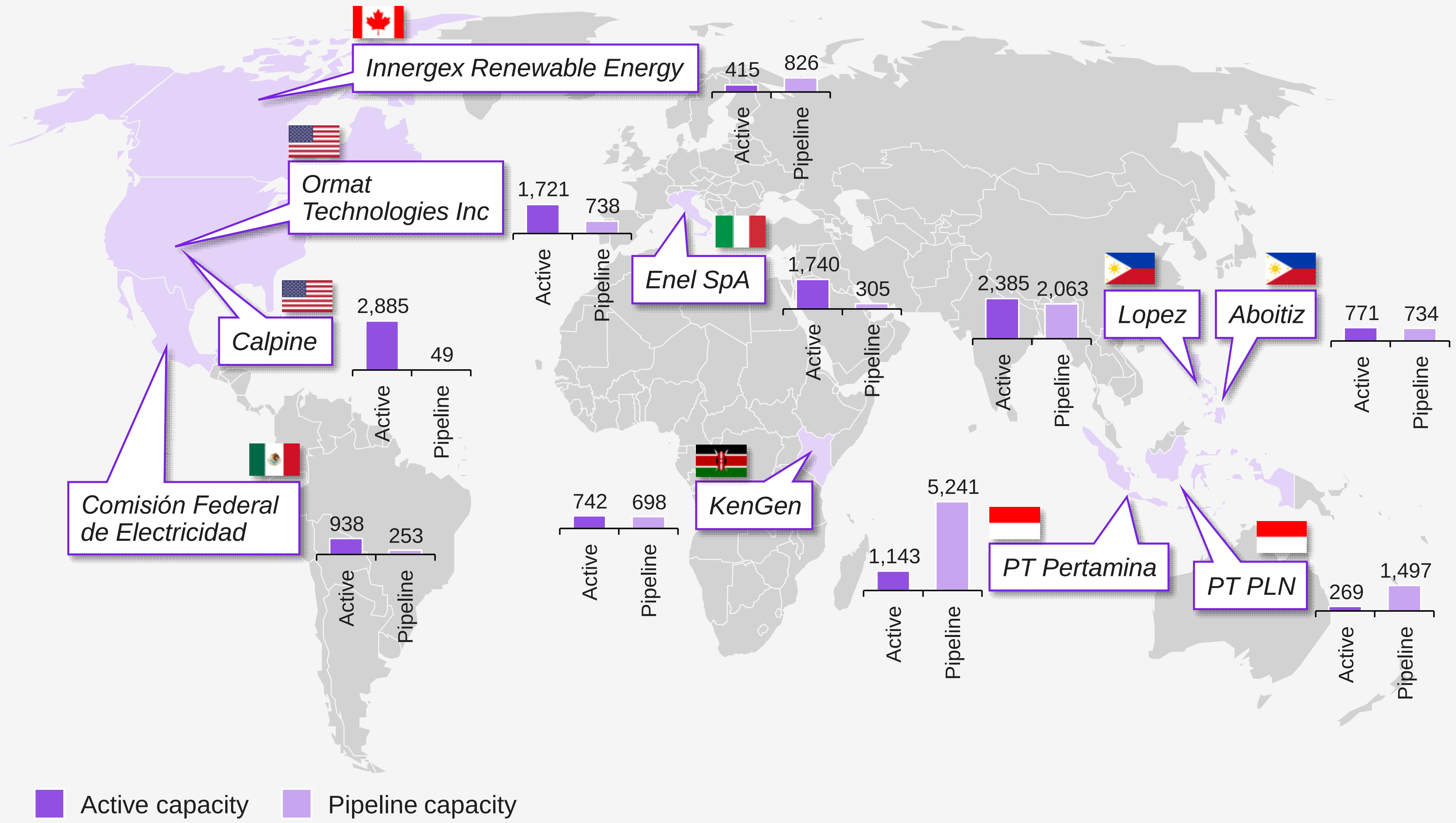
The geothermal industry is largely dominated by traditional geothermal operators with well-developed expertise in the field

Electricity generation

5.3 Value chain players

Geothermal electricity capacity of top 10 developers

MW_e, 2024



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

Oil and gas companies leverage expertise to unlock new opportunities in geothermal energy

Direct-use geothermal

Scope: Use their drilling expertise and wells to access geothermal heat for direct use or electricity generation.

Business case: Shell and Gaia (formerly Tullip Energy) activity in the Netherlands.

1

Geothermal district heat

Scope: Develop large-scale geothermal heating projects.

Business case: Sinopec's joint venture with Arctic Green.

2

Geothermal heat from oil fields

Scope: Extract geothermal heat as a byproduct of oil production.

Business case: In various countries, like the United States, China, and France, there are examples of geothermal heat production from oil wells with high water cuts and temperatures.

3

Oil services companies in geothermal

Scope: Expand into geothermal by providing drilling services, equipment, and expertise.

Business case: SLB, Halliburton, Baker Hughes, and others engagement in geothermal development .

4

Venture capital and joint venture

Scope: Invest in geothermal start-ups or form joint ventures with geothermal companies.

Business case: BP and Chevron investment in geothermal start-up Eavor.

5

Equity investments in startups and innovation

Scope: Start-ups with a focus on geothermal energy can act as early innovators, often backed by oil and gas companies.

Business case: Sage Geosystems founded by former oil and gas professionals.

6

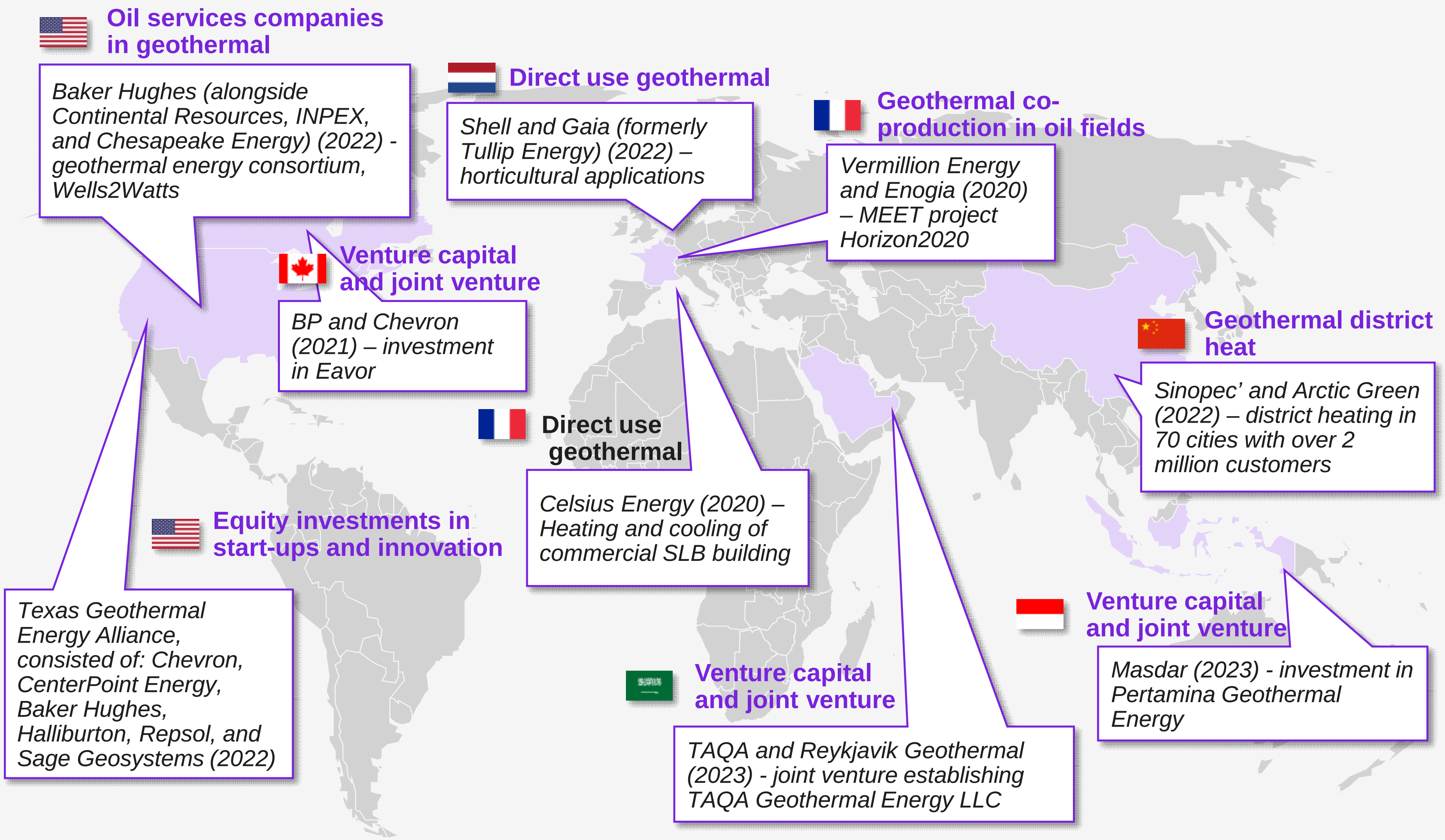
Sources: The University of Texas at Austin, 2023, The Geothermal Business Model & the Oil and Gas Industry: Challenges and Opportunities; Céspedes, S. et al., 2022, Technical and Environmental Feasibility Study of the Co-Production of Crude Oil and Electrical Energy from Geothermal Resources: First Field Trial in Colombia, Processes; Cano, N.A. et al., 2022, Power from Geothermal Resources as a Co-product of the Oil and Gas Industry: A Review, ACS Omega; Kearney Energy Transition Institute analysis based on desktop research

Traditional oil and gas players are venturing into the geothermal energy deployment

Non-exhaustive

The oil and gas industry's expertise in engineering, location identification, well repurposing, and regulatory frameworks can significantly benefit the development of geothermal energy.

Recent developments in the oil and gas-geothermal industry



5.4 Oil and gas players

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

6. Business models for geothermal energy

Business models for geothermal energy

Business models for geothermal heat pumps

- **New business models based on heat purchase agreements** encourage the development of **geothermal heat pumps.**
- **These models** are similar to those used for traditional heat pumps and **are typically structured under heat-as-a-service frameworks**, which offer **fixed pricing** for heat networks and specific temperature settings.

Business models for district heating and cooling

- **In the district heating and cooling sector, geothermal business models can vary.** Some are built around **selling** heating and cooling services at **pre-agreed prices**, while others involve real estate companies acting as investors by **purchasing heat from various sources**. **Social initiatives** also play a key role in some cases.

Business models for geothermal direct use

- Geothermal direct use business models, which are mostly **found in industrial applications, vary significantly based on the business case** and will require tailored regulatory support, financial incentives, and institutional frameworks to develop.

Business models for electricity production

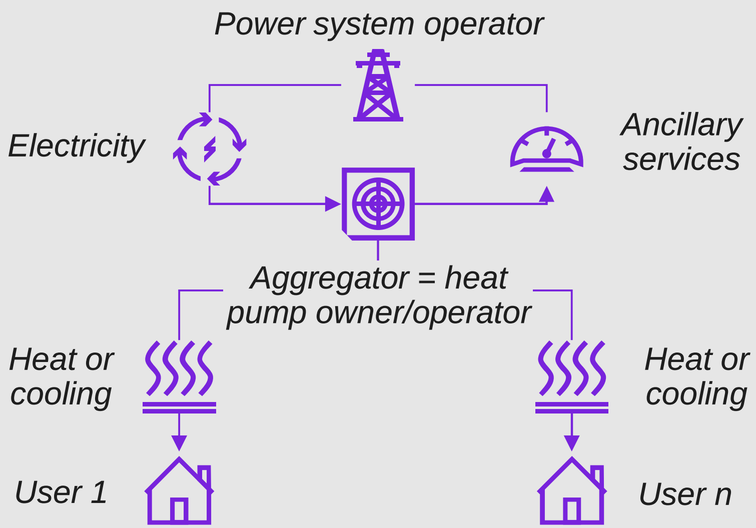
- **The rise in geothermal power purchase agreements and emerging technologies marks a new phase in geothermal energy commercialization**, despite geothermal PPAs comprising less than 3% of renewable PPAs in the US in 2022.
- **In 2024, Fervo achieved a milestone by signing the largest geothermal PPA for 320 MW**, highlighting the sector's evolving business model and growing competitiveness in electricity generation.
- **Nonetheless, a signed PPA does not guarantee project success** if the constructed asset does not realize the desired economics to make the PPA profitable under the contracted terms.

New business models based on heat purchase agreements encourage the development of geothermal heat pumps

Geothermal heat pumps can be supported by business models similar to those used for traditional heat pumps. These models fall under the heat-as-a-service frameworks, featuring fixed price tariffs on heat networks and specific temperature.

6.1 Business models for geothermal heat pumps

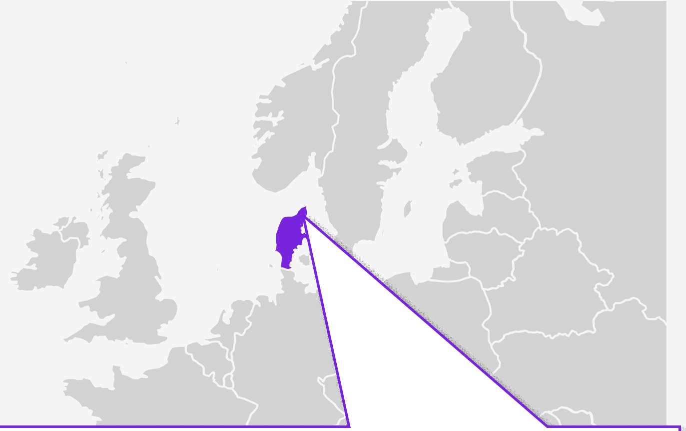
Heat purchase agreement (HPA)



- HPA is a contract between a user and an aggregator where the user hosts a heat pump owned by the aggregator.
- The aggregator installs the heat pump at low or no cost to the user, and the user selects their desired indoor air temperatures.
- The user pays the aggregator for the heat or cooling produced by the heat pump, while the aggregator covers electricity costs and maintenance.
- The aggregator can also sell the flexibility of their electrical load in power system markets, through ancillary services.
- At the end of the HPA, ownership of the heat pump transfers to the user.

Heat-as-a-service models potentially applicable to geothermal heat pumps

Frameworks	Fixed-price tariffs	Set temperature for fixed price
Business cases	**Danish Energy Agency**, Thermondo	EnergieSprong, ENGIE, Eneco



The **Danish Energy Agency** launched a subsidy scheme to promote heat pumps in oil-heated homes. **Customers pay an upfront installation fee, a fixed price per MWh of heat, and an annual service fee, with a minimum 10-year subscription.** While the pricing structure is set by the agency, energy providers can adjust these fees based on their business model.

In some cases, cooling can offer an even more profitable opportunity if heating is displacing cheaper natural gas.

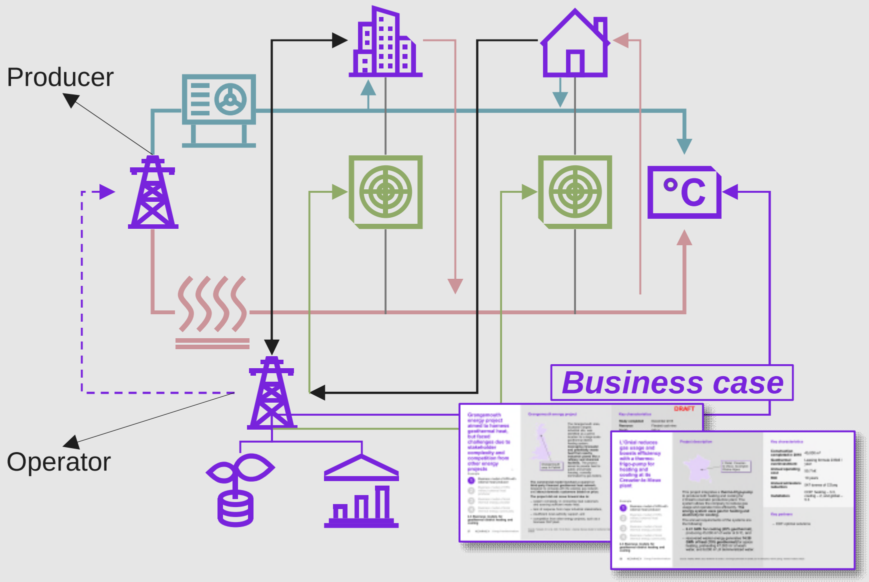
Sources: ClimateXChange, 2021, The potential of Heat as a Service as a route to decarbonisation for Scotland; IEA, 2024, The Future of Heat Pumps in China; Kircher, K. J. and Zhang, K. M., 2021, Heat purchase agreements could lower barriers to heat pump adoption, Applied Energy; Kearney Energy Transition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

District heating and cooling business models can rely either on heating and cooling services being sold at agreed prices…

Producers / operator | *Cooling*
Heating | *Prosumers*
Consumers | *Heat pump*
Heat accumulation | *Investors, loans*
Governmental support, funds | *Energy community*

6.2 Business models for district heating and cooling

Heat purchase agreement with external heat producer



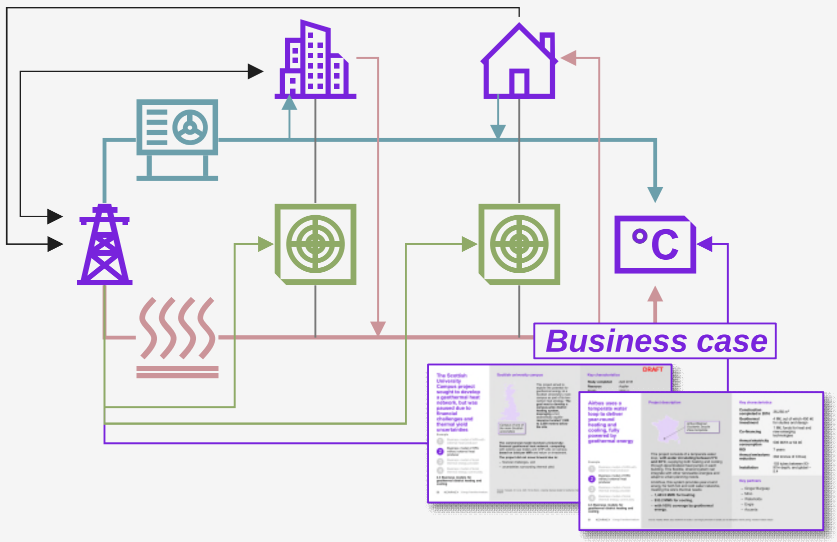
– **The district heating operator finances and owns the network, selling** heating and cooling services to end users **at agreed prices** while maintaining the infrastructure and ensuring heat supply.

– The **operator** may not directly produce the heat but **is responsible for procuring it** from external producers.

– The **operator collects payments** from end users and prosumers, **receives project-related investments** and grants, but also **assumes all financial risks** associated with the system.

– **Heat pumps can either be owned and maintained by the operator**, with costs included in customer tariffs, **or owned by users**, with maintenance handled by users.

Heat purchase agreement without external heat producer



– **The district heating operator finances and owns the network whilst producing thermal energy,** reducing the number of participants involved in the energy supply chain.

– The **operator** may not directly produce the heat but **is responsible for procuring it** from external producers; regardless, the operator is responsible of maintaining the system and ensuring a reliable supply for consumers and takes on all associated financial risks.

– Since the operator also produces the energy, **there is no need for external heat producers, streamlining the process** and reducing complexity in financial and operational roles.

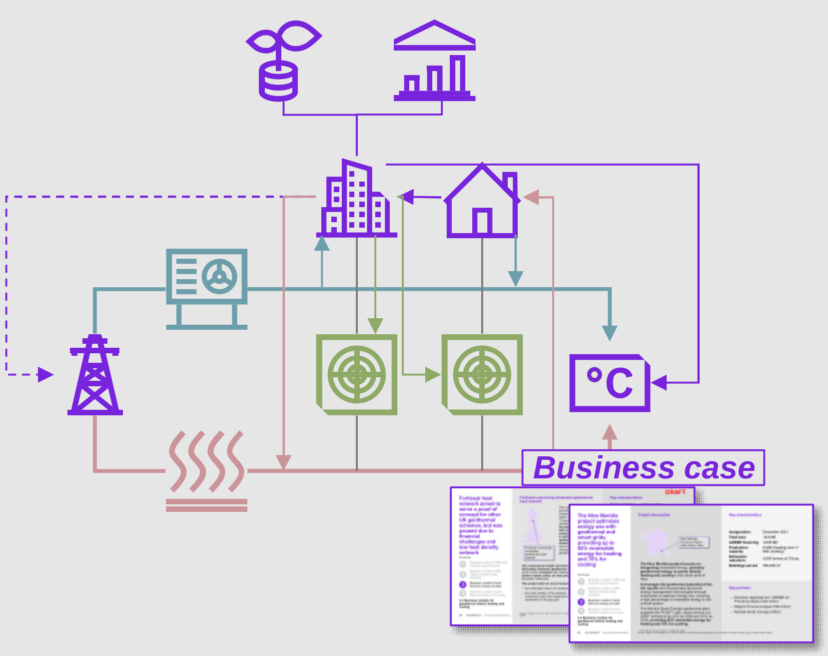
Sources: Pakere, I. et al., 2023, Comparison of Suitable Business Models for the 5th Generation District Heating System Implementation through Game Theory Approach, Environmental and Climate Technologies; Kearney Energy Transition Institute analysis

…or on both real estate companies acting as investors, purchasing heat from various sources, and social initiatives

Producers / operator
Cooling
Heating
Prosumers
Consumers
Heat pump
Heat accumulation
Investors, loans
Governmental support, funds
Energy community

6.2 Business models for district heating and cooling

Local thermal energy provider

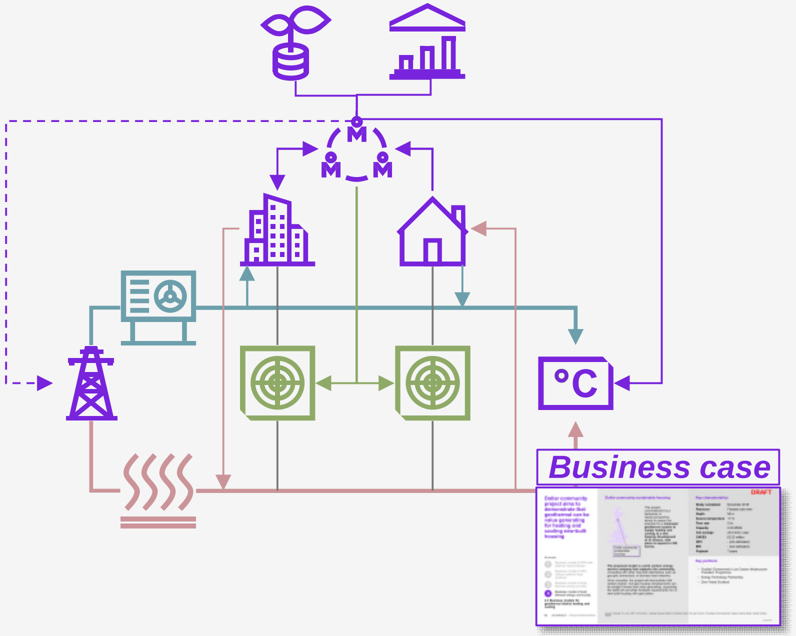


– **Real estate companies** invest in and operate the network, **purchasing heat from various sources.**

– There is no external operator and **prosumers manage the energy and value network**, regulating energy use.

– Prosumers might own the production of additional energy, such as the heating boilers and the cooling equipment, potentially selling it to the producers.

Local thermal energy community



– **This scenario involves a local energy community** formed through a social initiative.

– **These communities may receive higher approval rates** for projects and governmental funding, potentially reducing expenses.

– However, **securing loans can be challenging**, as banks tend to prefer established organizations with a proven track record.

Sources: Pakere, I. et al., 2023, Comparison of Suitable Business Models for the 5th Generation District Heating System Implementation through Game Theory Approach, Environmental and Climate Technologies; Kearney Energy Transition Institute analysis

Business models for geothermal direct use (GDU) necessitate specialized regulatory support, financial incentives, and institutional frameworks to develop

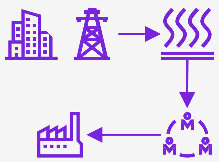
Private company · *Geothermal direct use project* · *Community* · *Industrial applications* · *Institutions and governments* · *Producer / operator* · *Green financing*

6.3 Business models for geothermal direct use

Business models

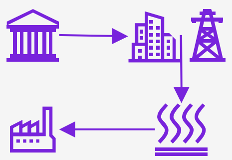
Traditional

Corporate social responsibility



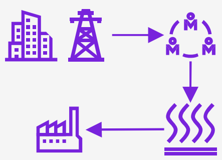
Companies invest in GDU projects as part of their social responsibility initiatives.

Government-led



Governments can invest in geothermal projects, either through public funding or public-private partnerships (PPPs).

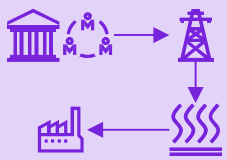
Private investment



Private companies invest in GDU projects to create profit-driven ventures, requiring significant capital, technology, and risk management.

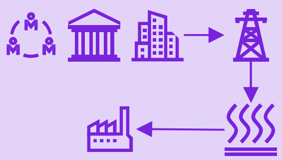
Emerging

Community ownership



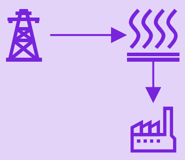
Local communities invest in and own geothermal projects, typically through cooperatives or community funds.

Hybrid / public-private partnerships



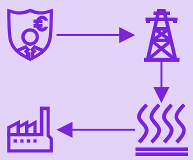
Hybrid models blend elements from various traditional models and can encourage collaboration among public, private, and community stakeholders.

Energy service company (ESCOs)



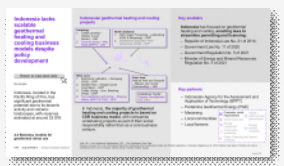
ESCOs handle the design, construction, financing, ownership, and operation of GDU projects, selling the thermal energy to end users.

Green financing and impact investing



These models attract investment from parties interested in environmental benefits and social impact.

Business cases





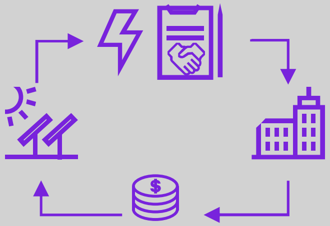


Sources: Al Asy'ari, M.R. et al., 2024, Beyond Electricity: Geothermal Direct Use Business Models and Potential Applications in Indonesia, Stanford University; Kearney Energy Transition Institute analysis

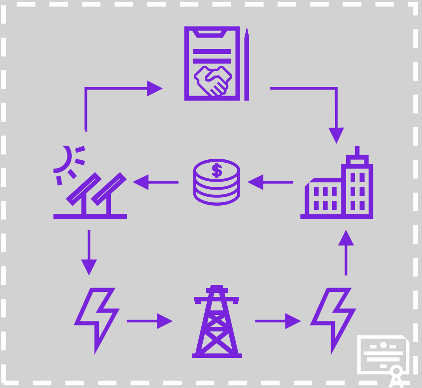
Geothermal business models are adapting to the transformation of the power system; they are based on the competition of geothermal with other generation sources

Power purchase agreement (PPA)

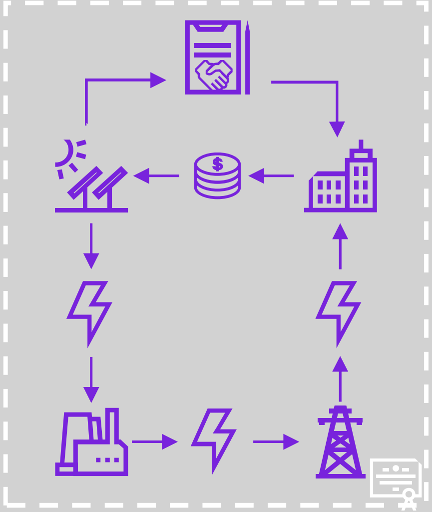
PPAs are contracts between electricity producers and buyers (off-takers) ensuring the transaction of electricity volumes under a defined price and period of time.



On-site PPA



Off-site PPA



Virtual PPA

Physical PPA

Also called direct PPA, this is a direct exchange between the electricity producer and its customer. **The generation can be:**

– **Located on the premises of the consumption site** (on-site PPA)

– **Located remotely with the electricity injected to the grid** (off-site PPA) and the off-taker receives a guarantee of origin to ensure the source of the electricity bought.

Virtual PPA

Also called financial PPA, these are agreements **without physical delivery of electricity and are defined as a financial transaction between parties**.

These agreements are usually defined as contracts for difference (CFD), where a price is agreed—a strike price. If the selling market price is lower than agreed, the producer pays the profit to the off-taker. If the market price is above the negotiated price, the off-taker pays the producer the difference.

Sources: Cluster TWEED, 2024, Smart contracts and virtual purchase agreement for water, heat and electricity; Kearney Energy Transition Institute analysis

6.4 Business models for electricity production

The increase in geothermal PPAs and the transition to next-generation geothermal technologies marks a new phase in geothermal energy commercialization

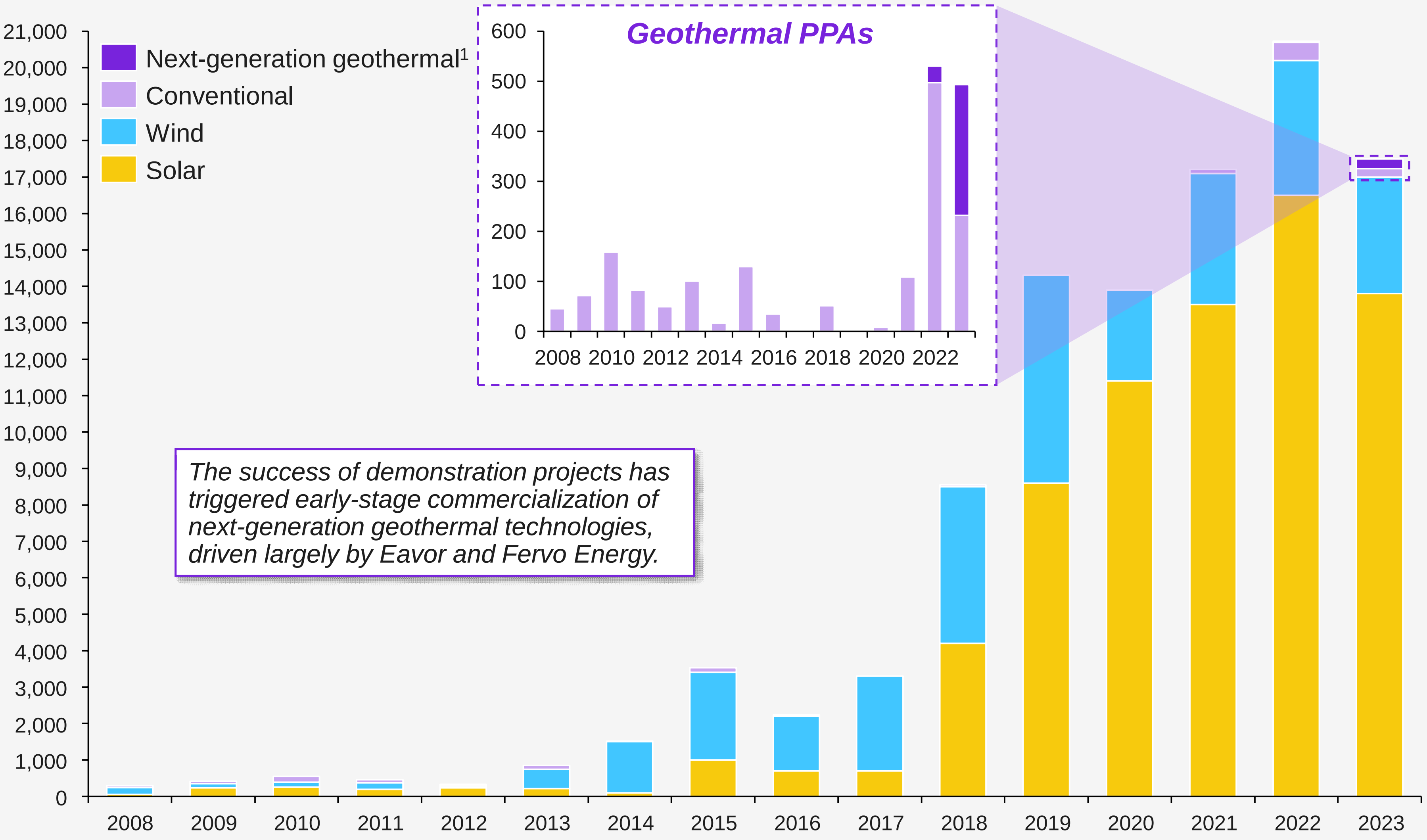
Example

The percentage of renewable PPAs that use geothermal is still quite low, less than 3% in 2022 in the United States; however, in **2024, Fervo signed the largest geothermal PPA**, totaling 320 MW, to narrow gap to a competitive LCOE.

6.4 Business models for electricity production

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

7. Cost of geothermal energy

Cost of geothermal energy

Fewer data is available for less-mature applications such as resource extraction. Therefore, this FactBook considers the costs of geothermal heat provision and electricity generation alone.

7.0 Chapter summary

Levelized cost of heat

- **Geothermal heat pumps are an attractive technology on a levelized cost of heating basis, offering a source of thermal energy that competes with natural gas in Europe** at 0.03-0.11 USD/kWh compared to 0.03-0.23 USD/kWh, respectively.
- **Geothermal district heating realizes a lower LCOH, although more varied, via economies of scale** (0.004-0.417 USD/kWh in Europe).

Levelized cost of electricity

- **Conventional geothermal power is among the most competitive renewable power sources,** offering a globally-weighted average levelized cost of electricity (LCOE) ~0.071 USD/kWh in 2023 falling behind onshore wind and solar PV at ~0.033 USD/kWh and ~0.044 USD/kWh, respectively.
- **Critically, conventional geothermal electricity generation offers a cheaper alternative to fossil-based power** at 0.075-0.200 USD/kWh in 2023.
- **Emerging geothermal technologies, AGS and EGS, offer less competitive LCOE ~0.230 USD/kWh,** which must fall to encourage uptake, expanding scope of suitable geographies for geothermal energy extraction, which is critical as site availability for convectional geothermal saturates.

Upfront investment

- **Upfront investment is the key cost driver of conventional geothermal power, representing ~80% of LCOE at 3,011 USD/kW$_e$**, exceeding all renewables except concentrated solar power.
- Elevated upfront cost due to market nascency, which is yet to benefit from economies of scale and learning by doing, and extensive resource assessment and testing required prior to construction.
- **Large upfront investment is the key challenge for conventional and emerging geothermal uptake in the short term;** however, geothermal is among the most competitive technologies by payback period (5-12 years) and return on investment (6-15%) in the long term due to higher capacity factors and longer lifetimes.

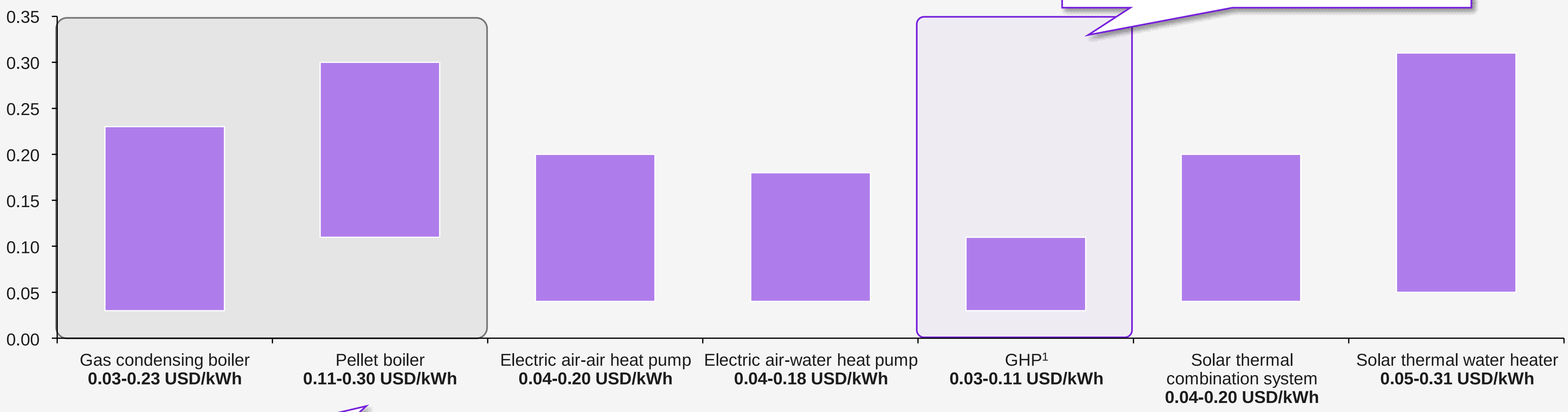
Capacity factor

- **Globally-weighted average geothermal capacity factor of 82% in 2023**, exceeding all renewable energy sources, trailed most closely by bioenergy at 72%.
- While geothermal O&M costs are high due to continuous well and reservoir management to ensure production remains stable over lifetime, higher CF brings LCOE in line with other renewable energy sources.

Geothermal heat provision using GHP is an attractive option on a levelized cost basis, offering a source of thermal energy that competes with natural gas in Europe

Non-exhaustive; example

LCOH per selected technology
USD/kWh, 2021



Unlike renewable technologies, **fossil technologies are more sensitive to price fluctuations,** e.g., 2022 European energy crisis

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

The average LCOH for European GDH is 55 USD/MWh, but there is variation by country

- GDH[1] LCOH varies by country, where **higher reservoir temperatures, shallower reservoir depths, higher well flow rates, higher utilization rates, and lower drilling costs** are key drivers to lowering LCOH.
- Countries with more established geothermal resources, such as **Iceland, Denmark, Italy, and France, offer lower LCOH values**, benefiting from learning-by-doing effects and economies of scale.
- **Netherlands and Germany closely follow with mid-range LCOH values,** committing to geothermal heat capacity growth by 2030 (deploying USD 1.1 billion and USD 1.5 billion, respectively), riled by energy security created by the sudden drop in incoming Russian natural gas flows.
- **UK is late to the party given previous focus on geothermal power,** creating a small 20 MW_{th} of thermal capacity (hence limited data is available on LCOH), but is expected to increase rapidly given commitments from the government to spend more than GBP 360 million on geothermal heating by 2030.
- Regions of **Ile-de-France (France) and Molasse Basin (Germany) show the lowest LCOH of 17-61 USD/MWh and 33-44 USD/MWh**, respectively, compared to projects in other areas of Europe, such as Rhine Graben (Germany), the Netherlands, and Switzerland (55-83 USD/MWh, 72 USD/MWh, and 71 USD/MWh, respectively)[2].

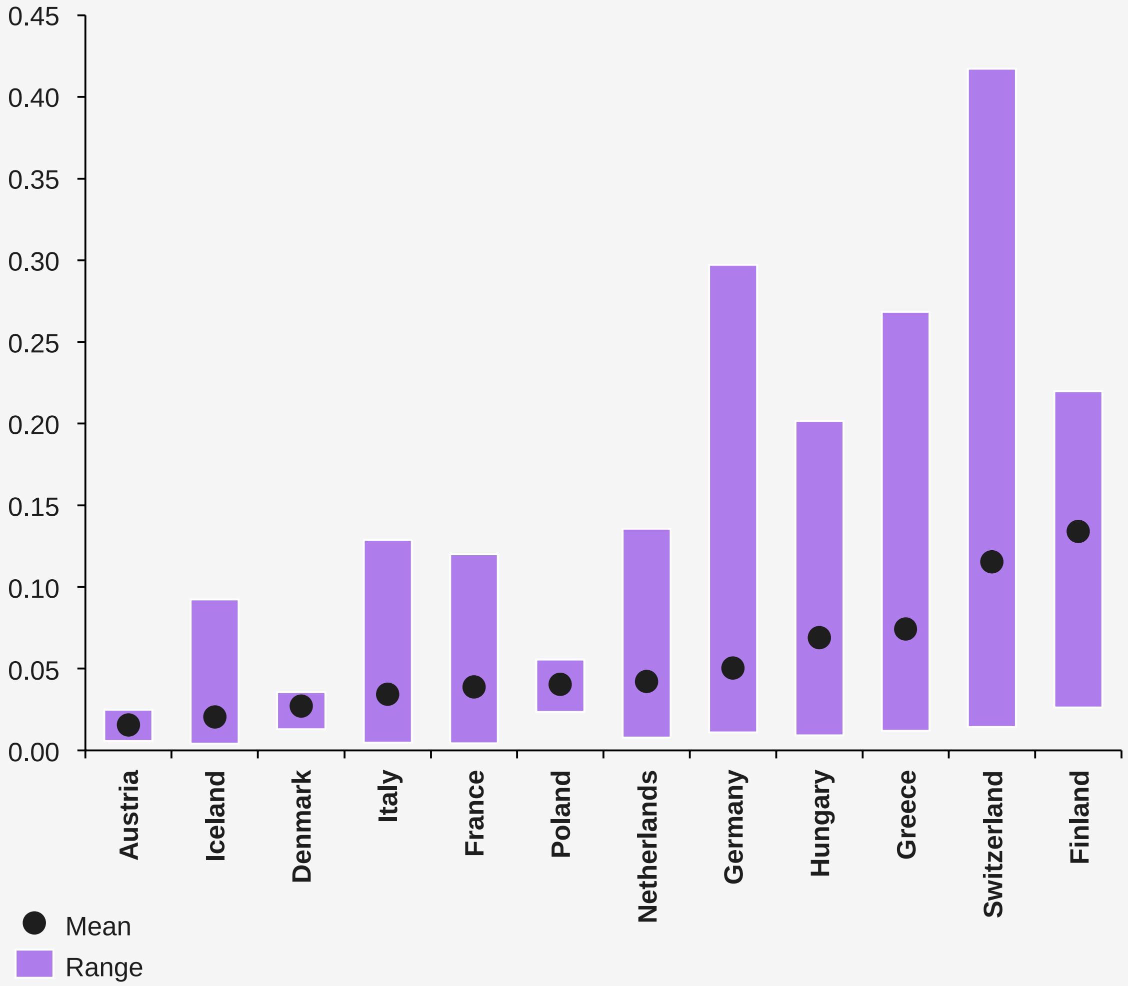
Non-exhaustive; example

Heat provision

7.1 Levelized cost of heat

GDH LCOH range by selected European country

USD/kWh, 2022



1. Geothermal district heating; 2. Based on USD/EUR of 1.11

Note: LCOH range does not include network expenditure, therefore the drilling cost constitute the main expense.

Sources: Abesser, C., Gonzalez Quiros, A. and Boddy, J., 2023, Evidence report supporting deep geothermal energy white paper; Akar, S. et al., 2023, Techno-Economic Analysis for a Potential Geothermal District Heating System in Tuttle, Oklahoma; Rystad Energy, 2022, Full steam ahead: Europe to spent $7.4 billion on geothermal heating, capacity to reach 6.2 GW by 2030; Kearney Energy Transition Institute analysis

Conventional GDH[1] is competitive with natural gas in Europe, but remains a more expensive option in the United States

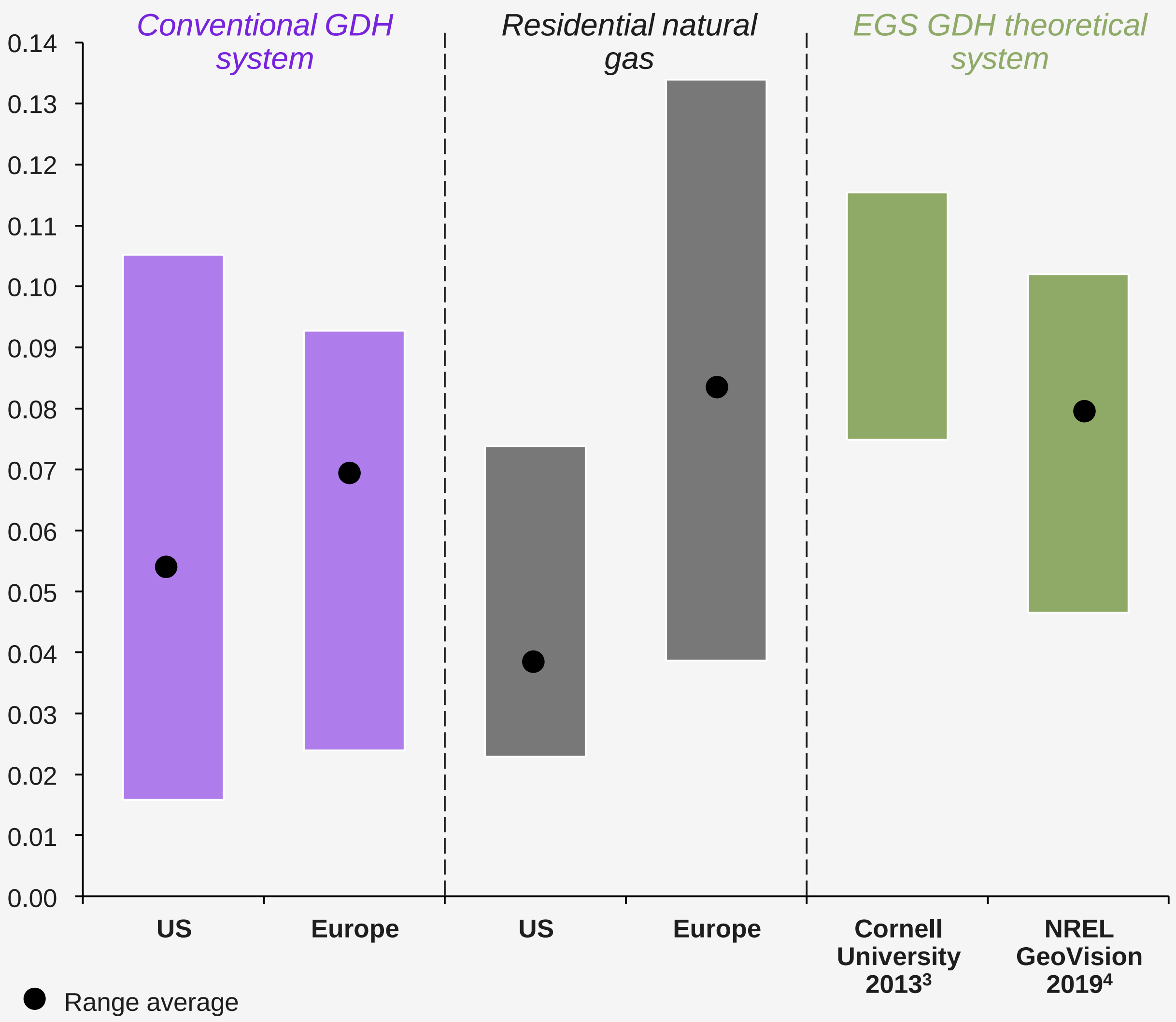
The **potential of EGS[2] district heating has been explored academically, deemed financially uncompetitive;** development remains stagnant since initial studies in 2013.

Heat provision

7.1 Levelized cost of heat

Worldwide comparison of LCOH values for GDH systems and natural gas prices

USD/kWh, 2021



- Existing conventional GDH systems are **competitive with residential natural gas in Europe** at 0.07 USD/kWh vs. 0.08 USD/kWh, respectively.
- Despite a lower conventional GDH LCOH of 0.05 USD/kWh **in the United States, the systems are not competitive with natural gas** at 0.04 USD/kWh.
- **Data on emerging EGS GDH systems remains theoretical since initial studies in 2013;** Cornell University ad NREL predict that the system in the United States will be **more expensive than conventional GDH in the US and Europe,** although comparable to natural gas in Europe.

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

Conventional geothermal power is competitive with select renewable sources, rivaling fossil fuels on a levelized cost basis

Non-exhaustive

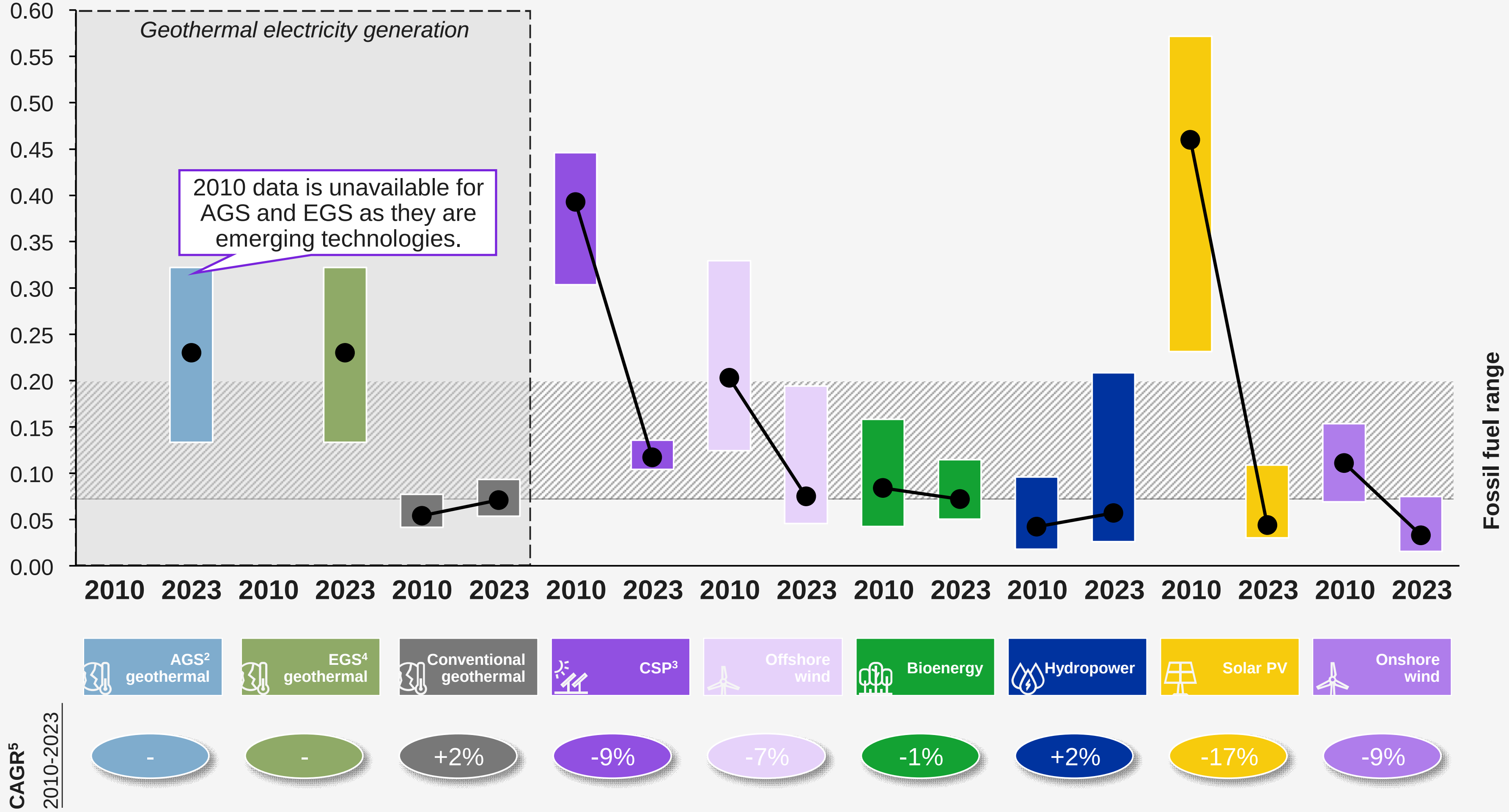
While conventional geothermal is competitive at **~0.071 USD/kWh in 2023,** AGS and EGS are among the most expensive generation technologies

Electricity generation

7.2 Levelized cost of electricity

Global-weighted average LCOE[1] by power generation technology

USD/kWh, 2010 vs. 2023

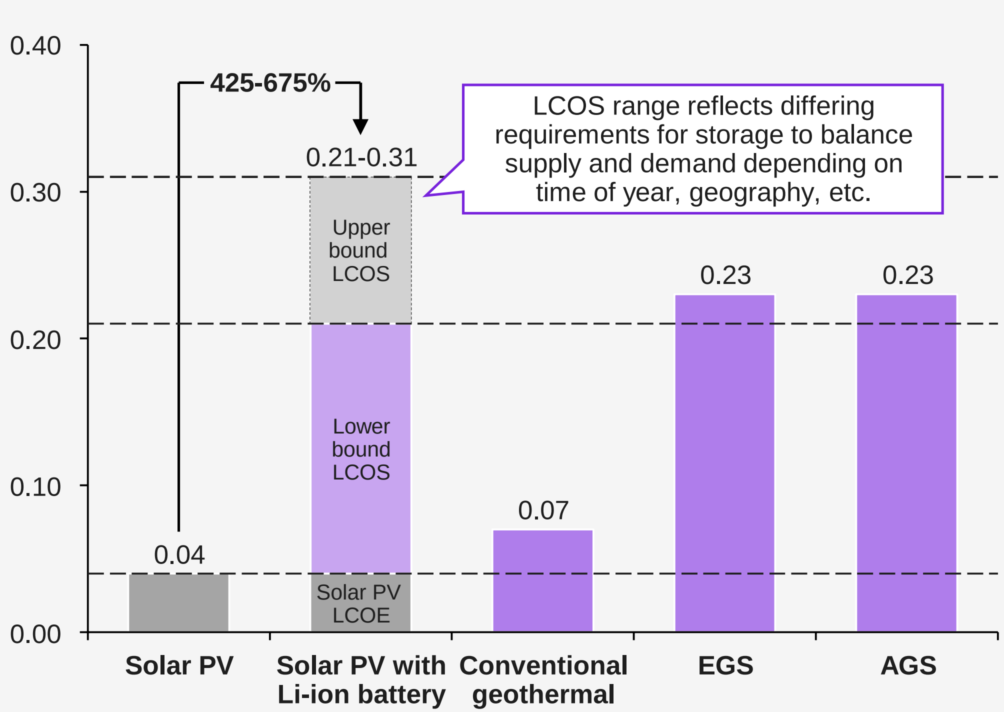


1. Levelized cost of electricity; 2. Advanced geothermal system; 3. Concentrated solar power for which there is no value range given a lack of 2022 project data; 4. Enhanced or engineered geothermal system; 5. Compound annual growth rate.

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 unification; Kearney Energy Transition Institute analysis based on desktop research

Solar PV offers a lower LCOE than geothermal, but is potentially less competitive considering the requirement for co-location with storage solutions to deliver flexible supply

LCOE[1] of geothermal technologies, solar PV, and solar PV with Li-ion battery (USD/kWh)



To produce a **comparable level of energy services to geothermal, solar PV must be complemented by an electricity storage solution to ensure a flexible power supply** (namely overnight), mirroring the intraday consumption profile of the power grid.

The subsequent cost of such a hybrid solution = Solar PV (LCOE) + Li-ion (LCOS[2]) = USD (0.04+(0.17-0.27))/kWh = **USD 0.21-0.31/kWh**

LCOE vs. power service cost

- **LCOE indicates the expected average electricity production cost over the economic lifetime of a technology**. The LCOE considers all directly-associated cost elements (construction, financing, fuel, maintenance, and costs associated with carbon price), but **excludes indirect costs related to the network, and does not reflect the quality of energy services provided.**
- **Crucially, LCOE does not consider the economic value of flexibility services provided by a technology.** For instance, solar PV does not generate power overnight, while geothermal is a dispatchable electricity source that can be switched on and off on demand.
- **To offer the same level of services as geothermal, solar PV must be complemented with electricity storage** to continuously release power outside production periods.
- Most power grids have sufficient flexibility to integrate variable power supply (also supported by "merit order" regulation), but this **capacity falls with the growing importance of variable energy sources** in the power mix. Beyond a certain threshold (intrinsic to each power grid), flexibility cost must be considered to reflect the real cost of the technology.

1. Levelized cost of electricity; 2. LCOS for a Li-ion battery used for energy arbitrage (value will vary by application)
Sources: IEA, 2020, Projected Costs of Generating Electricity; IRENA, 2024, Renewable Power Generation Costs in 2023; Schmidt et al., 2019, Projecting the Future Levelized Cost of Electricity Storage Technologies; Kearney Energy Transition Institute analysis

The LCOE of geothermal power is driven by upfront investment, accounting for around 70% of the total ~0.071 USD/kWh

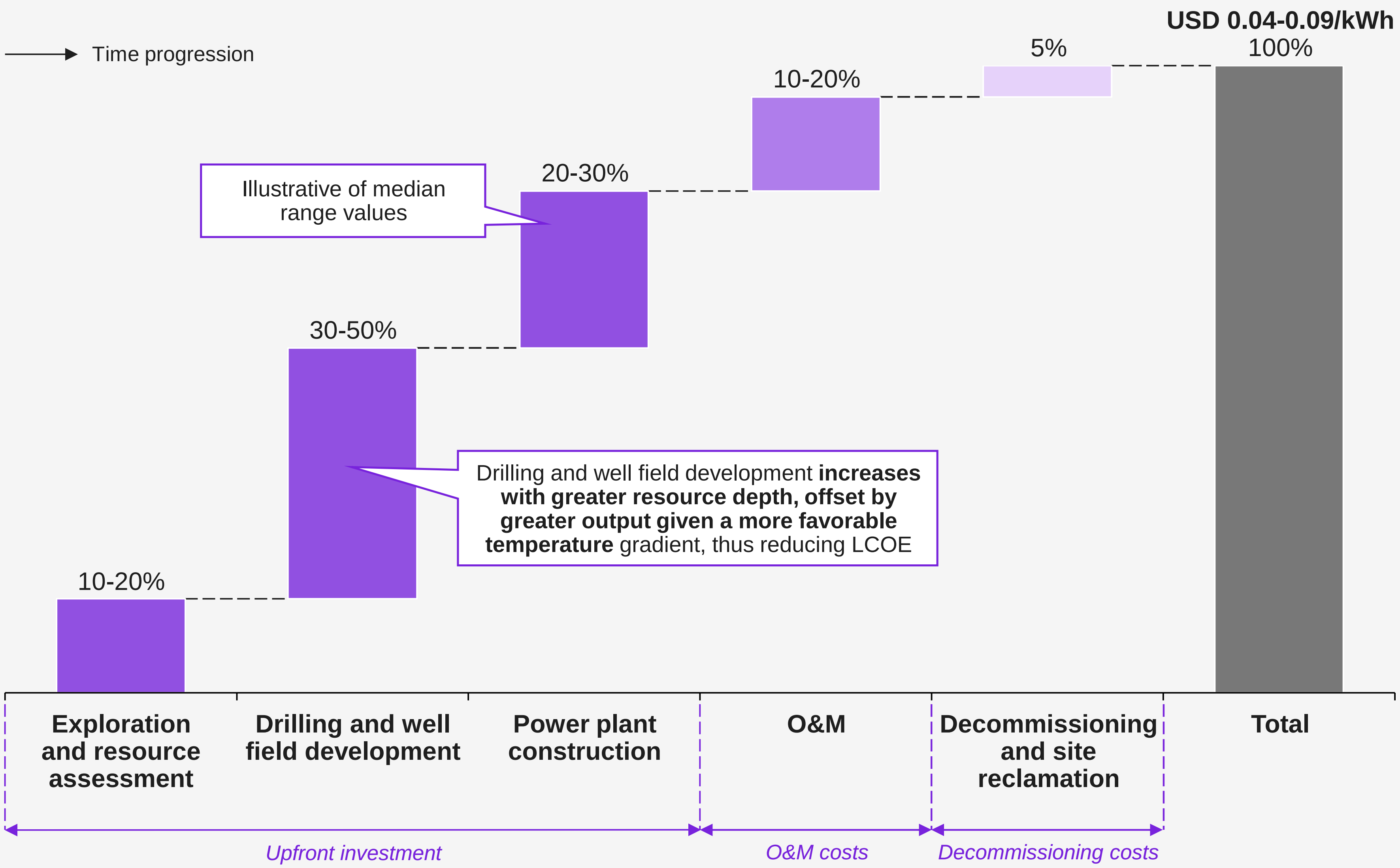
Illustrative

LCOE reflects **production cost per unit electricity over the generation asset's lifetime**, accounting for upfront investment and annual O&M[3] discounted to the current value.

Electricity generation

7.2 Levelized cost of electricity

LCOE[1] breakdown of a conventional geothermal power facility by project stage[2]
USD/kWh, 2023



1. Levelized cost of electricity; 2. Considering a 200 MW facility with an economic lifetime of 25 years and capacity factor of 85%, discounted at a rate of 6.5%; 3. Operation and maintenance
Sources: African Development Group, 2018, Geothermal energy powering Kenya's future; IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

Geothermal upfront investment is higher than other renewables, although falling at a comparative rate since 2019

– Upfront **geothermal investment is less competitive in the short term** than solar PV and onshore wind, as well as bioenergy and hydropower; it is more **comparable to offshore wind or CSP at USD 3,478/kW$_e$**, driven by:

1 **Technology maturity and scale**
More established renewable energy technologies benefit from **economies of scale and learning-by-doing** in a competitive market, while geothermal is more nascent.

2 **Resource variability and size**
Geothermal resources **must be deemed reliable for an economic business case** for a project prior to construction, requiring extensive exploration and testing to mitigate the risk of progressing with an unsuitable resources – the greater the size, the greater the extent of exploration and testing required

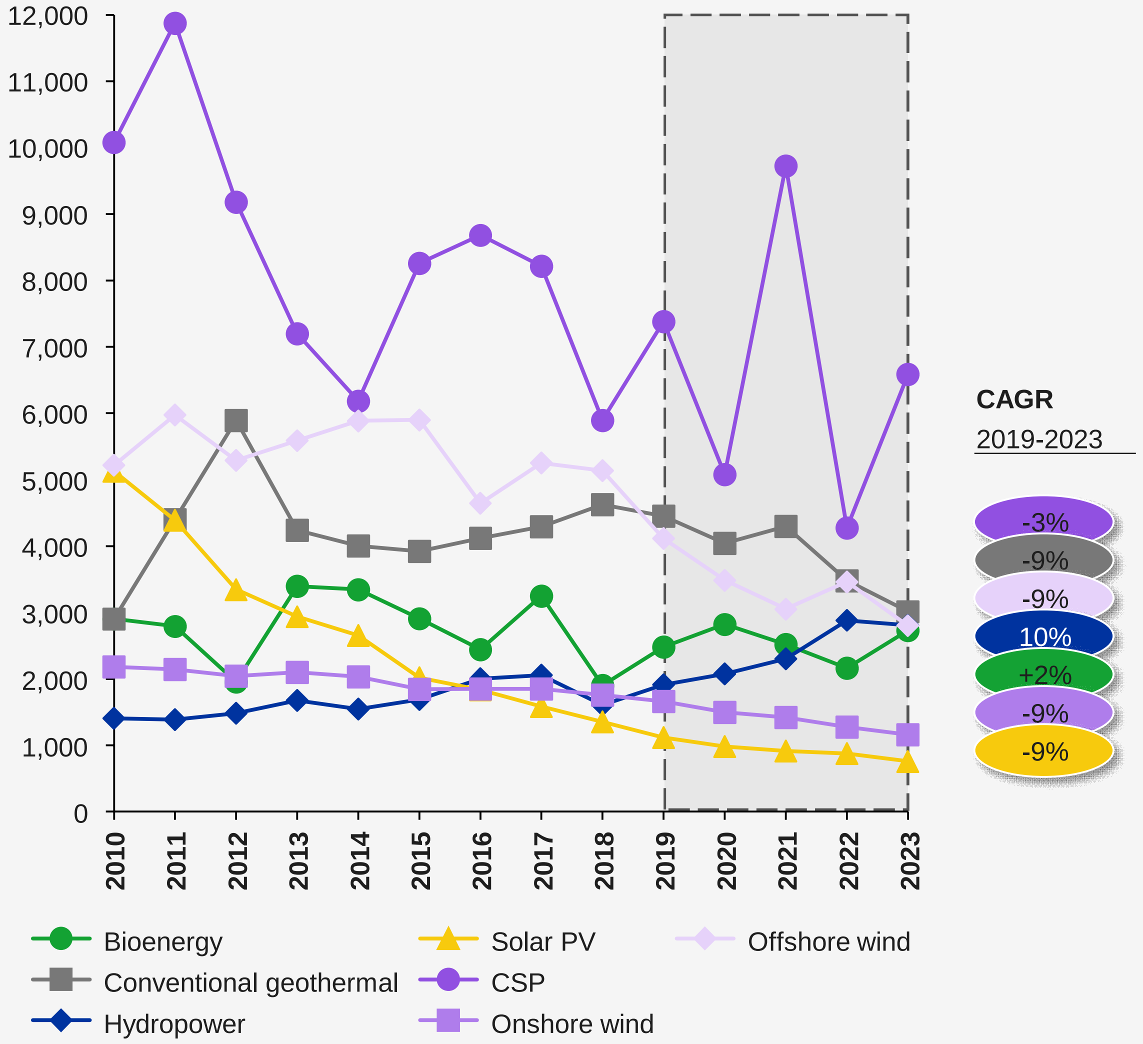
3 **Resource quality**
Temperature, depth, flow rate, and permeability determine the technology and numbers of wells required for a given capacity

4 **Deployment time**
Geothermal projects require **several years of exploration, drilling, and construction**, incurring more time-related costs and creating greater financial risks

On the other hand, **geothermal can provide dispatchable electricity and offers a lifespan of 30+ years** to recoup the higher upfront investment in the long term.

Global-weighted average upfront investment by power generation technology
USD/kW$_e$, 2010-2023

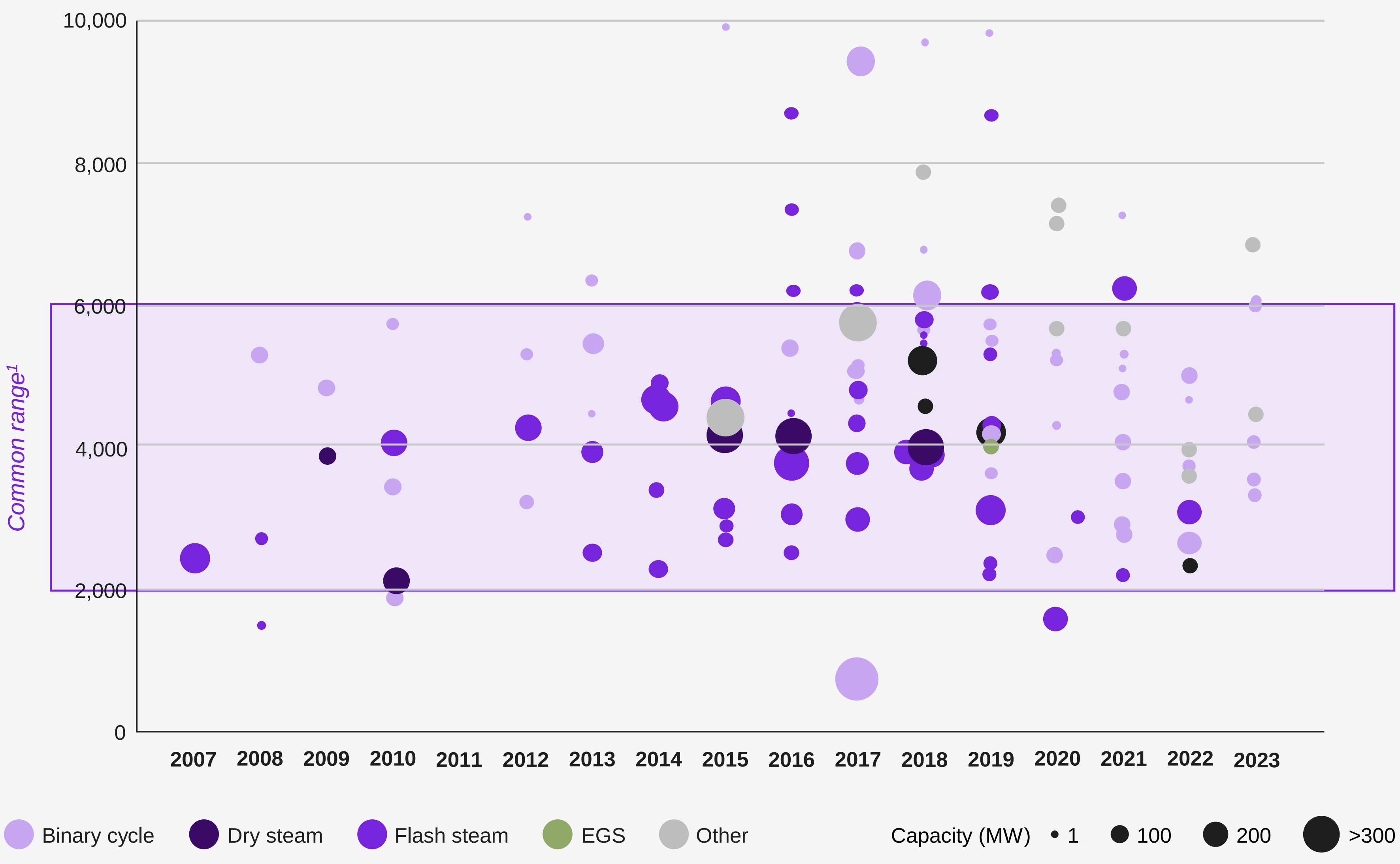
Upfront investment is the **total cost to get the project off the ground**, including land acquisition, equipment, installation, and any licensing or permitting fees



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

Upfront investment for a geothermal power project varies by technology and capacity with a lower bound of about USD 2,000/kW

Geothermal power upfront investment by project, technology, and capacity
USD/kW$_e$, 2010-2023



1. Range excludes outlier projects, typically small and/or remotely located, and is representative of the norm
Source: IRENA, 2024, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

Electricity generation

7.3 Upfront investment

Geothermal offers strong potential ROI, but is development is hindered by a high upfront investment

Despite greater upfront investment, **geothermal energy is financially attractive in the long run;** risk of failed performance stems from energy source suitability and sustainability

Electricity generation

7.4 Cost-associated challenges and risks

Challenge

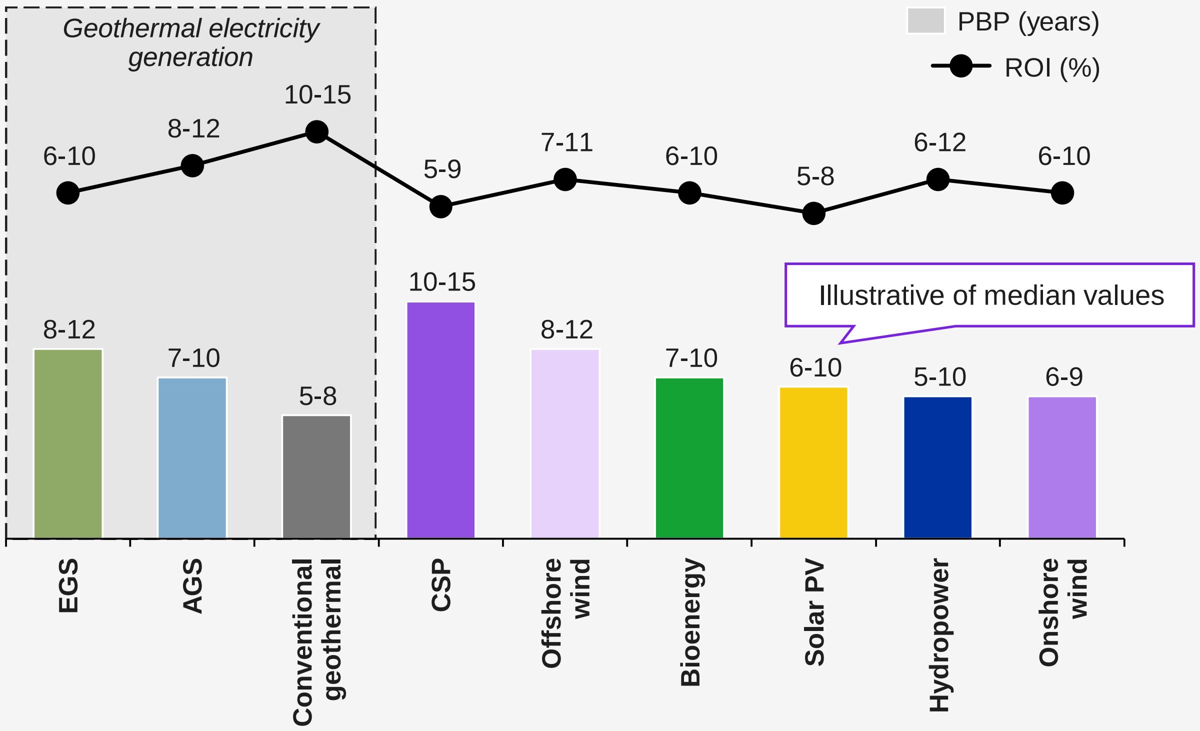
- **Greater upfront investment required,** decreasing at a slower pace in recent years due to limited economies of scale and learning-by-doing effects.
- For example, upfront investment for an electricity generation facility is **297% and 160% higher than that for solar PV and onshore wind,** respectively, although comparable to offshore wind.
- High cost **deters investment and stands as key barrier to development.**

Risk

- Potential for **failed return on upfront cost** due to unviability of geothermal resource following extensive exploration and testing.
- Potential for **unprofitability in long term due to natural depletion** of resource over time.

1. Return on investment; 2. Payback period; 3. Capacity factor
Sources: Kearney Energy Transition Institute analysis

Globally weighted average ROI[1] and PBP[2] of selected electricity generation technologies



- Assuming the geothermal energy source is deemed suitable following exploration and testing and is properly managed to prevent depletion, geothermal technologies offer a competitive ROI and PBP.
- Long-term favorable financial performance is driven by the following:
  - **Higher CF[3]:** Geothermal plants produce electricity near continuously; conventional geothermal averages at 82% compared to 16% and 41% for solar PV and onshore wind, respectively.
  - **Longer lifetime:** Geothermal plants operate for 30+ years compared to 25 years and 20 years for solar PV and onshore wind, respectively.

Despite an elevated upfront investment, geothermal power is competitive on an LCOE basis due to always-on capacity, reflected by a higher CF[1]

Non-exhaustive

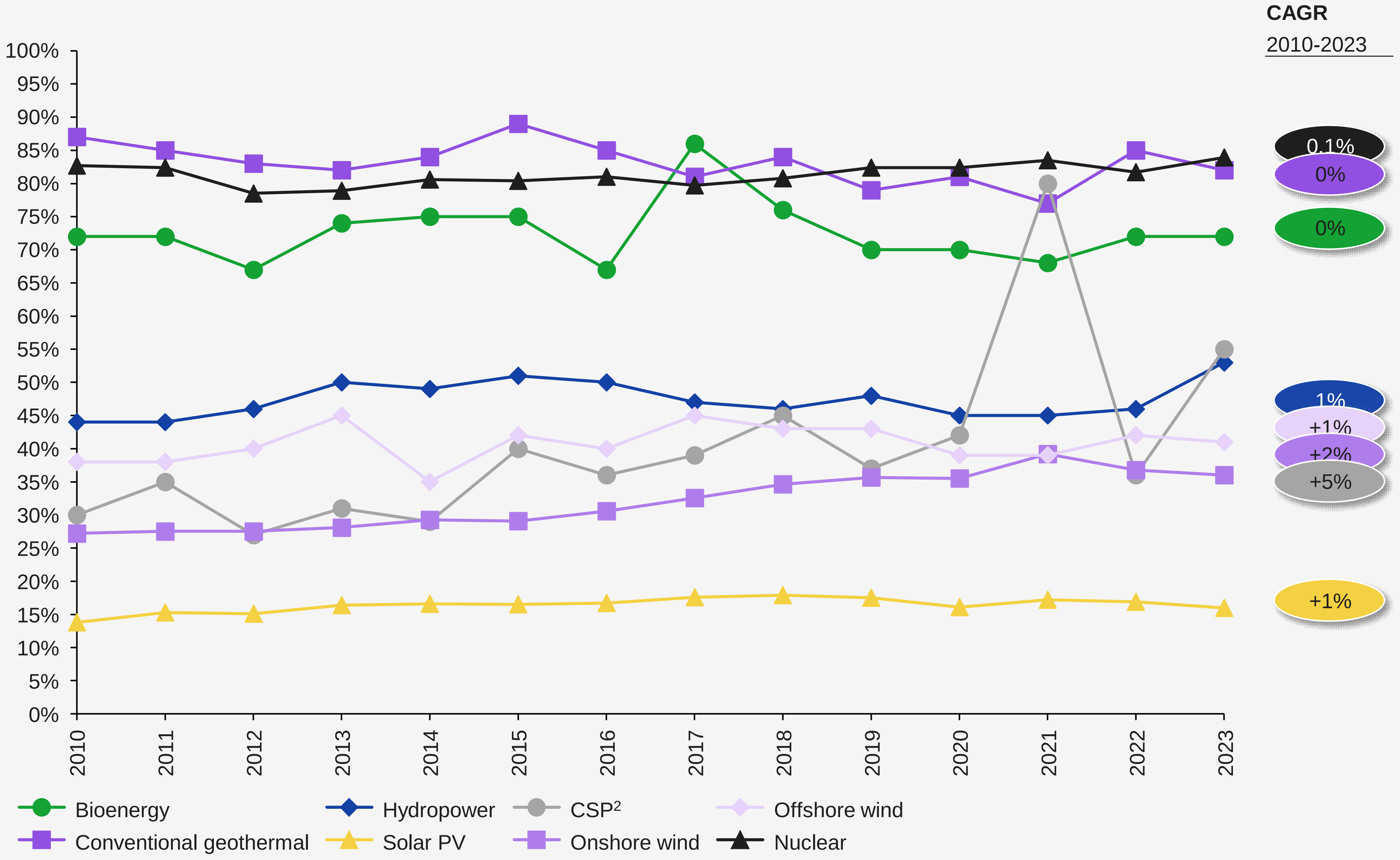
Geothermal facilities produce more electricity for a given capacity given a higher CF, thus **reducing the associated O&M cost per unit of electricity generated.**

Electricity generation

7.5 Capacity factor

Global-weighted average CF by power generation technology

2010-2023

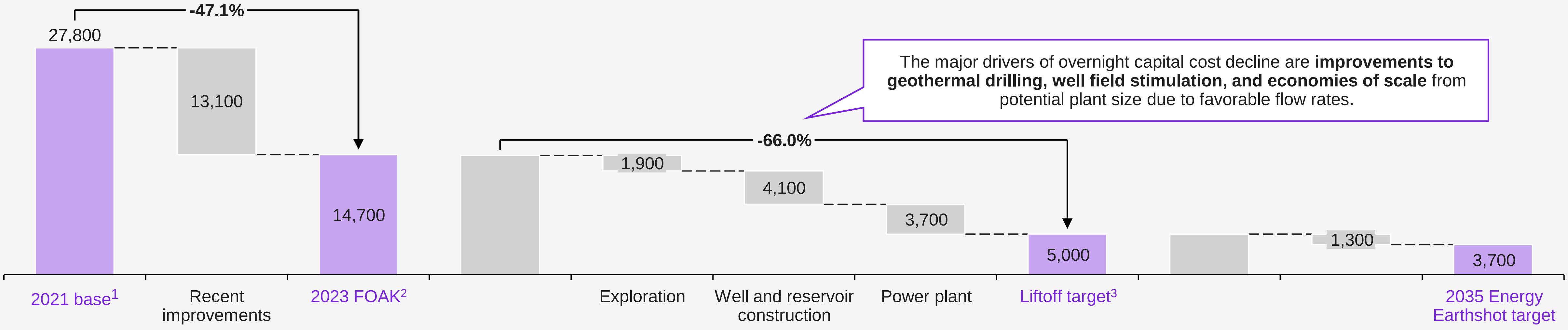


Note: CF = Total annual electricity generated [kWh/year]/(Capacity [kW]*Hours per year [h/year[)
1. Capacity factor; 2. Concentrated solar power.
Sources: EIA, 2024, Glossary; IRENA, 2024, Renewable Power Generation Costs in 2023; World Nuclear Association, 2024, Global Nuclear Industry Performance; Kearney Energy Transition Institute analysis

Recent technical successes have led to significant overnight capital cost reductions for EGS, catalyzing momentum in the emerging geothermal market

Potential reduction in national average overnight capital costs for EGS

USD/kW_e, 2024



Key drivers of cost reduction						
Recent improvements	Exploration	Well and reservoir construction	Power plant	Liftoff target		2035 Energy Earthshot target
– Drilling cost – Well stimulation – Lower number of exploration wells required	– Improved data collection and analysis – Lower number of exploration wells required	– Drilling cost – More/larger wells – Cement and casing costs	– Higher fluid flow rates from drilling – Centralized development	USD 60-70/MWh unsubsidized LCOE equivalent		USD 45/MWh unsubsidized LCOE equivalent

1. NREL ATB 2021 Base Case; 2. NREL ATB Advanced Case where FOAK denotes first-of-a-kind; 3. 2030 target based on trajectory to Energy Earthshot 2035
Sources: US DOE, 2024, Pathways to Commercial Liftoff: Next-Generation Geothermal Power; Kearney Energy Transition Institute analysis

8. Policy intervention for geothermal energy

Policy intervention for geothermal energy

Overview

– **Energy policy can serve to encourage uptake and commercialization of renewable energy technologies, such as geothermal heat and power.** The policy is designed to address key barriers to adoption, such as driving technology development via research and development grants and ensuring revenue certainty via feed-in-tariffs, thus strengthening the business case for adopting by mitigating risk.

Policies by technology

– **Geothermal technologies sit at different stages of maturity,** thus hold inherent differences in risk, requiring different policy support. Emerging technologies need a “supply push” via research funding and knowledge building to reach demonstration stage, while more mature conventional technologies benefit from increased public awareness and financing / business models to create “demand pull”.

– **Notable support for nascent emerging geothermal power to drive technology maturity** includes EUR 91.6 million funding granted to Eavor Technologies via EU Innovation Fund to demonstrate its closed-loop system in Germany in 2023 and USD 60 million granted to three EGS projects in the United States in 2024.

– **More mature geothermal heat pumps (GHP) have surged in response to energy transition targets and financial incentives.** The five leading global countries in terms of GHP capacity have combined demand- and supply-side policy to drive technology development through demonstration to commercialization with minimal delay.

– **The most established conventional geothermal power remain hindered by high upfront cost;** policy aims to address the associated financial risk by increasing confidence in return on investment via financial mechanisms, e.g., acceleration of installed capacity in Türkiye following introduction of 10-year feed-in-tariff for projects operational pre-2026, capped at 86 USD/MWh_e.

Scaling up geothermal energy faces various challenges, which policy interventions seek to address through different solutions based on technology maturity and country dynamics

Non-exhaustive; illustrative

Challenge description	Policy intervention
Technology development: certain technologies are yet to be commercialized, and R&D is needed to access and fully exploit some geothermal resources. **Upfront cost remains high for emerging technology.**	– R&D grants – Support measures for specific technologies of interest
Geological resource uncertainty: geological uncertainty about the viability of a geothermal resource and long exploration time frames. Uncertainty how long a resource will be productive.	– Government-sponsored resource mapping and publication of resource maps – Reservoir management and modeling over the lifetime of a project
Institutional expertise: lack of knowledge on geothermal technologies, geothermal resources, or a skilled workforce.	– International cooperation – Encourage skilled worker immigration – Develop academic and reskilling education programs
Financing frameworks: high upfront cost for geothermal makes it difficult to compete with other renewable power or heating and cooling solutions. Tailored financing frameworks are required to commercialize emerging and mature technology.	– Geothermal-specific feed-in tariffs and power auctions – Tax credits and other fiscal benefits – Government subsidies
Investor risk: high upfront capital requirements for geothermal exploration and drilling, e.g., for projects in deeper and more uncertain geologies, create significant investor risk.	– Risk mitigation facilities with guarantees for early investors – Contracts tailored to geothermal energy which are based on drilling results – Investor insurance strategies
Development frameworks: overlapping mining codes, water rights, and geothermal frameworks complicate permitting, leading to lengthy development timelines.	– Permitting tailored to geothermal energy – Reduced requirements for shallow projects – One-stop shop for permitting – Adjusted mining codes
Environmental concerns: Negative environmental impacts, such as seismicity risks, must be weighed against environmental restrictions that block geothermal exploitation.	– Simplify environmental approval through geothermal-specific frameworks – Require seismicity monitoring
Public awareness: opposition to geothermal projects; misunderstanding of risks; unawareness of benefits; fear of fracking and seismic events.	– Educational programs – Stakeholder involvement – Public awareness campaigns – Projects in disadvantaged communities
Broader policy environment for renewable energy and sustainable technologies doesn't support geothermal development.	– Decarbonization policies – Synergistic technology development – Supporting infrastructure development (electricity and heating grids)

Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; Kearney Energy Transition Institute analysis.

Geothermal technologies benefit from different policy focus areas

Non-exhaustive

✓ Required policy focus

– Not a required policy focus

Policy focus area

Technology	Technology development	Resource uncertainty	Institutional expertise	Financing framework	Investor risk	Development frameworks	Environmental concerns	Public awareness	Broad policy environment
GHP[1]	–	✓	✓	✓	–	✓	–	✓	✓
Direct use	–	–	✓	✓	–	✓	–	–	✓
Combined cycle	–	✓	✓	✓	✓	✓	–	–	–
Binary cycle	–	✓	✓	✓	✓	✓	–	–	–
Dry steam	–	✓	✓	✓	✓	✓	–	–	–
Flash steam	–	✓	✓	✓	✓	✓	–	–	–
Wellhead generator	–	✓	✓	✓	✓	✓	–	–	–
AGS[2]	✓	–	✓	✓	–	–	✓	–	–
EGS[3]	✓	–	✓	✓	–	–	✓	–	–

- Geothermal technologies are at **various stages of maturity and have inherent differences in associated risks.**
- **Emerging technologies** require a “supply push” via R&D funding and knowledge building to reach the demonstration stage.
- **More mature technologies** benefit from developing public awareness, institutional capabilities, and financing / business models to reach widespread deployment.
- **Deeper geothermal projects,** even with mature technology, must still address high upfront costs and possible geological uncertainty.
- **Direct use,** while a mature application, needs support to reach wider commercial adoption.

1. Geothermal heat pump; 2. Advanced geothermal system; 3. Enhanced or engineered geothermal system.
Sources: EERA, 2018, Low-Temperature Sensible Heat Storage; IEA, 2023, Clean Energy Technology Guide; IRENA, 2023, Global Geothermal Market and Technology Assessment; Kearney Energy Transition Institute analysis.

Emerging geothermal technologies require supply-side support

Non-exhaustive

Government, research organizations, and private sector funding provides the bulk of support for emerging technologies. Early research reduces technology costs, accumulates data, and improves technology.

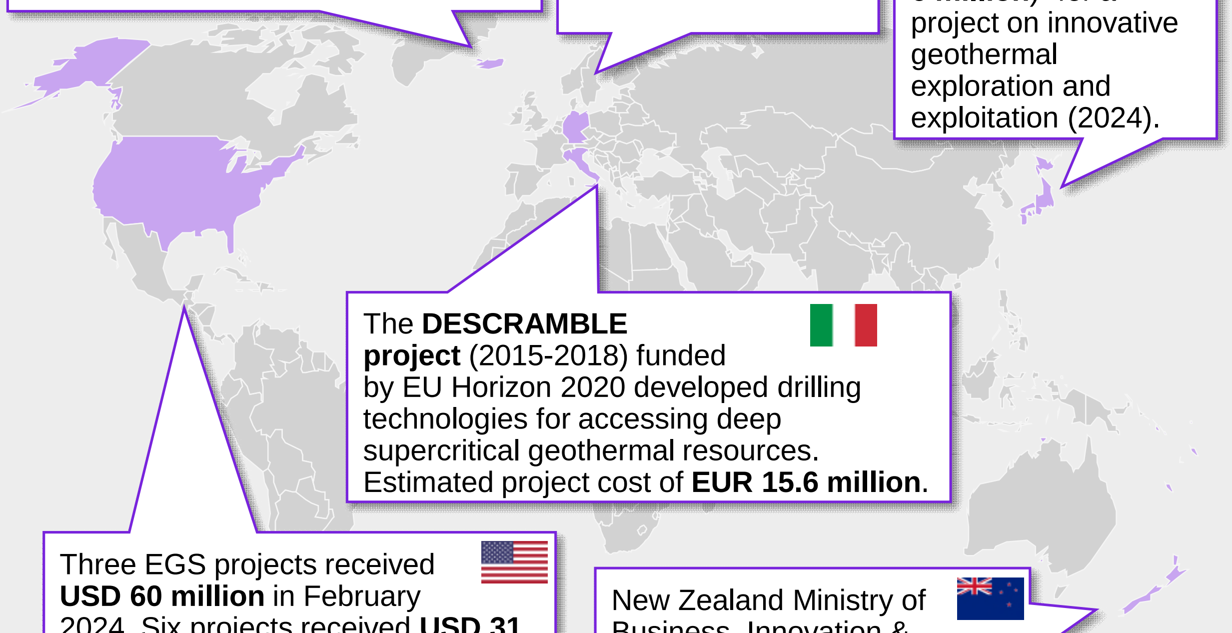
8.2 Policies by technology

Examples of emerging geothermal technology R&D support mechanisms

Iceland Deep Drilling Project (2000-present) created a public-private collaboration to conduct research on supercritical geothermal resources. Three main wells have been drilled; IDDP-2 is estimated to cost around **USD 15 millon**.

EU Innovation Fund granted **EUR 91.6 million** to Eavor Technologies in 2023 to demonstrate its closed-loop system in Bavaria.

New Energy and Industrial Technology Development Organization funded JPY 900 million (**USD 6 million**)[1] for a project on innovative geothermal exploration and exploitation (2024).



The **DESCRAMBLE project** (2015-2018) funded by EU Horizon 2020 developed drilling technologies for accessing deep supercritical geothermal resources. Estimated project cost of **EUR 15.6 million**.

Three EGS projects received **USD 60 million** in February 2024. Six projects received **USD 31 million** in August 2024 for wellbore construction. Utah FORGE facility carries out EGS research.

New Zealand Ministry of Business, Innovation & Employment funds The Next Generation project on **supercritical geothermal resources** (2019-2024).

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.

Key policies for emerging technologies

R&D grants, funds, long-term project support.

Create knowledge in emerging technologies:
- Build on conventional technology knowledge.
- Create collaborations between academia, government, and industry.
- Promote use of oil and gas industry knowledge to develop enhanced geothermal drilling and fracking techniques.

Finance demonstration, prototype, and first-of-a-kind projects, which may use a variety of financing structures.

Countries involved in geothermal R&D typically already have developed conventional geothermal technology expertise. Established government departments or funds support research in partnership with academia and/or industry.

Geothermal heat pump deployment has been encouraged by sustainability targets and financing frameworks

Non-exhaustive

The five leading countries for installed geothermal heat pumps (GHP) in 2020 have combined **sustainability policies** and **financial incentives**, as well as other **demand- and supply-side incentives**.

8.2 Policies by technology

Leading GHP countries created demand-side mandates and incentives for heat pump adoption[1]

Worldwide leaders in GHP capacity and supporting policies

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.

Other demand- and supply-side incentives help GHP uptake

In addition to sustainability polices and financial incentives that overcome cost barriers to GHP, policies can address **non-cost barriers to GHP adoption**. This can include one-stop platforms for consumers or pathways to install GHP in multi-resident buildings. Other policies can address **supply-side challenges**, such as manufacturing and supply chain capacity building and training of skilled workers.

Key policies for deploying GHP

- Spread public awareness of GHP; develop consumer platforms to learn about technology; sponsor demonstration projects.
- Create subsidies and incentives with clear distribution timeline.
- Enact energy efficiency, clean heating, and pollution reduction policies.
- Create frameworks that reduce permitting and licensing delays, for example increase depths for which drilling permits are given.
- Publicize geothermal resource maps.
- Develop GHP industry and workforce (supply side policies).

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 CO_2 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.

Conventional geothermal power requires sufficient demand pull to overcome high upfront costs

Government policy can create demand pull by **leading project development** or creating **financing frameworks** with sufficient incentives for **private sector project development**.

8.2 Policies by technology

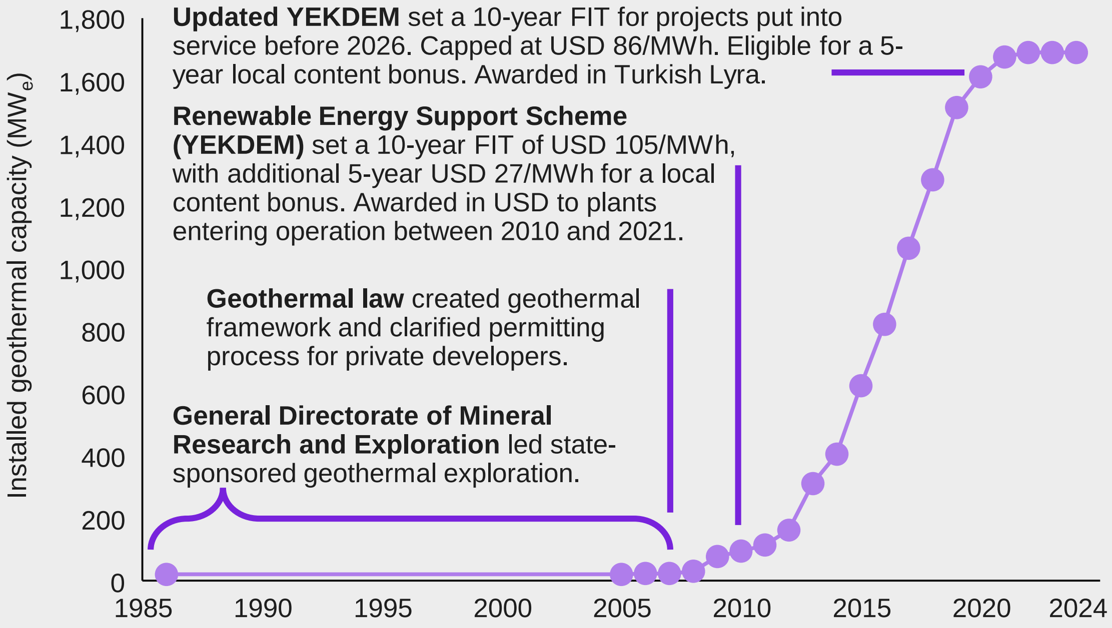
Conventional geothermal power development can be led by public or private sector, depending on government capability

– Public sector leadership of geothermal projects requires a commitment to develop the technologies and available capacity and skills to take on projects at scale. Examples of countries with successful public sector-led geothermal power development include **Mexico** and the **Philippines**.

– On the other hand, **financing frameworks** can encourage private sector development. This is especially relevant for countries where state resources may not be sufficient to fully develop the geothermal potential.

– An example is Türkiye, where the creation of a renewable energy feed-in tariff (FIT) led to exponential growth in geothermal power capacity.[1]

Acceleration of conventional geothermal capacity after creation of a feed-in tariff in Türkiye (1985-2024)



1. Most of the developed capacity uses binary cycle technology, as many of Türkiye's geothermal resources are not of high temperature.

Sources: ESMAP, 2016, Comparative Analysis of Approaches to Geothermal Resource Risk Mitigation; Fridriksson, T., 2018, Regional Workshop on Geothermal Financing and Risk Mitigation in Africa; IRENA, 2015-2024, Renewable Capacity Statistics; Mertoglu, O. et. al., 2021, Geothermal Energy Use: Projections and Country Update for Türkiye; Kearney Energy Transition Institute analysis.

Key policies for conventional geothermal power development

- Sponsor early resource exploration and share results.
- Build government capacity and institutional knowledge to develop geothermal projects with public funds.
- Develop financing frameworks that incentivize private sector participation in the geothermal power industry.
- Enact risk mitigation mechanisms to encourage investment.
- Streamline development frameworks and permitting processes.

Direct use in district heating and cooling requires centralized coordination and tailored financing models

Non-exhaustive

The decarbonization of district heating and cooling using geothermal energy has not been tapped to its full potential. Expanding it requires **central planning and creative business models.**

8.2 Policies by technology

Government planning and centralized funding is needed to enact geothermal district heating and cooling systems

- Technology for conventional district heating and cooling (DHC) is established but remains underdeveloped; ~90% of district heating is currently fossil-based.
- DHC is **centralized and government-led,** requiring **forward planning, especially for next-generation DHC**,[1] which involves redesigning and retrofitting networks to function at lower temperatures and integrate distributed heat sources and heat pumps.[2] **The required retrofit is costly to step away from high temperature fossil-based systems.**
- **Government funding frameworks and public-private partnerships** are required to incentivize demand. E.g., **Heerlen Mine Water DHC** in the Netherlands incorporated **Mijnwater**, financed by **equity, loans, and municipality funding** between 2013-2019. Phase II (2021-2025) is anticipated to require an additional EUR 130 million, EUR 55 million from customer contributions and subsidies.

Example DHC financing framework and Mijnwater example (EUR, 2013-2019

Equity
Venture capital, crowdfunding cooperatives, consumer connection fees

Loans
Banks, finance companies, specialized funds, loan guarantees, debt provision

Grants
International funds, national funds, city-level subsidies

26.1% Equity[3] 8 million	53.1% Municipality of Heerlen 16.3 million	20.8% Loans 6.4 million

1. Also known as fifth-generation district heating and cooling (5GDHC). 2. Note that district heating systems can use secondary waste heat, such as from industrial installations, data centers, or power plants, and heat pumps to extract this heat. Highly energy-efficient district heating and cooling systems may use a combination of geothermal and secondary heat sources.
3. 100% of equity is owned by Limburg Energy Fund (LEF), the energy fund of the Province of Limburg.
Sources: Ben-Hamo, A. and Delpon de Vaux, O., 2020, Case study of the Heerlen experience – baseline report on opportunities and barriers; Euroheat & Power, 2024, District Heating and Cooling Market Outlook 2024; IEA, 2022, The Future of Heat Pumps; 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.

Key policies to support geothermal district H&C

- Carry out DHC planning with cities and communities; build knowledge of geothermal alternatives and district heating technologies.
- Develop new business models for DHC that combine public and private finance.
- Create government funding schemes for DHC feasibility studies and to subsidize project costs.
- Require buildings to connect to DHC networks.
- Remove regulatory barriers to developing DHC systems.
- Require decarbonization of buildings and district heating systems.

The grant funding percentages for GDH[1] projects in the United States are comparable to European GDH, which range from 19% to 80% of total project capital costs

Capital costs of GDH systems and amount of grant funding
USD/EUR million, 2021

Project location	Project name / description	Capital costs (million USD for US and million EUR for Europe)	Loans and grants (million USD for US and EUR for Europe)
	Canby	1.4	0.8
	Lakeview Prison	1.3	-
	Lakeview Hosp/Schools	3.8	3.8
	Alturas	5.0	4.0
	Small GDH for 25 buildings	0.9	0.7
	2.5 MW GDH	1.4	0.9
	Development of well field to supply existing GDH	15.9 (for wells)	9.2
	GDH system with 5-km district heating network	9.7	5.4
	Expansion of existing GDH system	19.0 (for GDH expansion)	4.0
	Development of smart grid for campus heating	40.0	7.5
	GDH system for 5,016 inhabitants	12.0	2.3

Operational[2] Under construction Planned

1. Geothermal district heating; 2. The status of these projects reflects the situation as of 2020.
Source: NREL, 2021, 2021 US Geothermal Power Production and District Heating Market Report; Kearney Energy Transition Institute analysis

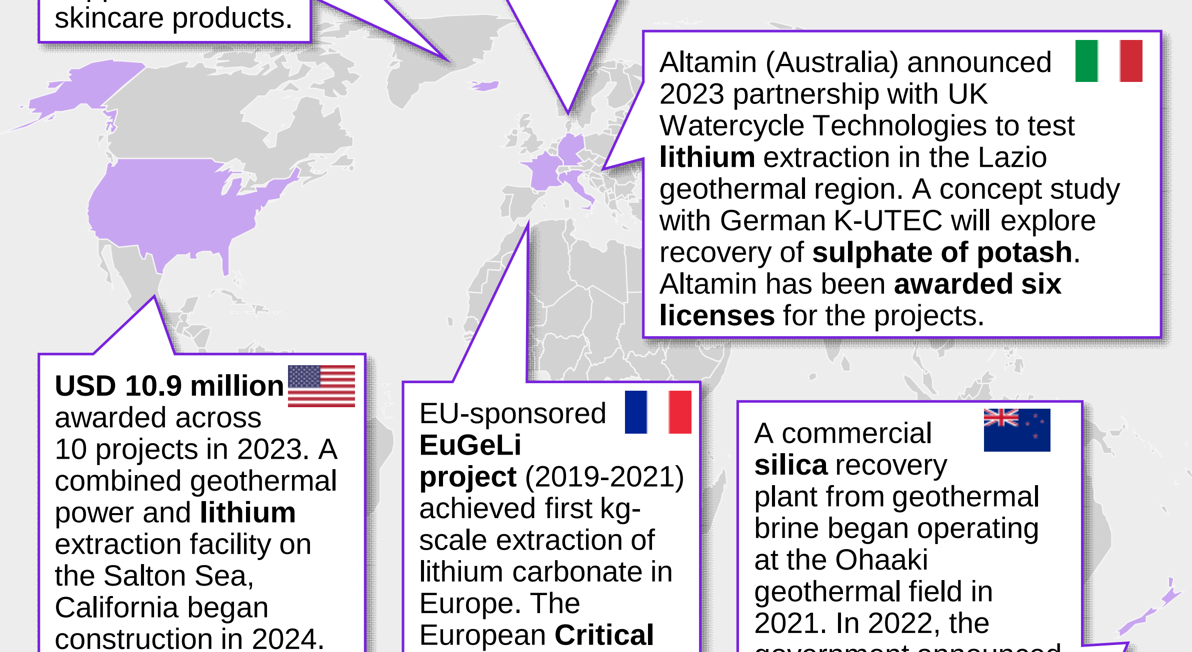
Synergistic technologies like mineral extraction are driven by sustainability, energy security goals, and to grow geothermal plant profitability

Non-exhaustive

Demonstration projects and research have shown that pairing geothermal brine mineral extraction with power generation can **increase geothermal plant profitability**. Policy support is also driven by the **desire to reduce critical mineral imports**.

8.2 Policies by technology

Example support for mineral extraction from geothermal brine



Silica is extracted at the Hellisheiði and Svartsengi geothermal power plants for dietary supplement and skincare products.

The **Zero Carbon Lithium Project** by Vulcan Energy Resources in Germany produces battery-quality lithium from geothermal brine in the Rhine Valley. Their Lithium Extraction Optimization Plant began operating in 2024.

Altamin (Australia) announced 2023 partnership with UK Watercycle Technologies to test **lithium** extraction in the Lazio geothermal region. A concept study with German K-UTEC will explore recovery of **sulphate of potash**. Altamin has been **awarded six licenses** for the projects.

USD 10.9 million awarded across 10 projects in 2023. A combined geothermal power and **lithium** extraction facility on the Salton Sea, California began construction in 2024. Total project costs are estimated at USD 1.85 billion, with several private investments from the auto industry.

EU-sponsored **EuGeLi project** (2019-2021) achieved first kg-scale extraction of lithium carbonate in Europe. The European **Critical Raw Materials Act** (2023) supports strengthening domestic supply of critical materials.

A commercial **silica** recovery plant from geothermal brine began operating at the Ohaaki geothermal field in 2021. In 2022, the government announced **USD 1.3 million equity investment** in **Geo40** to scale **lithium** extraction.

Key policies to support mineral recovery

- Support R&D for synergistic technologies that have not yet reached maturity.
- Spread awareness of the sustainability, political, and financial benefits of synergistic technology solutions.
- Explore public-private cost sharing models to spearhead private sector investment.
- Use policy to promote various sustainability technologies. Support solutions that increase energy security.

Sources: BRGM, 2021, EuGeLi: Lithium extraction from geothermal brines in Europe; Cariaga, C., 2024, Altamin expands geothermal license area in Lazio, Italy, ThinkGeoEnergy; Dulian, M., 2023, Geothermal Energy in the EU, European Parliament Research Service; IEA, 2023, Energy Technology Perspectives 2023; IRENA, 2023, Global Geothermal Market Assessment; Vulcan Energy, 2024, Vulcan Plants; Kearney Energy Transition Institute analysis.

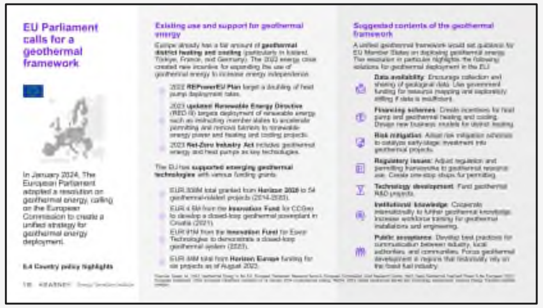
Countries around the world have established dedicated geothermal policies

Navigate to a country of interest by pressing Ctrl and clicking on the relevant page.

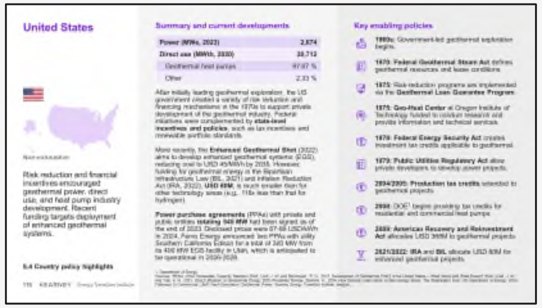
8.3 Country policy highlights

Overview of geothermal policies by country

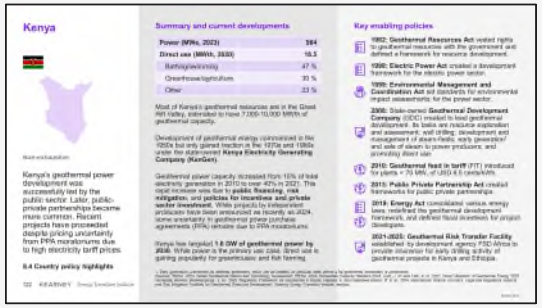
European Union



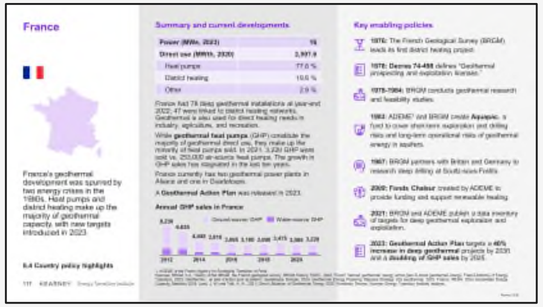
United States



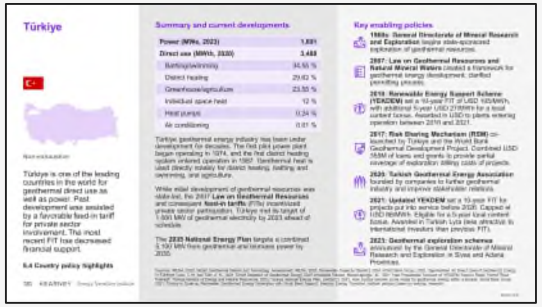
Kenya



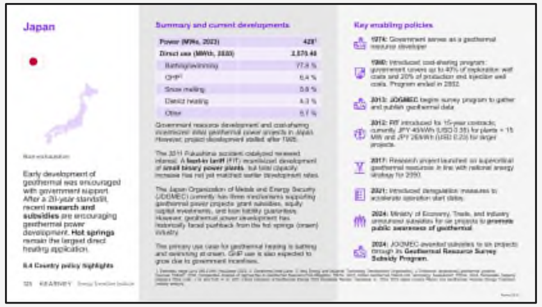
France



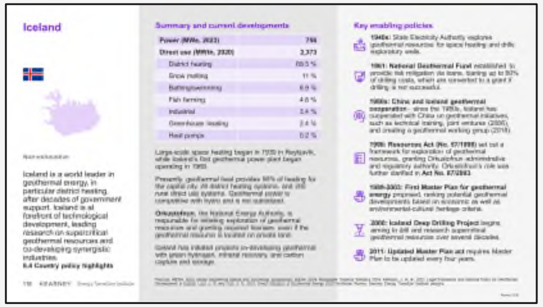
Türkiye



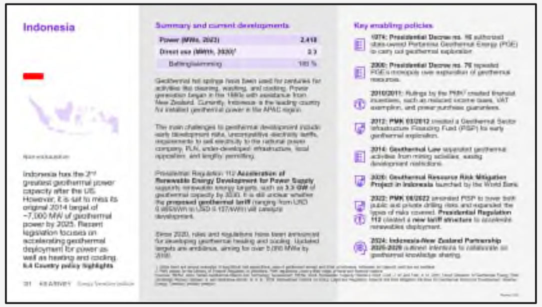
Japan



Iceland



Indonesia



Sources: Kearney Energy Transition Institute analysis based on desktop research

9. Environmental impact and social acceptance

Environmental impact and social acceptance

Environmental impact

- **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.
- **Geothermal power technologies produce relatively fewer GHG emissions** compared to traditional thermal sources but has a higher carbon footprint than other renewables**.** On a life-cycle basis, conventional geothermal technologies emit 38 gCO_2-eq per kWh, while EGS systems are estimated to emit around 54 gCO_2-eq per kWh.
- **Geothermal energy generally uses limited water**, but optimization is needed to reduce water stress. EGS systems have significantly higher water requirements than conventional geothermal technologies due to differing operating characteristics.
- **Geothermal power has one of the smallest land use footprints**, with the second-lowest land intensity. **The land use of geothermal heat pumps is also very small as most of the system is located underground.**
- Geothermal energy poses radiation risks due to its extractive nature and logs highest exposure rate when calculated per unit of electricity generated among different energy sources.

Social acceptance

- **Geothermal energy faces lower social awareness and acceptance compared to solar**, hindering development as protests have led to project cancellations.
- **Community concerns around geothermal energy development include seismicity, groundwater and atmospheric pollution**, further amplified by a negative technological spill-over effect of similar subsurface technologies such as shale gas development.

Social benefits

- **In 2022, geothermal energy accounts for ~1% of global renewable energy employment** and offers more long-term jobs than other electricity generation technologies. Geothermal technologies also offer alternative jobs to oil and gas drilling and piping roles.
- In 2023, geothermal power supported 140,000 jobs globally, with 59% from on-site construction and manufacturing and 80% of jobs are in developing and emerging economies, increasing to 250,000 when including heating and cooling.

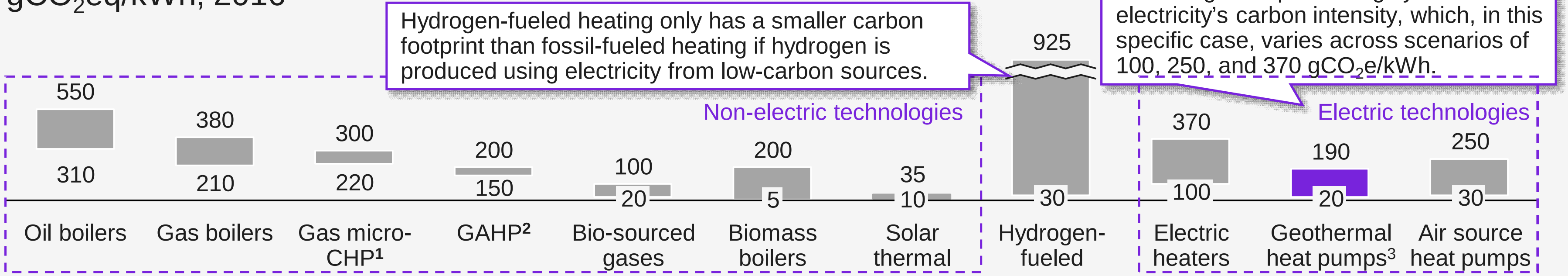
Different heating and cooling technologies have varying environmental impacts, with geothermal systems standing out for their low carbon footprint

Geothermal-based heating and cooling technologies and systems demonstrate lower environmental impacts compared to fossil fuel-based systems.

9.1 Environmental impact

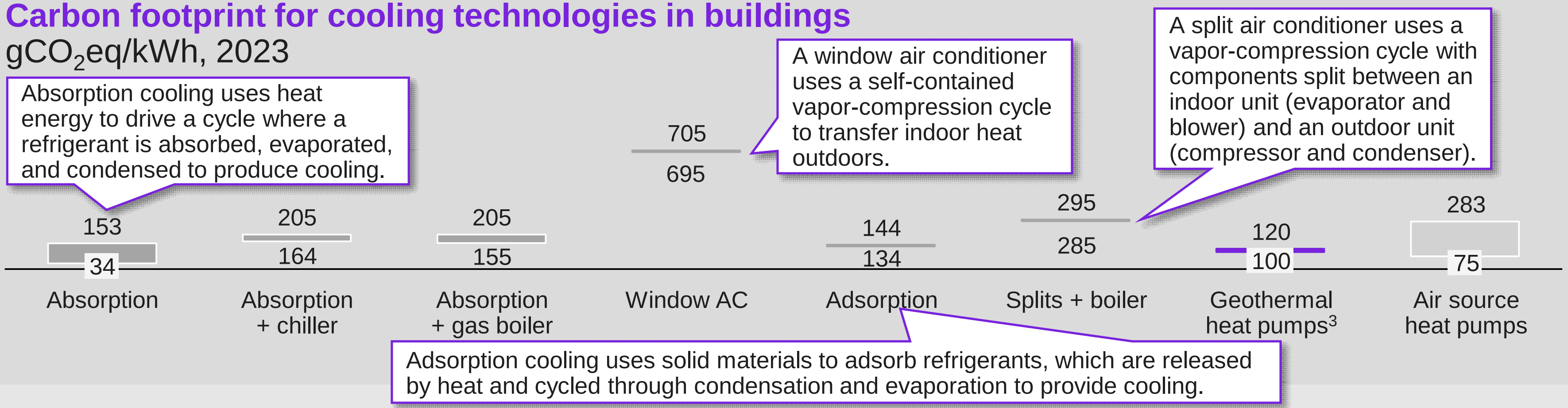
Carbon footprint for heating technologies in buildings

gCO_2eq/kWh, 2016



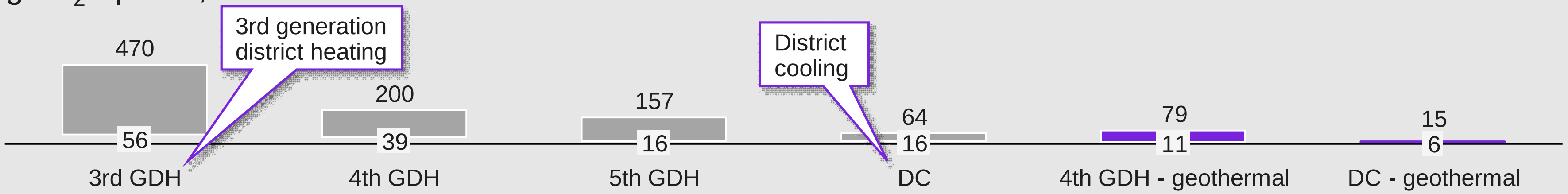
Carbon footprint for cooling technologies in buildings

gCO_2eq/kWh, 2023



Carbon footprint for district heating and cooling systems

gCO_2eq/kWh, 2024



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.

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; Kearney Energy Transition Institute analysis

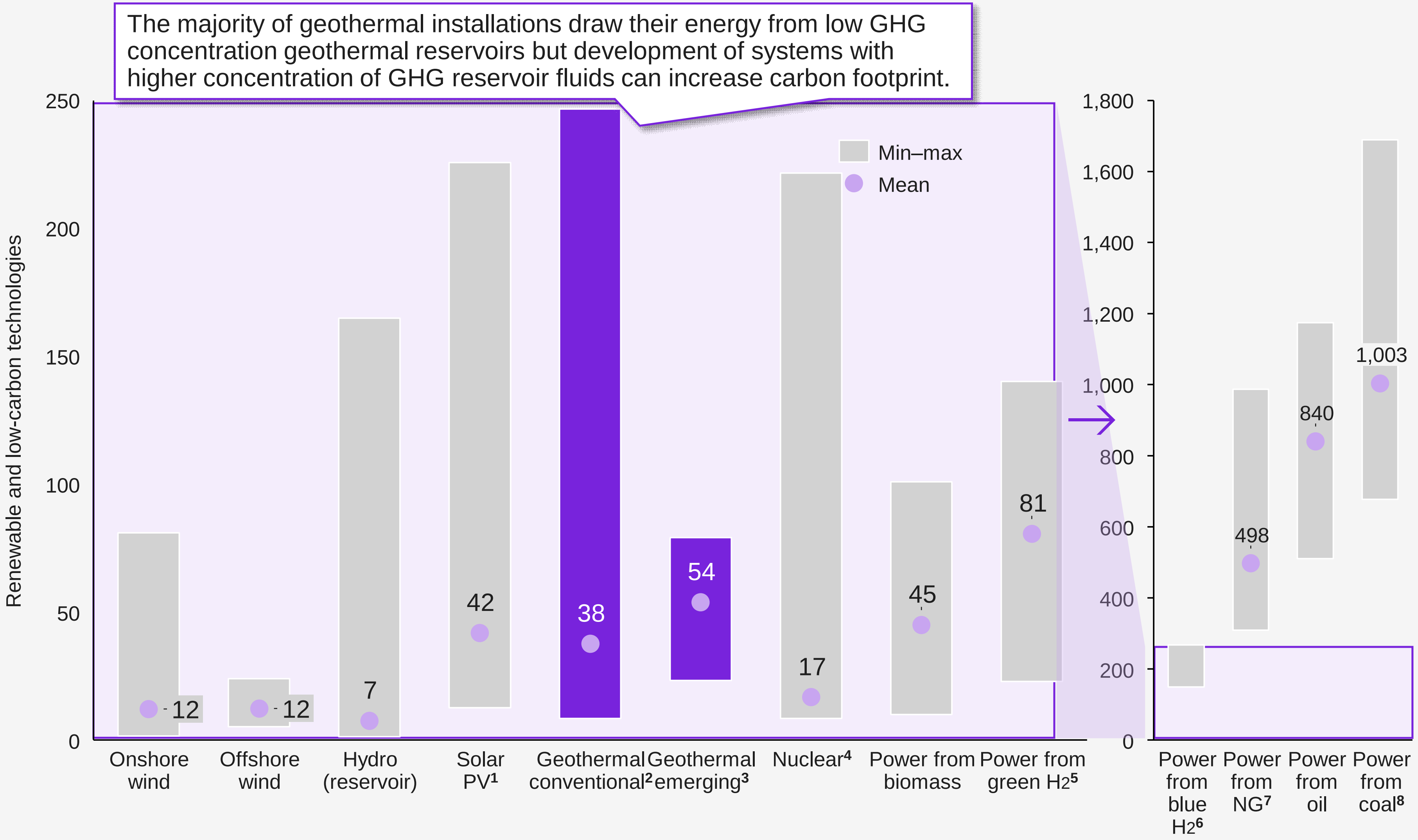
Geothermal power has relatively higher GHG emissions within renewables and low-carbon sources, but much lower than carbon-emitting energies

LCA results for various electricity sources show high variability in terms of related carbon footprint, which should be considered when assessing other value chains embodying energy inputs.

9.1 Environmental impact

Life cycle assessment (LCA) - carbon footprint

gCO_2eq/kWh, 2021



1. Crystalline silicon, thin film; 2. Flashed steam; 3. 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.; 4. LWR, PWR, and BWR; 5. 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%; 6. 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%. Combustion turbine and combined cycle; 7. Combustion turbine and combined cycle; 8. Subcritical, IGCC, fluidized bed and supercritical.

Sources: 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

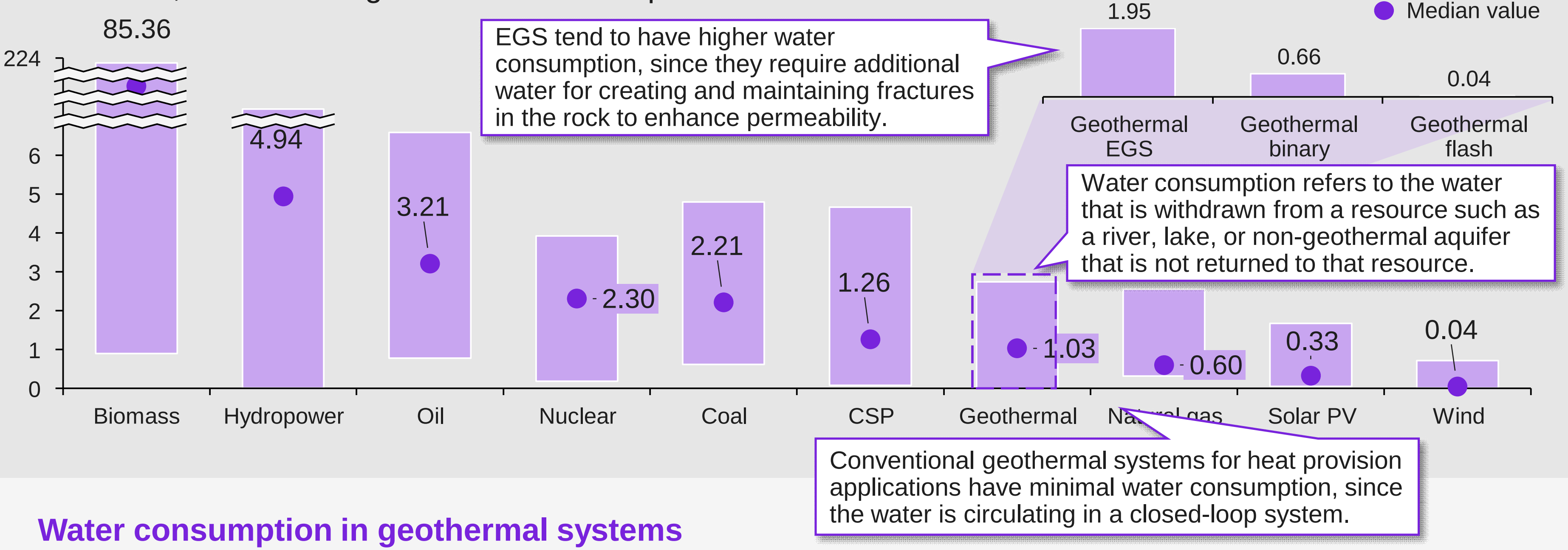
Water consumption in geothermal systems is low compared to most conventional thermoelectric power plants

However, many geothermal projects are in areas with existing or potential future water stress and/or without existing water infrastructure (i.e., remote) and hence, should be **optimized for water consumption.**

9.1 Environmental impact

Water consumption comparison[1]

Liter/kWh, min-max range with median and percentile values



Water consumption in geothermal systems

- Water consumption in geothermal energy development occurs at several stages along the life cycle of the plant but the majority of it occurs in the **plant operation phase.**
- **Geology, reservoir characteristics, and local climate** have various effects on elements such as drilling rate, the number of production wells, and production flow rate which can impact water consumption.
- **Cooling systems of the power plant** (air or water cooled) will significantly impact the water use. Flash plants use a geofluid directly for cooling, which significantly reduces the need for external makeup water.
- Lower flow rates per well, which leads to higher number of wells needed per plant, the assumed well depths, and the hydraulic stimulation contribute to additional requirements for **EGS plants.**

1. Water consumption is defined as the volume withdrawn that is not returned to the source. Geothermal power production uses two sources of operational water use (geothermal fluid and freshwater) but geothermal fluid is not typically considered as freshwater consumption because it is not sourced from a body of freshwater.
Sources: US DOE, 2024, Geothermal Basics; Jin et al., 2019, Water use of electricity technologies: A global meta-analysis, Renewable and Sustainable Energy Reviews; Clark et al., 2011, Water use in the development and operation of geothermal power plants; Kearney Energy Transition Institute analysis

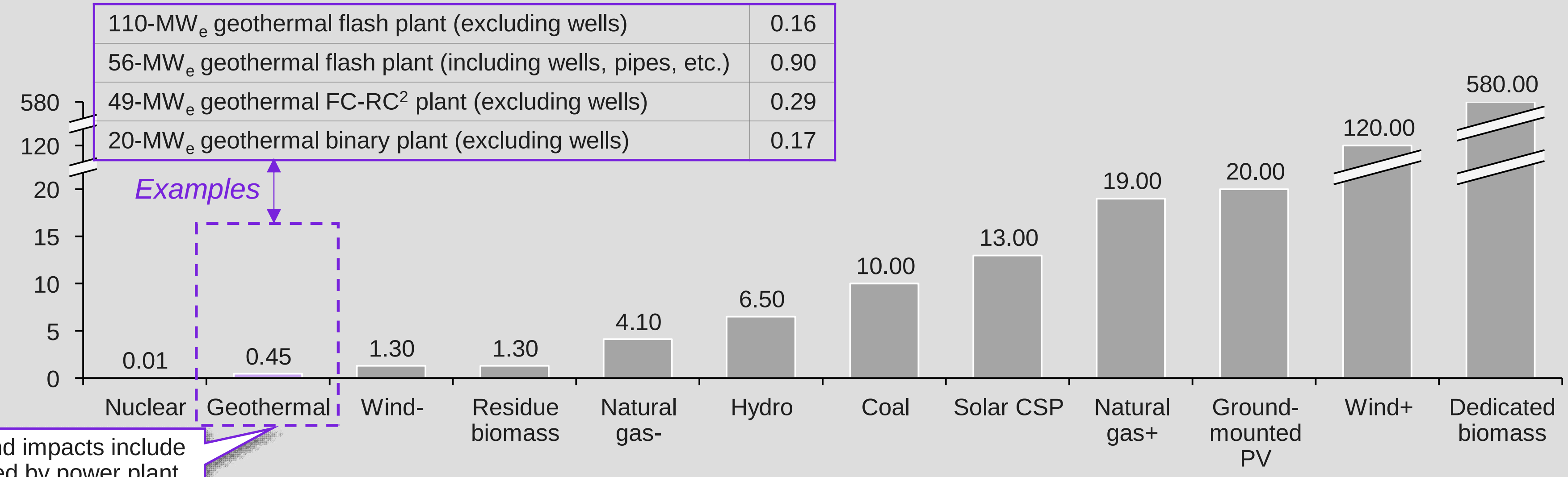
Geothermal heat pumps require more land compared to other heating and cooling technologies

Geothermal energy has one of the smallest land use footprints of all energy sources. The above-ground land area that is not covered by surface installations can still be used for other purposes such as farming, horticulture, and forestry.

9.1 Environmental impact

Land use intensity of electricity production (LUIE)[1]

Total direct and indirect land use, median values, km²/TWh



Geothermal land impacts include the area covered by power plant infrastructure and injection wells.

Geothermal power plant land requirement

- The above-ground footprint is **much smaller** than the space needed underground.
- Land requirement can vary per the **type of geothermal power plant.**
- Connecting a geothermal station to the grid may require **significant development of transmission infrastructure,** with the footprint varying by location and geothermal resource size.
- Modern geothermal technologies, like Eavor-loop, utilize minimal land, requiring only 0.3% of the space of wind energy and 2.9% of solar PV.

Land is disturbed during the construction phase. Once a GHP is installed, the system is almost entirely underground.

Geothermal heat pump system land requirement

- **Horizontal loop systems** typically require trenches 100 meters long and 1–2 meters deep, each holding about 200 meters of pipe (100 meters out and back). The number of trenches depends on the home's size and heat load. On average, the land needed is about 2.5 times the property's square meterage.
- **Vertical loop systems** are typically drilled to a depth of 100 meters and spaced 5–6 meters apart if multiple are needed. The number required depends on the property's heat load and ground type, with one borehole needed per 6 kW.

1. '–' denotes excluding spacing and '+' denotes including spacing. Spacing area is defined as the entire area within the perimeter of a production site.; 2. FC: Flash cycle, RC: Rankine cycle
Sources: Lovering et al., 2022, Land-use intensity of electricity production and tomorrow's energy landscape; Eavor, 2024, FAQs; IPCC, 2011, Geothermal Energy; Kearney Energy Transition Institute analysis based on desktop reserach

Geothermal energy poses radiation risks due to its extractive nature

Limited data on radon emissions from geothermal power suggest a potentially significant collective dose per unit of electricity. However, due to its limited use, geothermal contributes less to global radiation exposure than other technologies, such as coal.

9.1 Environmental impact

Overview

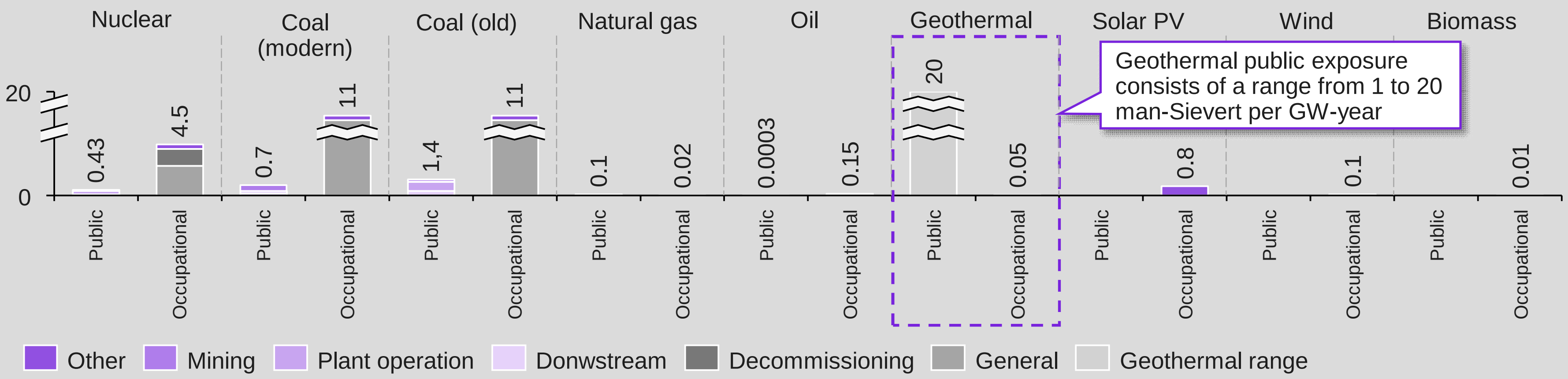
- The human environment is characterized by radioactive exposure and **natural sources account for up to 85% of the annual human radiation dose**, with medical sources contributing most of the remainder.
- The worldwide average human dose is **2.4 mSv per year**, but some regions' natural background is more than 10 times this value. High doses and high dose rates of ionizing radiation are well-known to cause detrimental health effects hence the safe limits.
- Science-based conservative approach stipulates a **maximum dose limit of 20 mSv per year for nuclear workers, and 1 mSv per year for the general public.**

Non-nuclear technologies

- Exposition to radionuclides is not exclusive to nuclear power-related activities.
- **Resource extraction** in general is a source of exposition for workers due to the natural presence of radionuclides in ores.
- Example: **coal** power plants are a source of radionuclides exposure because of direct combustion and coal ash deposits.
- Similarly, **geothermal energy** also generates exposure during its operation and logs **highest exposure rate** when calculated per unit of electricity generated (shown below).

Public and occupational exposures from electricity generation

Normalized to electricity generated in man-Sievert/GW-year (8,760 GWh)



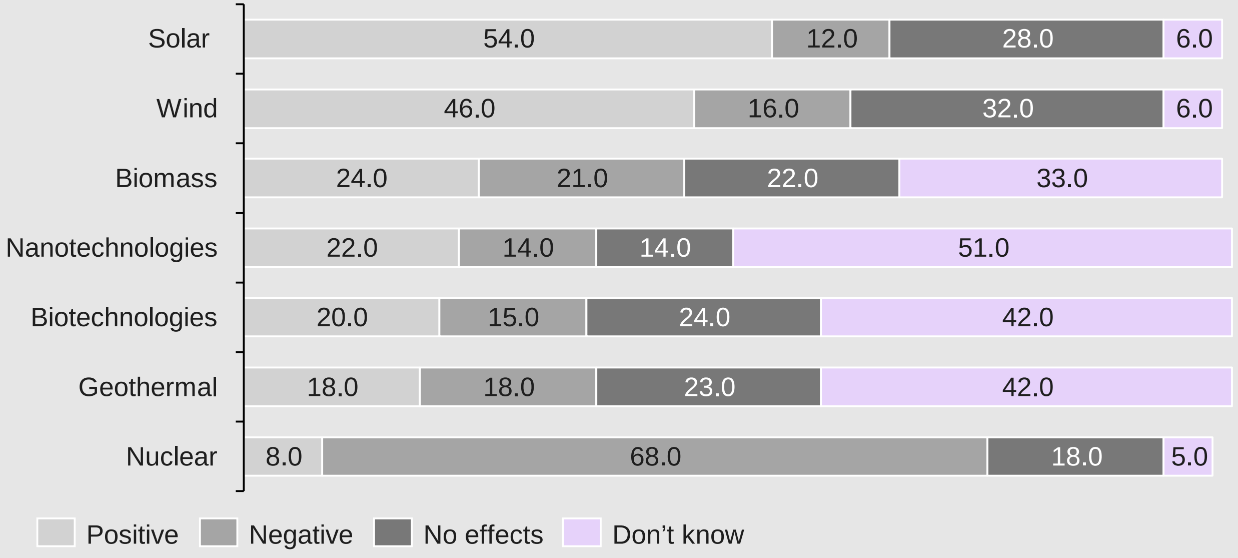
Note: In SI (International System of Units), sievert (Sv) is a unit intended to represent the stochastic health risk of ionizing radiation. 1 millisievert (mSv) is the dose produced by exposure to 1 milligray (mG) of radiation. The collective dose, expressed in man-sieverts, gives a measure of the extent to which a group of people or a population has been exposed. It is equal to the sum of the individual doses.
Sources: UNECE, 2022, Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity; Kearney Energy Transition Institute analysis

Public’s awareness and optimism of geothermal is generally much less than that for solar

Non-exhaustive

Low awareness and acceptance of geothermal energy often poses a barrier toward its development.

Optimism about technologies in Italy (%)



Acceptance of renewable technologies: as per a social acceptance survey conducted in Italy, solar and wind energy technologies are more socially accepted than geothermal, despite Italy having the first operating geothermal plant in the world (Larderello, operating since 1911, in Southern Tuscany, Italy).

Examples of projects impacted by community protests

Padarincang, Indonesia

– **2024**, local communities successfully protested and halted the development of a geothermal project due to concerns over environmental risks and damages to their traditional livelihoods.

Meiningen, Germany

– **2014**, plans for an explorative drilling for a Deep Geothermal project were made public in January 2013 and led to massive and swift protests due environmental concerns.
– Neither the power plant nor the explorative drilling materialized. In May **2014** the city council, after supporting the project, gave in to popular pressure and voted with a majority to abandon the project.

9.2 Social acceptance

Sources: NREL, 2019, GeoVision Analysis: An Analysis of Non-Technical Barriers to Geothermal Deployment and Potential Improvement Scenarios; Kearney Energy Transition Institute analysis based on desktop research

Many factors influence social acceptance, and they should be addressed to realize geothermal energy's potential

Non-exhaustive

Technology spill-over effect negatively affects perception. For example, shale gas and other subsurface technologies' previous experience and unfavorable coverage can heighten concerns around seismicity and ground-water pollution.

Information and communication gaps

- Lack of trust in decision-makers, especially, for a technology that is less known and perceived as immature or evolving.
- Lack of opportunities for participation and consultation in planning and permitting process.
- Local profits and income gains not communicated or understood. Communities may see geothermal as a potential threat to local industries, such as farming or fishing due to water-related risks.

Seismicity

- Induced seismicity is a major concern for communities and is often considered a critical risk for geothermal projects, especially in the development of EGS technology.
- Geothermal hydraulic stimulation caused a magnitude 5.5 earthquake in November 2017 near the EGS demonstration project site in Pohang, Republic of Korea.
- Few EGS projects in Europe, such as those in Basel (Switzerland) and Landau (Germany), have also experienced induced seismicity.
- Better resource assessment decreases the chances of seismicity.

Groundwater pollution and consumption

- Concerns about groundwater contamination from geothermal installation and operation. Drilling can lead to leaks into surrounding aquifers.
- Soil and surface contamination can affect agriculture
- Potential depletion of local water reserves, diverting water from agricultural, domestic, and industrial uses.

Atmospheric pollution

- Potential release of CO_2, hydrogen sulfide, ammonia, methane, and boron in open-loop systems, risking acid rain and damage to crops, forests, and soils.
- For example, geothermal power plants in Türkiye's Buyuk Menderes and Gediz grabens emit high levels of CO_2, ranging from 400 to 1,300 gCO_2/kWh, due to the region's extensional tectonics, graben formations, crustal thinning, and carbonate sedimentary and metamorphic rocks like limestone and marble.

Sources: Renoth et al., 2023, Social acceptance of geothermal technology on a global view: a systematic review; Fridriksson, T. et al., 2017, Greenhouse Gas Emissions from Geothermal Power Production, The World Bank; Kearney Energy Transition Institute analysis

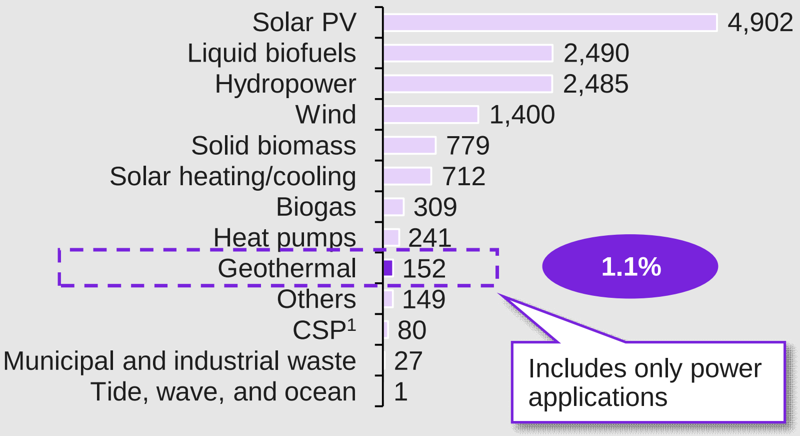
Global geothermal power employment fluctuates with project development but can create more long-term jobs than other electricity-generation technologies

Geothermal energy's current share in global renewables employment is ~1% (2022).

This technology offers alternative jobs to oil and gas drilling and piping roles.

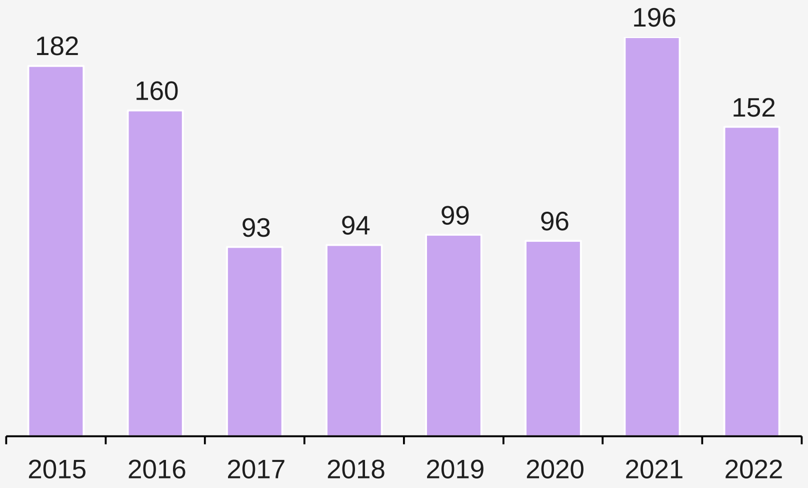
Global renewable energy employment by technology

Total thousand jobs, 2022

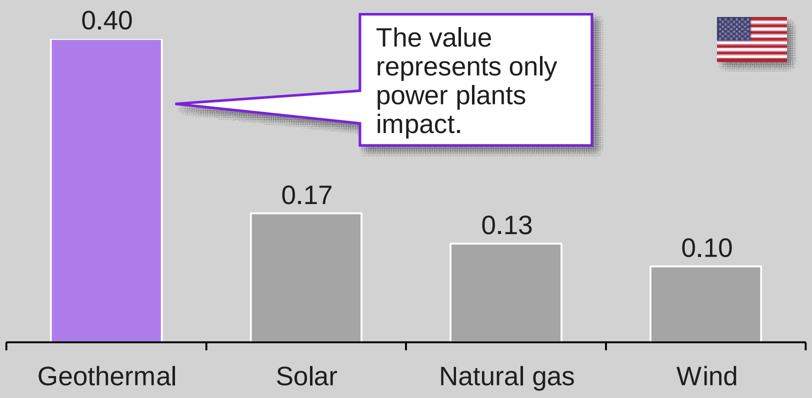


Global geothermal power employment

Total thousand jobs, 2015-2022



Long-term jobs per 1,000 homes powered by technology in California[2]



- At a local level, geothermal power plants can provide **more than double** the long-term jobs per powered household in comparison to other utility-scale power generation technologies including renewables and fossil fuels.
- Long-term geothermal jobs are generally operations O&M[3] positions filled mainly by local workers.
- Hence, wages generated by these jobs are also more likely to be spent locally.

1. Concentrated solar power; 2. Data vary geographically; 3. Operation and maintenance.

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; Kearney Energy Transition Institute analysis

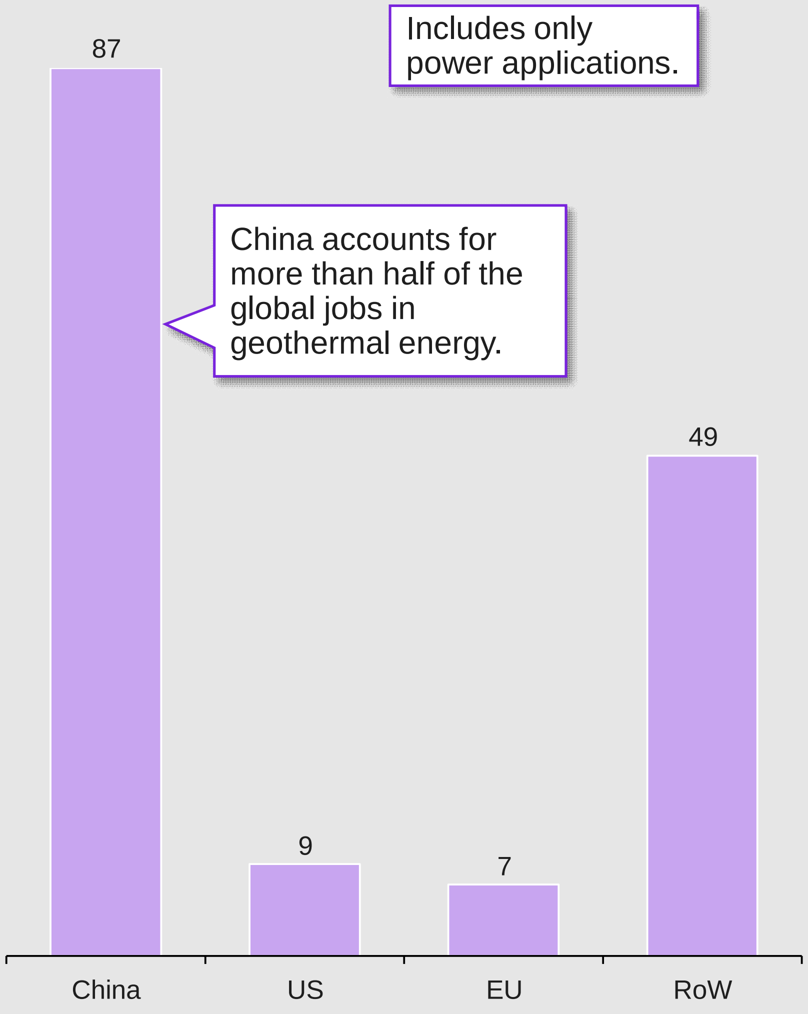
In 2023, global geothermal power development and operations support around 140,000 jobs, rising to 250,000 when including heating and cooling activities

On-site construction and supply chain manufacturing create most jobs but they are short-term in nature and last 1-3 years (i.e., the lifetime of construction).

9.3 Social benefits

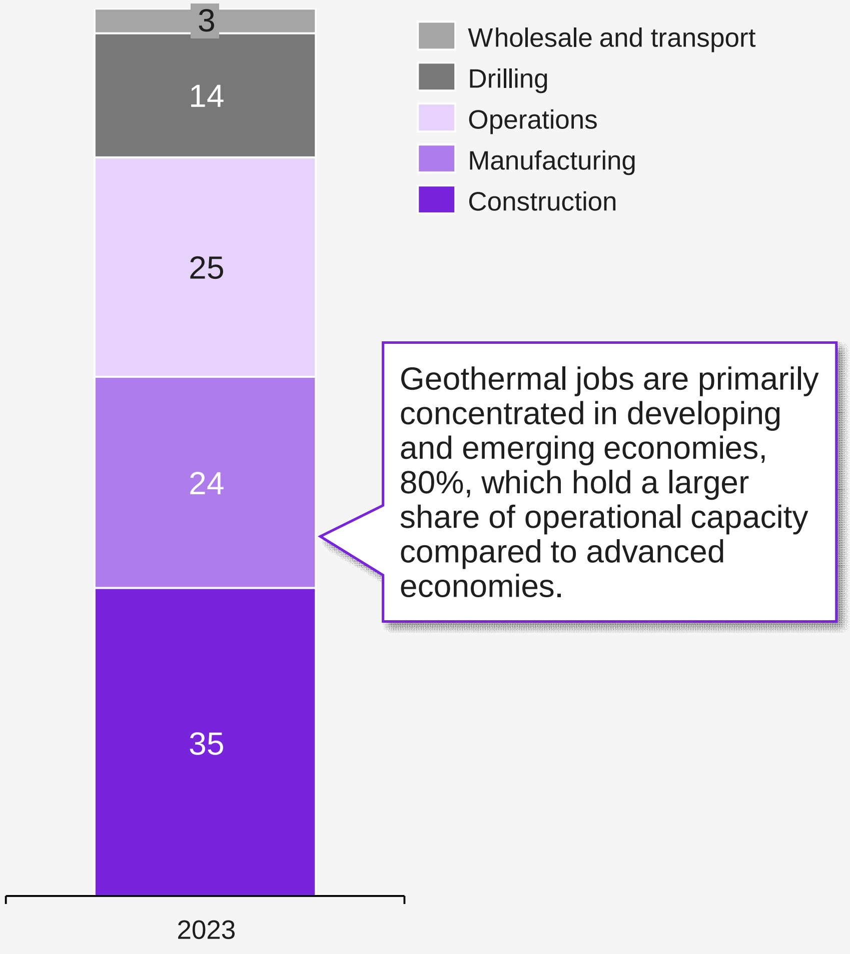
Geothermal energy employment by selected region

Total thousand jobs, 2022



Geothermal-for-power employment by type[1]

%, 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

10. Glossary, bibliography, and appendix

Glossary (1/4)

AGS	Advanced geothermal systems are deep, large, artificial closed-loop circuits in which a working fluid is circulated and heated by subsurface rocks through conductive heat transfer.
Albian sands	Sedimentary deposits from the Albian stage of the Early Cretaceous period (approximately 113 to 100 million years ago), primarily composed of sandstones.
Ambient	Natural condition of the environment at any given time.
Aquifer	Water-bearing stratum of permeable sand, rock, or gravel.
Aquifer thermal energy storage	ATES is an innovative open-loop geothermal technology. It relies on seasonal storage of cold and/or warm groundwater in an aquifer.
Binary-cycle power plant	A geothermal electricity-generating plant using heat from lower-temperature reservoirs. The technology uses the heat of the geothermal fluid (the "primary fluid") to vaporize a “working fluid” with a lower boiling point, which drives a turbine/generator set to generate electricity.
Brine	Subsurface fluids containing appreciable amounts of sodium chloride or other salts.
Cascading heat	A process that uses a stream of geothermal hot water or steam to perform successive tasks requiring lower and lower temperatures.
Closed-loop	A closed-loop geothermal drainage system is a type of drainage where a working fluid circulates within a closed loop of pipes buried deep underground. This fluid absorbs heat from the Earth’s hot rock reservoir without directly contacting the rock.
Combined cycle	In the combined cycle the direct flash cycle constitutes the "topping cycle" and the binary cycle the "bottoming cycle". With this solution the steam turbine expansion ends at a pressure slightly higher than the atmospheric pressure: the two cycles are then “joined” by the steam condensation process which provides low-temperature input heat for the binary cycle.
Co-production	Creating geothermal energy from oil and gas wells that are still active. Oil and gas wells often encounter hot or warm fluids along with oil and gas, and co-production captures the heat from this hot or warm fluid to generate electricity, which can be used immediately or stored for later use.
Crust	Earth's outer layer of rock. Also called the lithosphere.
Deltaic sandstones	Sedimentary rocks formed from sand deposited in a deltaic environment, where rivers meet a standing body of water (e.g., a sea or lake).
Direct use	Use of geothermal heat without first converting it to electricity, such as for space heating and cooling, food preparation, industrial processes, etc.

Glossary (2/4)

Dogger limestones	The Dogger refers to the Middle Jurassic epoch, approximately 174 to 164 million years ago. Dogger limestones are sedimentary rocks formed during this period.
Drilling	Boring into the Earth to access geothermal resources, usually with oil and gas drilling equipment that has been modified to meet geothermal requirements.
Dry rock	Dry rock, often referred to as hot dry rock (HDR), is a type of geothermal resource found deep underground where the rock formations are hot but contain little to no water. These rocks can reach very high temperatures, making them a potential source of geothermal energy.
Dry steam	Very hot steam that doesn't occur with liquid. Dry steam power plants use hydrothermal fluids that are already mostly steam, which is a relatively rare natural occurrence. Dry steam power plant systems are the oldest type of geothermal power plants.
EGS (engineered geothermal systems)	Human-made underground geothermal reservoirs that extract geothermal energy from the Earth for electricity generation and/or heating applications. EGS reservoirs are created by drilling wells and injecting water to frack the rocks and create permeability.
Fault	A fracture or fracture zone in the Earth's crust along which slippage of adjacent Earth material occurs.
Flash steam	Steam produced when the pressure on a geothermal liquid is reduced. The depressurization of geothermal fluid to transform it into steam is also called “flashing”. Flash steam plants are the most common type of geothermal power plants in operation today.
Fluvial limestones	These sandstones are formed from sediments deposited by ancient river systems. Their composition and structure are influenced by fluvial processes, making them distinct in terms of porosity and permeability.
Fracking	Fracking, sometimes spelled fracing, is a colloquial term for hydraulic fracturing. Fracking is used to create engineered geothermal systems. Hydraulic fracturing is one method of reservoir stimulation. High-pressure fluid is injected into rock to create new fractures and/or increase the size, extent, and connectivity of existing fractures.
Fumarole	A vent or hole in the Earth's surface, usually in a volcanic region, from which steam, gaseous vapors, or hot gases issue.
Geothermal district heating	A type of direct use in which a utility system supplies multiple users with hot water or steam from a geothermal plant or well field through a distribution network.
Geothermal gradient	Geothermal gradient, often referred to as thermal gradient, is the rate of temperature increase in the Earth as a function of depth.
Geothermal heat pumps	Technologies that use the constant temperature of the shallow earth (4.5–21°C) to provide heating and cooling solutions. These systems utilize heat pumps to transfer heat to and from the ground.

Glossary (3/4)

Geyser	A spring that shoots jets of hot water and steam into the air.
Horizontal wells	Horizontal wells are drilled horizontally underground to access geothermal reservoirs. This technique is often used in areas where vertical drilling is not feasible or cost-effective.
Hydrothermal resource	A conventional geothermal resource (underground system of hot water and/or steam) that can be tapped by drilling to provision heat or produce electricity.
Igneous rock	Igneous rock refers to any of various crystalline or glassy rocks formed by the cooling and solidification of molten earth material.
Injection	The process of returning spent geothermal fluids to the subsurface. Sometimes referred to as reinjection.
Lusitanian limestones	These limestones date back to the Lusitanian stage of the Late Jurassic period, around 150 to 145 million years ago. They are characterized by their carbonate composition.
Magma	Molten rock within the Earth, from which igneous rock is formed by cooling.
Mantle	The Earth's inner layer of molten rock, lying beneath the Earth's crust and above the Earth's core of liquid iron and nickel.
Neocomian sands	Originating from the Neocomian, an informal term often referring to the earliest part of the Cretaceous period (approximately 145 to 130 million years ago), these sands are also important aquifers. They are typically found beneath the Albian sands and are composed of similar sedimentary materials.
Open-loop	An open-loop geothermal drainage system is a type of system that uses geothermal fluid to transfer energy. Open loops can be designed to use fluid from a well as a source and sink, a pond or lake as a source and sink, or a well as the source and a pond or lake as the sink.
Metamorphic rock	Metamorphic rock is a class of rock that results from the alteration of preexisting rocks in response to changing environmental conditions, such as variations in temperature, pressure, mechanical stress, or the addition or removal of chemical components. The preexisting rocks may be igneous, sedimentary, or other metamorphic rocks.
Permeability	The capacity of a solid substance (such as rock) to transmit a fluid. The degree of permeability depends on the number, size, and shape of the pores and/or fractures in the rock and their interconnections. It is measured by the time it takes a fluid of standard viscosity to move a given distance. The unit of permeability is the Darcy.

Glossary (4/4)

Plate tectonics	A theory of global-scale dynamics involving the movement of many rigid plates of the Earth's crust, called tectonic plates. Tectonic activity is evident along the margins of the plates where buckling, grinding, faulting, and vulcanism occur as the plates are propelled by the forces of deep-seated mantle convection currents. Geothermal resources are often associated with tectonic activity, since it allows groundwater to come in contact with deep subsurface heat sources.
Porosity	The ratio of the aggregate volume of pore spaces in rock or soil to its total volume, usually stated as a percent.
Rhaetian sandstones	The Rhaetian is the latest stage of the Triassic period, around 208 to 201 million years ago. Rhaetian sandstones are sedimentary rocks formed during this time, characterized by their clastic nature, consisting of sand-sized mineral particles.
Sedimentary rock	Sedimentary rock is a rock formed at or near Earth's surface by the accumulation and lithification of sediment (detrital rock) or by precipitation from solution at normal surface temperatures (chemical rock).
Supercritical conditions	Supercritical conditions are characterized by very high temperatures and a natural reservoir containing fluid in the supercritical state. For pure water, this means a temperature of at least 374°C and a pressure of at least 221 bar. Such supercritical fluids can be found deep in volcanic hydrothermal systems such as Iceland, Japan, Kenya, Mexico, and New Zealand.
Thermal energy storage	Thermal energy storage means heating or cooling a medium to use the energy when needed later.
UTES	Underground thermal energy storage is the seasonal storage of heat and/or cold into a portion of the underground that is generally performed using a shallow geothermal system.
Vertical wells	Vertical wells are drilled straight down into the Earth’s crust to access hot water or steam reservoirs. These wells are typically used in areas where the geothermal resource is located directly beneath the surface of interest.
Well	A conduit for fluids and information into/out of the thermal reservoir. Geothermal wells include production well and reinjection well. Production well transmits heat-containing fluids up from a hydrothermal reservoir to Earth’s surface. Reinjection well is used to reinject heat-depleted fluid and dissolved minerals back into the hydrothermal reservoir after thermal energy has been extracted in the power plant.
Wet rock	Rocks where the natural geothermal heat of the Earth has been trapped deep underground in the water of permeable rocks (aquifers) capped by impermeable rocks above. The heat can be extracted by pumping out the water.
Working fluid	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.

Acronyms (1/2)

AGS	Advanced geothermal system
5GDHC	Fifth-generation district heating and cooling
ATES	Aquifer thermal energy storage
CAGR	Cumulative annual growth rate
CCS	Carbon capture and storage
CCUS	Carbon capture utilization and storage
CF	Capacity factor
CFD	Contracts for difference
CHP	Combined heat and power
CO2	Carbon dioxide
CSP	Concentrated solar power
DHC	District heating and cooling
DSO	Distribution system operator
EGS	Enhanced geothermal system
EJ	Exajoule
EPC	Engineering, procurement and construction
ESCOs	Energy service companies
EU	European Union
EUR	Euro
FC	Flash cycle
FID	Final investment decisions
FIT	Feed-in tariff
FOAK	First-of-a-kind
gCO_2	Grams of carbon dioxide
GDH	Geothermal district heating
GDU	Geothermal direct-use
GHP	Geothermal heat pump
GWh	Gigawatt-hour
GW_{th}	Gigawatt thermal
H2	Hydrogen
HPA	Heat purchase agreement
HT	High temperature
HTS	High temperature steam
km	Kilometer
kW	Kilowatt
kW_e	Kilowatt electricity
kW_{th}	Kilowatt thermal
kWh	Kilowatt-hour
l	Liter
LCA	Life-cycle assessment
LCOE	Levelized cost of electricity
LCOH	Levelized cost of heat

10.1 Acronyms

Acronyms (2/2)

mg	Micrograms
MTES	Mine thermal energy storage
MW	Megawatt
MW_e	Megawatt electricity
MW_{th}	Megawatt thermal
MWh	Megawatt-hour
NF	Near-hydrothermal field
NG	Natural gas
NZE	Net-zero emissions
O&M	Operations and maintenance
ºC	Celsius degrees
OEMs	Original equipment manufacturers
ORC	Organic Rankine cycle
PBP	Payback period
PPA	Power purchase agreement
PPPs	Public-private partnerships
PV	Photovoltaic
PWh	Petawatt-hour
RC	Rankine cycle
ROI	Return on investment
RoW	Rest of world
TES	Thermal energy storage
TSO	Transmission system operator
TWh	Terawatt-hour
USA	United States of America
US gal	US gallon
USD	US dollar
UTES	Underground thermal energy storage

Photo credits

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Appendix of Section 2: Geothermal energy systems and technologies

Reservoir settings depend on the naturally or artificially occurring conditions of rock porosity and permeability

Natural porosity and permeability

Natural porosity refers to the void spaces created in the rock matrix by intergranular spaces and by the fault and fracture networks occurring in a geological formation. It is expressed in percentage (volume of pores / total volume of rock)

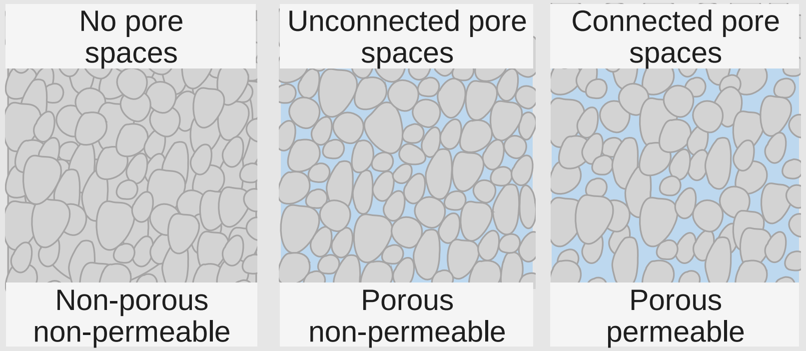
Permeability quantifies the ability of a fluid to circulate through the rock formation. It is expressed in millidarcies (mD) or m²

Rock porous media

The porous media porosity is directly related to the **size and shape of the grains and** corresponds to the number of empty spaces in a soil or rock.

Fault and fracture networks

Rock formations may have **naturally occurring faults and fractures** which contribute to the porosity of the rock (volume of void spaces generated) while also enhancing its permeability.



Artificial porosity and permeability

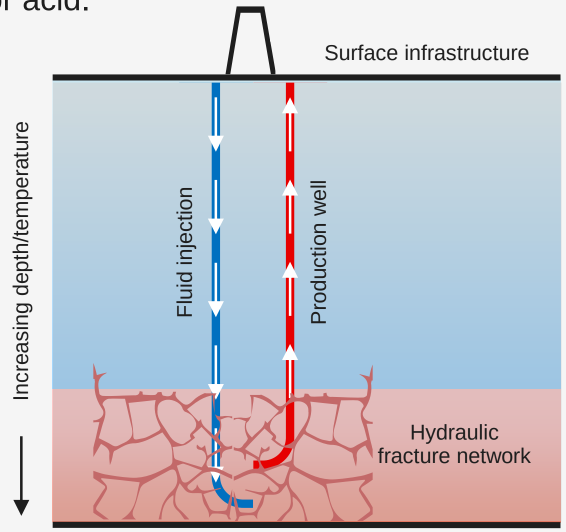
Porosity and permeability of the rock can be **artificially modified** through different stimulation techniques[1], although for geothermal, hydraulic fracking is the most used.

Hydraulic fracking

Mechanical process of **injecting water, sand,** and/or chemicals in wells at high pressure to **create fractures in the bedrock** to increase permeability and porosity.

Other methods

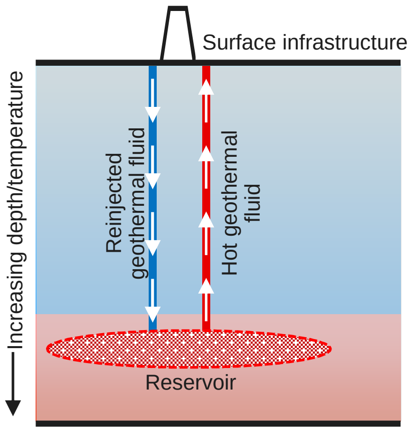
Other methods include acidizing, thermal stimulation, or fracturing with nitrogen, proppant or acid.



1. Stimulation techniques correspond to well interventions used in low-permeable rocks to increase production by cleaning the rock formation or extending the tunnels and fractures, usually used in oil or gas wells.
Sources: USGS, 2019, Hydraulic Fracturing: Resources Victoria, accessed October 2024, Understanding porosity and permeability; Kearney Energy Transition Institute analysis.

Exploitation systems

Conventional power generation: FactCard



Key data

Lower/shallower — Higher/deeper

Global installed capacity	16,290	MW_e
Average plant capacity	5.5-48	MW_e
Resource temperature	100-374	°C
Resource depth	<3.5	km
Lifetime	~25	years
Upfront investment	1,500-6,000	USD/kW_e
LCOE[1]	0.05-0.09	USD/kWh
CF	10-85	%
Geothermal resource	Geothermal fluids (water, brine, steam)	
Primary heat mechanism	Convection	

Electricity generation

Return to main-deck slide

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Description

– **Conventional geothermal** exploitation systems correspond to those that have **naturally occurring geologic conditions** (e.g., heat, permeability, fractures and fluid). These systems **do not require man-made intervention** and drilling to reach and harness the reservoirs and they have been exploited for decades.

– The **heat transfer** of conventional systems **is mostly ensured by geothermal fluid convection**, which corresponds to fluid circulation where cold fluids descend, and the resulting warm fluids ascend to the surface.

– The geothermal fluids can be in the form of **water or steam**, and their composition varies depending on the geologic formation (e.g., fresh ground water, seawater or brines with different compositions, usually rich in sodium, potassium, calcium, sulfates, and others).

– These conventional systems have a **heated fluid reservoir** which **can be depleted** if the fluid is not reinjected into the reservoir. Depending on the geothermal energy surface technology, the hear content can also be depleted over time (e.g., binary-cycle plants).

– To harness conventional resources, the exploitation system can use **open loop** by extracting the geothermal fluid from the reservoir **or closed loops** to circulate a working fluid through the geothermal reservoir.

– **Limitations** of these systems are related to **site occurrence and reservoir temperature**.

Technology R&D and focus areas for innovation

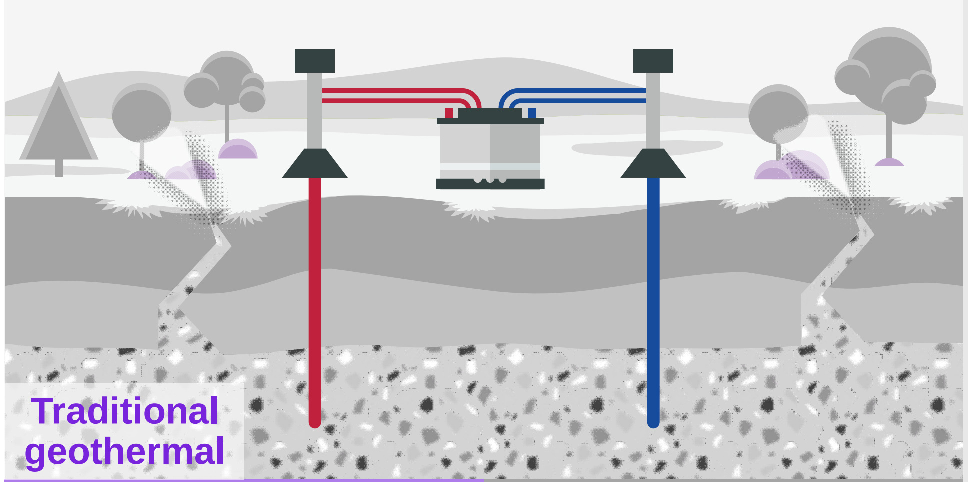
– Mostly focused on **improved exploration techniques to identify and characterize geothermal reservoirs in a more accurate way.**

– **Improved system longevity** and **reduced maintenance** by evaluating new materials and chemical treatments **to limit corrosion and scaling** in geothermal wells and equipment.

– Implementing **digital solutions** to improve operational optimization, plant performance, pipeline conditions monitoring, among others.

1. LCOE varies depending on the surface technology, please refer to the specific FactCard for further information.
Sources: Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; Kearney Energy Transition Institute analysis based on desktop research.

Conventional geothermal electricity generation requires the presence of heat, water, and permeability



Pros	Cons
– Geothermal power is continuous and is not affected by seasonal or weather changes, unlike other renewables. – Conventional geothermal power is an established, renewable power that is competitive with other electricity generation technologies.	– Conventional technologies are limited to specific geographies where suitable reservoirs are available. – If geothermal fluid is not reinjected into the reservoir, the geothermal resource can be depleted over time.

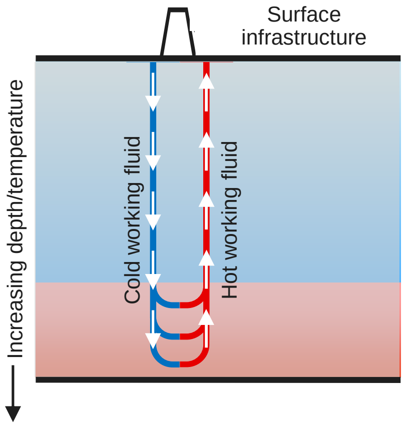
Overview and working principle

- Conventional geothermal electricity generation requires **hydrothermal** reservoirs, characterized by **heat, fluid, and permeability**. Conventional geothermal power technologies were first used in 1904 in Larderello, Italy.
- While the easiest-to-access resources are near the surface, conventional geothermal electricity generation can include deeper wells but typically **shallower than 3.5 km**.
- Conventional power generation is typically near tectonic plate boundaries with volcanic intrusive heat as geothermal electricity generation requires **at least 100°C.**
- Conventional plants can either use geothermal resources directly or indirectly to generate electricity. **Dry steam** and **flash steam** technology use the geothermal resource directly. **Binary cycles** use the geothermal resource indirectly by passing heat from the resource to another working fluid via a heat exchanger. **Combined-cycle** technology combines a direct cycle with an indirect cycle.
- **Wellhead generators** are small-scale geothermal electricity generators which use either direct or indirect methods. They are used strategically, such as to begin electricity generation at a single well before a central power plant is constructed.
- **Investment costs** vary significantly between projects but typically fall between **1,500-6,000 USD/kW**. The global weighted average LCOE[1] in 2022 was **0.056 USD/kWh**.
- Lifetime cost estimates typically assume a **25-year lifetime** for conventional plants. However, in practice, geothermal power plants often operate for much longer.

1. Levelized cost of electricity.

Sources: IRENA, 2017, Geothermal Power Technology Brief; IRENA, 2023, Global Geothermal Market and Technology Assessment; IRENA, 2023, Renewable Power Generation Costs in 2022; Nardini, I., 2022, Geothermal power generation, The Palgrave Handbook of International Energy Economics; Kearney Energy Transition Institute analysis.

Advanced geothermal systems (AGS): FactCard



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity	< 5	MW_e	◔
Average plant capacity	1-10	MW_e	○
Resource temperature[2]	100-250	°C	◔
Resource depth	0.30-5.5	km	◑
Lifetime[3]	~30	years	◕
Upfront investment[4]	2,300-14,500	USD/kW_e	◕
LCOE	0.13-0.32	USD/kWh	◕
CF	Unknown	%	-
Geothermal resource	Hot reservoir or hot dry rocks		
Primary heat mechanism	Conduction		

Electricity generation

Heating

Return to main-deck slide

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Description

– AGS[1] uses **closed loops** to circulate working fluid through a geothermal reservoir, it does not use stimulation. As a result, the seismicity risk is lower, although there is a risk of induced microearthquake as the host rock cools down. Pre-existing reservoir fluid or permeability are not required, making it **applicable in many geographies**.

– The injection and production well can be co-axial (single well) or form a U-loop (two wells) system. The working fluid can be water, an organic fluid, or supercritical CO_2.

– Challenges include subsurface drilling and finishing conditions, high drilling costs, limited surface area for heat transfer, and low thermal output at shallow depths.

– AGS technology is still at the early stages of development and commercialization. **Eavor Technologies** demonstrated an AGS system in Alberta, Canada (**Eavor-Lite**) in 2019, drilling to 2.4 km. A second demonstration project in New Mexico (**Eavor-Deep**) in 2023 drilled to ~5.5 km, reaching 250°C. **GreenFire Energy** demonstrated its **GreenLoop System** in 2019 in California with in an idle well at 330 m, generating 1-1.2 MW_e with a double flash cycle. **Chevron New Energies** and **Mitsui Oil Exploration Co.** agreed to pilot an ACL system in 2023 in Japan.

Technology R&D and focus areas for innovation

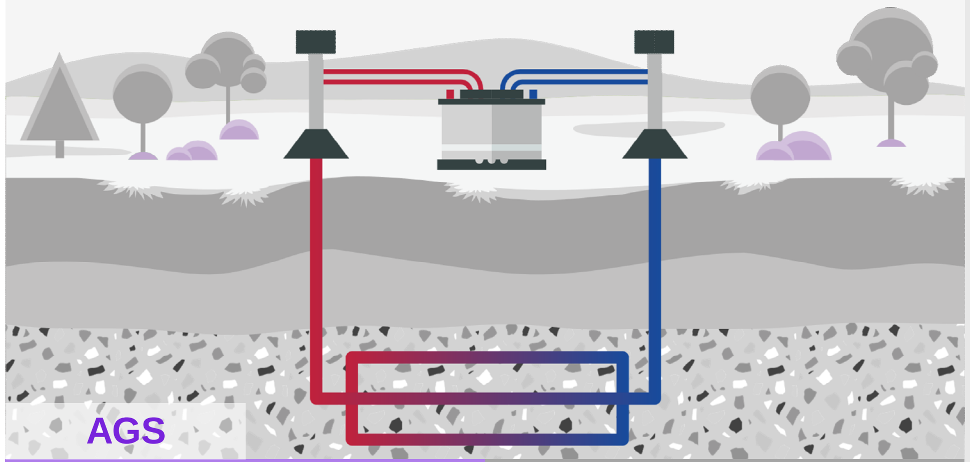
– Key areas of innovation: **reducing drilling cost, increasing drilling speed, increasing heat transfer rates, and overall technology demonstration**.

– **Eavor-Loop** –The technology is being adopted for a commercial project in Germany targeting a 4.5 km depth, with a capacity of 8.2 MW_e and 64 MW_{th}. The Eavor-Loop features two vertical wells which spread into a series of lateral wells at depth, creating a radiator design that maximizes surface contact with the hot rocks.

– **GreenLoop** - GreenFire has developed a co-axial down bore heat exchanger (DBHX) technology that can be adapted to non-productive conventional geothermal wells, old oil and gas wells, or new wells; a variety of working fluids; temperatures 70-250°C; and direct or indirect electricity generation of 2-9 MW_e.

1. Advanced geothermal systems; 2. Based on maximum temperature encountered by Eavor Deep demonstration project in New Mexico drilled to 5,480 m in 2022-2023; 3. Estimates for a sample Eavor-Loop design with 7.5 km depth, bottom-hole temperatures of 235°C and 460°C, and a 30-year lifetime. 4. Lower estimate based on GreenFire demonstration at an existing well at The Geysers, funded by USD 2.7 million grant, assuming 1.2 MWe capacity. Upper estimate based on scaling Eavor Loop to 200 MW at a cost of USD 2.9 billion.
Sources: Beckers, K. F. and Johnston, H. E., 2022, Techno-Economic Performance of Eavor-Loop 2.0; Brown, S. et. al., 2024, Accelerating geothermal development in Kenya with GreenFire's GreenLoop® technology; European Commission Joint Research Centre, 2023, Deep geothermal heat and power in the European Union; IRENA, 2023, Global Geothermal Market and Technology Assessment; Kearney Energy Transition Institute analysis based on desktop research.

AGS technologies expand access to new geothermal resources without introducing or extracting fluids from the earth



Pros	Cons
– AGS expand potential access to geothermal resources in a wide range of geographies. – AGS present lower risk of induced seismicity. – Deeper drilling allows access to hotter and more powerful geothermal resources.	– AGS technology has not been demonstrated for scale-up. – AGS are expensive, presenting high development costs.

Overview and working principle

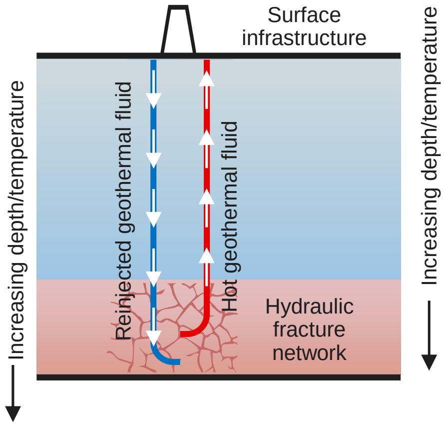
- **AGS is characterized as an emerging geothermal power technology.** Emerging geothermal power technologies refer to a category of next-generation geothermal technologies that increase the possible geographies and power capacities of geothermal projects.
- While these technologies are primarily intended to be used for **electricity generation** due to the high drilling costs, delivering high-temperature heat is also a possible use case.
- The various technologies have overlapping innovations, such as advanced well-monitoring and drilling technology to drill faster and deeper.
- **Advanced geothermal systems** (AGS), also known as **advanced closed loop** (ACL) geothermal, refers to the use of a closed-loop system which pumps working fluid into drilled wells. Heat exchange occurs underground without direct contact between the earth and the working fluid.

Electricity generation

Heating

Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; Kearney Energy Transition Institute analysis.

Enhanced/engineered geothermal system (EGS): FactCard



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity[2]	< 10	MW_e	◔
Average plant capacity[3]	< 400	MW_e	◕
Resource temperature	150-400	°C	◑
Resource depth	2-7	km	◑
Lifetime	20-30	years	◑
Upfront investment[4]	8,000-19,500	USD/kW_e	●
LCOE[5]	0.13-0.32	USD/kWh	◕
CF	80	%	●
Geothermal resource	Hot dry rocks or unproductive conventional wells		
Primary heat mechanism	Convection		

Electricity generation

Heating

Return to main-deck slide

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Description

– EGS[1] is a technology that uses engineering to extract heat from unconventional geothermal resources or increase productivity of dried conventional wells.

– **Fluid is injected** into the rocks, and **stimulation** is used to increase permeability, opening cracks by hydraulic, thermal, or chemical means. The heated fluid is extracted through production wells for electricity generation. EGS can either have a multi-well or single-well, co-axial setup.

– Challenges include a **risk of inducing seismicity,** technical issues drilling in impermeable rock, connectivity between injection and production wells, drilling costs, and energy requirements for injecting and pumping water.

– Most EGS projects are found in Australia, Europe, Japan, the Philippines, and the United States. Early commercial projects have been started by **Fervo Energy** and **Sage Geosystems**. The technology of Fervo Energy and Sage Geosystems is also applicable to high-temperature thermal energy storage.

Technology R&D and focus areas for innovation

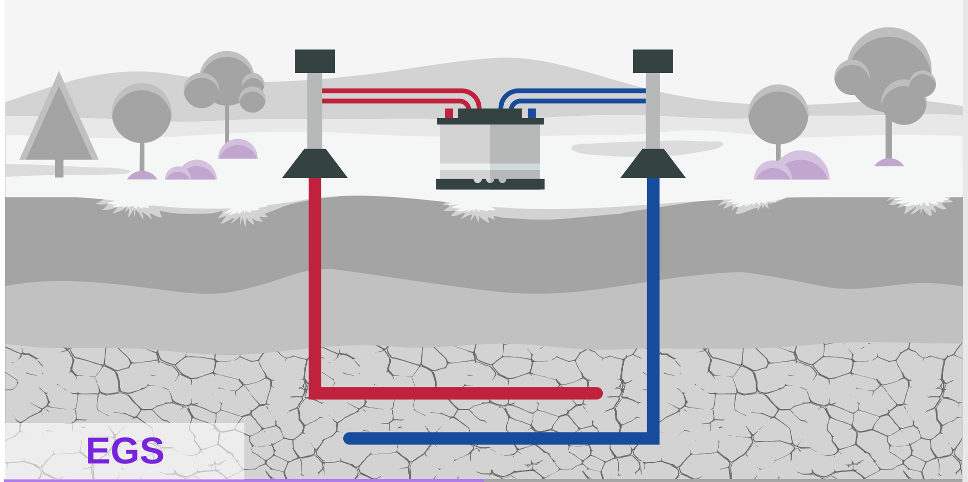
– The US DOE **Enhanced Geothermal Shot** identified key technologies that are needed for EGS to succeed: **subsurface sensing, mapping, and prediction technologies; drilling technology, well design and building, and fluid flow control and stimulation methods**.

– The **Japan Organization of Metals and Energy Security** began a project in 2021 that tests EGS technologies with **supercritical CO_2** as the stimulation and injection fluid. Phase 2 of the project (2025-2035) will demonstrate the technology in field.

– **Fervo Energy** began developing a 400 MW EGS facility in Utah in 2023. The design is based on Fervo's developed EGS well technology that uses **directional drilling**, drilling in multiple directions from the same well, to maximize well productivity.

1. Enhanced or engineered geothermal system; 2. Excluding conventional geothermal plants retrofitted with EGS; 3. Based on Fervo's planned 400 MW Cape Station project, set for full operation in 2028; 4. Wide range for EGS investments costs. NREL's Annual Technology Baseline estimated ~8,000 USD/kW for near-hydrothermal field flash steam EGS to ~19,500 USD/kW for deep-field binary cycle EGS in 2024; 5. Wide range for LCOE given EGS is an emerging technology. Current estimates focus on the US where commercial-scale pilot testing is concentrated. NREL projections range from ~0.067 USD/kWh for near-field EGS flash plant in 2024 with a 30-year cost recovery period and investment tax credits (ITC) to ~0.25 USD/kWh for deep EGS binary plant in 2024 with a 20-year cost recovery period and no ITC. US DOE Pathways to Commercial Liftoff projects 0.045-0.145 USD/kWh by 2035.
Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; NREL, 2024 Electricity ATB Technologies, Annual Technology Baseline; US Department of Energy, 2024, Pathways to Commercial Liftoff: Next-Generation Geothermal Power; US DOE Geothermal Technologies Office, 2023, The Enhanced Geothermal Shot™ Summit Recap; Yasukawa, K., 2024, 2023 Japan Country Report, IEA Geothermal; Kearney Energy Transition Institute analysis.

EGS technologies allow less-permeable geographies to be used for geothermal power



Pros	Cons
– EGS expand potential access to geothermal resources in a wide range of geographies. – EGS allows less-permeable geographies to be used for geothermal power. – Deeper drilling allows access to hotter and more powerful geothermal resources.	– EGS require engineering intervention, which may cause undesirable side effects, such as seismicity. – EGS technology has not been demonstrated for scale-up. – EGS are expensive, presenting high development costs. – Risk of short-circuiting and water circulation loss which diminishes system performance

Overview and working principle

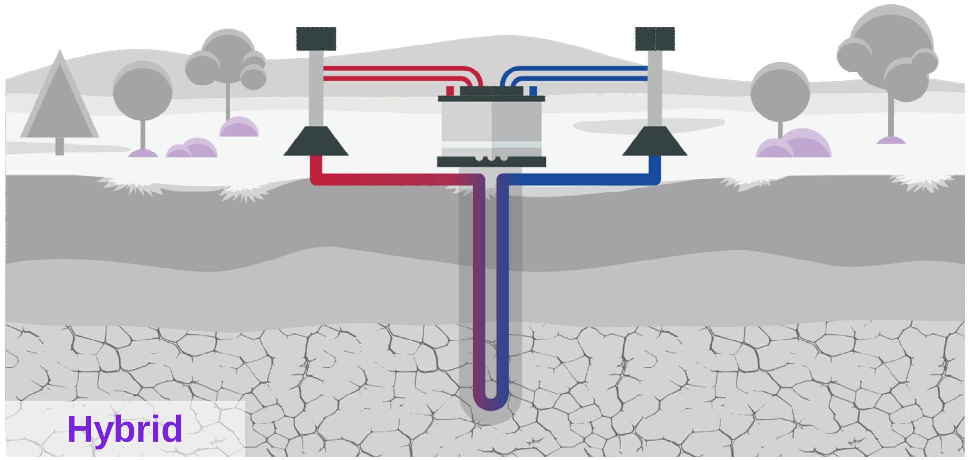
- **EGS is characterized as an emerging geothermal power technology.** Emerging geothermal power technologies refers to a category of next-generation geothermal technologies that increase the possible geographies and power capacities of geothermal projects.
- While these technologies are primarily intended to be used for **electricity generation** due to the high drilling costs, delivering high-temperature heat is also a possible use case.
- The various technologies have overlapping innovations, such as advanced well-monitoring and drilling technology to drill faster and deeper.
- **Enhanced** or **engineered geothermal systems** (EGS) utilize an open loop system to extract energy from **hot dry rocks** (HDR) that lack permeability or a fluid, making them unsuitable for conventional geothermal.

Electricity generation

Heating

Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; McLean, M. and Espinoza, N., 2022, Thermal destressing: Implications for short-circuiting in enhanced geothermal systems; Kearney Energy Transition Institute analysis.

Hybrid systems (AGS/EGS): FactCard



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity	0	MW_e	○
Average plant capacity	50[3]	MW_e	◑
Resource temperature	100-250	°C	◑
Resource depth	3-6	km	◑
Lifetime	20-30[4]	years	◑
Upfront investment	Unknown	USD/kW_e	○
LCOE	Unknown	USD/kWh	–
CF	Unknown	%	–
Geothermal resource	Hot dry rocks and areas with low natural permeability		
Primary heat mechanism	Convection and conduction		

Electricity generation

Heating

Return to main-deck slide

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Description

- **Hybrid AGS[1] and EGS[2] combine elements of both technologies to optimize geothermal energy extraction and retrofit preexisting boreholes.**
- **Hybrid systems leverage the closed-loop design of AGS with the enhanced permeability techniques of EGS** to maximize efficiency, through increased heat transfer, and applicability across various geological settings. Such hybrid systems work **by injecting water under high pressure**, the **water "inflates" the fractures,** the water is locked in the well through a valve and then restored at the optimum time (most need, best market signal). During **production, the water flows back with higher temperatures and pressure** to produce electricity (heat can also be recovered).

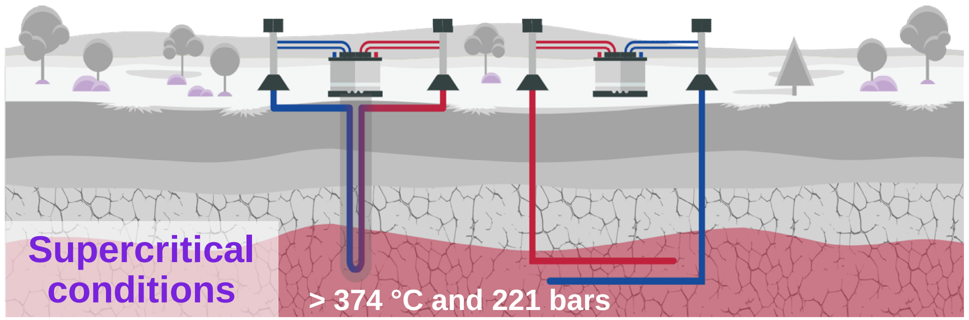
Technology R&D and focus areas for innovation

Research and development for hybrid AGS and EGS systems focus on several key areas:

- **Drilling technologies:** improving drilling efficiency and reducing costs through advanced materials and techniques.
- **Reservoir stimulation:** developing methods to enhance permeability and fluid flow in geothermal reservoirs.
- **Heat transfer fluids:** innovating with new working fluids like supercritical CO_2 to improve heat transfer efficiency.
- **Monitoring and modeling:** utilizing advanced sensors and modeling tools to optimize reservoir management and predict performance.
- **Integration with other technologies:** exploring synergies with solar power and energy storage systems to enhance overall energy output and reliability.
- **Sage Geosystems** has designed an 18-20 well platform called **HeatCycle**. The overall system is estimated to be able to produce up to 50 MW_e as it undergoes injection and production cycles.

1. Advanced geothermal systems; 2. Enhanced or engineered geothermal systems; 3. Value based on a single value from Sage Ecosystems' HeatRoot fracture, combined with Sage Ecosystems' HeatCycle well design; 4. Considered similar to AGS and EGS
Sources: Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; Livescu, S. et al., 2023, Geothermal and Electricity Production: Scalable Geothermal Concepts, The University of Texas at Austin; AlphaSense, 2024, 9th Annual Sustainability & Energy Transition Primer – Ahead Of Curve; Kearney Energy Transition Institute analysis based on desktop research.

Supercritical conditions: FactCard



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity	0	MW_e	○
Average plant capacity	0	MW_e	-
Resource temperature	> 374	°C	●
Resource depth	0.30-20	km	●
Lifetime	Unknown	years	-
Upfront investment	Unknown	USD/kW_e	-
LCOE	Unknown	USD/kWh	-
CF	Unknown	%	-
Geothermal resource	Supercritical geothermal reservoirs		
Primary heat mechanism	Convection and conduction		

Electricity generation

Return to main-deck slide

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Description

– Supercritical systems are characterized by **temperatures exceeding 374°C and pressures exceeding 221 bar**[1]**,** at which point water is in a supercritical state. Such conditions are typically found at depths near the brittle-ductile transition zone but can be found shallower at the roots of volcanic areas. **EGS**[2] **technology** has been used in attempts to drill to supercritical geothermal resources.

– The use of supercritical geothermal resources **could significantly improve power output and economic feasibility** of geothermal projects, offering **several times more power per unit fluid volume as conventional geothermal**. The enthalpy may be high enough to **repurpose old fossil fuel power plants**.

– Supercritical conditions have been encountered during drilling in the United States, Japan, Italy, Iceland, Mexico, and Kenya. However, this led to significant challenges, such as **low permeability, magma intrusion, and aggressive corrosion,** hindering drilling and well completion. These technical challenges need to be overcome before supercritical systems can be used to generate electricity.

– Ongoing research projects, the Iceland Deep Drilling Project, DESCRAMBLE in Italy, the Geothermal: Next Generation initiative in New Zealand, and a project by Japan's New Energy and Industrial Technology Development Organization, are exploring the use of supercritical geothermal resources.

Technology R&D and focus areas for innovation

– Exploration and resource assessment, including laboratory experiments and numerical simulation methods. In-field testing to gain knowledge and test geological conditions.

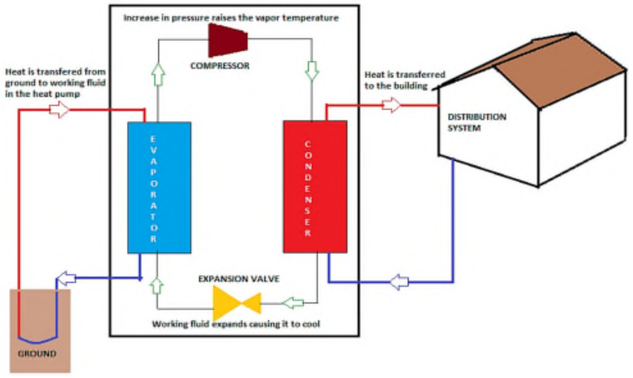
– Adapted drilling, well completion, and monitoring to cope with extreme conditions.

– **Next-generation drilling technologies**, using gyrotrons to generate **millimeter waves**, could drill deep enough to access supercritical geothermal resources without geographic constraint to volcanic areas. **AltaRock** and **Quaise Energy** are among the companies developing this technology, with Quaise set to begin field demonstrations in 2024.

1. Temperature and pressure values for supercritical conditions of pure water; 2. Enhanced or engineered geothermal systems.
Sources: Clynes, T., 2024, Fusion Tech Finds Geothermal Energy Application: MIT spinoff eyes microwave drills as route to robust geothermal rewards, IEEE Spectrum; IRENA, 2023, Global Geothermal Market and Technology Assessment; Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; Reinsch, T. et. al., 2017, Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities, Geothermal Energy; Kearney Energy Transition Institute analysis.

Geothermal energy surface technologies

Geothermal heat pump (GHP): FactCard (1/2)



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity[1]	77,500	MW_{th}	●
Average plant capacity	0.003-10	MW_{th}	○
Resource temperature	4.5-21	°C	○
Resource depth	0.001-2	km	○
Lifetime	20-50	years	◕
Upfront investment[2]	1,200-7,400	USD/kW_{th}	◔
LCOH	0.03-0.11	USD/kWh	○
COP[3]	3-6	-	-
CF[4]	25	%	◔
Geothermal resource	Subsurface		

Heat provision

Return to main-deck slide

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Description

- Geothermal heat pumps (GHP), also known as **ground-source heat pumps** (GSHP), move heat from the ground and into buildings to provide **heating**. They can also run in reverse in hot weather, moving heat from buildings into the ground to provide **cooling**.
- Although they are more expensive than air-source heat pumps, GHP are better suited to provide heating in cold climates, as the earth temperature remains relatively stable year-round, allowing GHP to be more efficient. GHP are expensive for single homes, especially existing ones.
- In **closed loop systems**, a working fluid circulates in a ground loop and does not contact the earth as it absorbs heat. Closed-loop systems are distinguished by the layout of their ground loop.
  - Examples of closed loop systems are **horizontal** (at least 1 m deep, often most cost-effective for a new construction), **vertical** (common for larger buildings which would require a large footprint for a horizontal system, but more expensive because boreholes must be drilled), and using a **body of water** (may be the cheapest option if a suitable body of water exists, and at least ~2.5 m deep to prevent freezing in winter).
- In **open loop systems**, the ground loop draws fluid directly from a water source. Due to environmental regulations, this method is less common.
- **Hybrid systems** use a combination of GHP with another heating technology, like a gas boiler.
- **Refrigerants** are used in heat pump cycles to concentrate heat. They have a relatively low boiling point, allowing them to evaporate and be compressed to raise their temperature.
- The efficiency of heat pumps is described by their **coefficient of performance** (COP), how much thermal energy is transferred per electrical energy used. Typical COPs fall between 3 and 6.
- While the heat pump itself typically has a life expectancy of ~20 years, ground loops have a longer life expectancy of ~50 years.

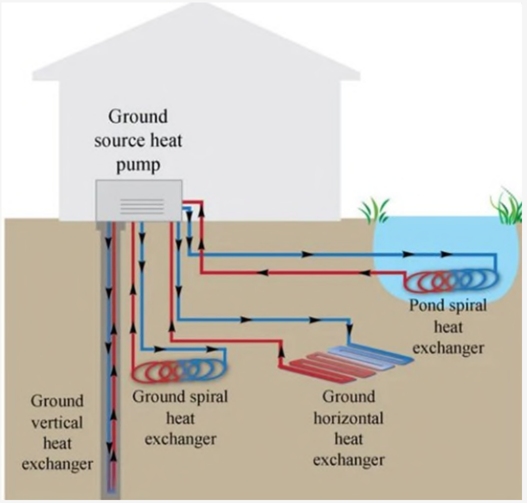
1. As of the end of 2019; 2. Assuming a 5 kW_{th} average capacity and upfront investment of USD 6,000-37,000 (IEA, 2021); 3. Coefficient of performance (the amount of thermal energy transferred per electrical energy used) is the standard metric for measuring heat pump efficiency, potentially changing significantly based on ambient temperature of heat pump operation.; 4. Global capacity factor of heat pumps is low given most do not operate for the entire year. This value does not consider cooling operations performed.
Sources: Belliardi, M. et. al., 2023, An innovative application of 5GDHC: A techno-economic assessment of shallow geothermal systems potential in different European climates, Energy; IEA, 2021, Levelized cost of heating (LCOH) for consumers, for selected space and water heating technologies and countries; IEA, 2022, The Future of Heat Pumps; Nardini, I., 2022, Geothermal Power Generation, The Palgrave Handbook of International Energy Economics; Lund, J. W. and Toth, A. N., 2021, Direct utilization of geothermal energy 2020 worldwide review, Geothermics; US DOE Geothermal Technologies Office, n.d., Geothermal Heat Pumps; Kearney Energy Transition Institute analysis.

Geothermal heat pump (GHP): FactCard (2/2)

Residential vs. large-scale heat pumps

- **Residential heat pumps**, providing heating and cooling for individual homes, typically at 10-20°C and depths less than 300 meters. Their capacities range from 3 kW for small single-family homes to >20 kW for a multi-family building.
- **Large heat pumps** operate at the district and industrial scale. They are typically drilled deeper than residential heat pumps and operate at higher temperatures. Large heat pumps can have capacities over 10 MW.
- While larger GHPs operate under the same principle as residential GHPs, they are typically more customized to specific applications, requiring different refrigerants, adapting to industrial process requirements, or to existing district heating and cooling layouts. District and industrial heat pumps often use waste heat, not geothermal energy.
- Currently, the share of GHP in district heating is low, and the sector has not developed much since the 1990s.
- An application of large-scale heat pumps is in a **geothermal energy use cascade**, which concentrates heat in between progressively lower temperature applications.
- Widespread use of large GHPs in **industry** remains challenging because many industrial processes require high temperatures. Using GHPs is possible for lower temperatures, typically < 140°C. Furthermore, waste heat is often available in industrial facilities, precluding the need of a GHP. For temperatures > 200°C, direct electrification is currently preferred. In GHP reports thus far, the IEA has excluded counts of industrial GHP energy use.

Heat provision

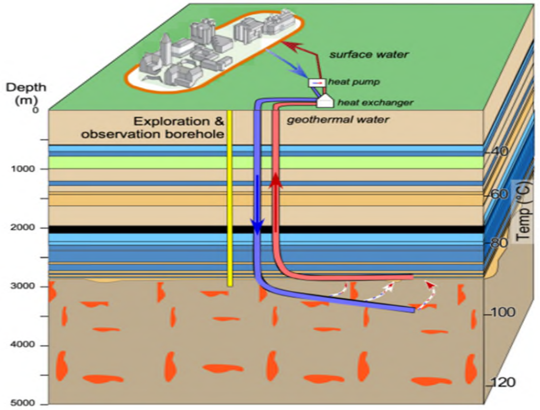


Technology R&D and focus areas for innovation

- **Refrigerants**: Develop new refrigerants that are more energy efficient and environmentally friendly.
- **Efficiency improvements**: Improve components of heat pump technology, such as more efficient compressors that require less electricity to pressurize the refrigerant, variable-speed compressors, and more effective heat exchangers.
- **Higher temperatures**: Currently, industrial heat pumps can reach max temperatures of 140-160°C, though most of them operate at lower temperatures (<80 – 140°C). Higher-temperature heat pumps can unlock new industrial applications, contributing to energy savings and decarbonization.
- **Ground loop construction: Celsius Energy** has developed a heat pump technology that makes use of directional drilling and heat exchangers that extend in multiple directions to maximize heat exchange surface area.
- **Cost reductions**: lower-cost systems would lower barriers to investment in geothermal heat pumps. Lower drilling costs may make deeper large-scale GHP projects feasible for heating and cooling applications.

Sources: Beckers, K. et. al., 2021, Geothermal Deep Direct-Use for Low-Carbon Heating: A Case Study at Cornell University; IEA, 2022, The Future of Heat Pumps; IRENA, 2023, Global Geothermal Market and Technology Assessment; Romanov, D. and Leiss, B., 2022, Geothermal energy at different depths for district heating and cooling of existing and future building stock, Renewable and Sustainable Energy Reviews; Kearney Energy Transition Institute analysis.

District heating: FactCard



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity[1]	13,000	MW_{th}	●
Average plant capacity	4-1,000	MW_{th}	●
Resource temperature	20-100	°C	○
Resource depth	0.20-2	km	○
Lifetime	~30	years	◕
Upfront investment	Unknown	USD/kW_{th}	-
LCOH	0.02-0.14	USD/kWh	○
CF	40	%	◑
Geothermal resource	Hot geothermal reservoirs or subsurface		

Heat provision

Description

- Geothermal district heating is very widespread, especially in certain countries. The countries with the greatest district heating installed capacity as of year-end 2019 were China (7,011 MW_{th}), Iceland (1,650 MW_{th}), Türkiye (1,033 MW_{th}), France (509.4 MW_{th}), and Germany (346.2 MW_{th}).
- District heating systems can make use of various heat sources, such as industrial waste heat, not only geothermal energy. Temperatures of 90-140°C are typically used in conventional district heating systems.
- Geothermal fifth-generation systems, include an ambient temperature thermal loop that connects heat pumps at each building with thermal balancing sources such as geothermal borehole fields.

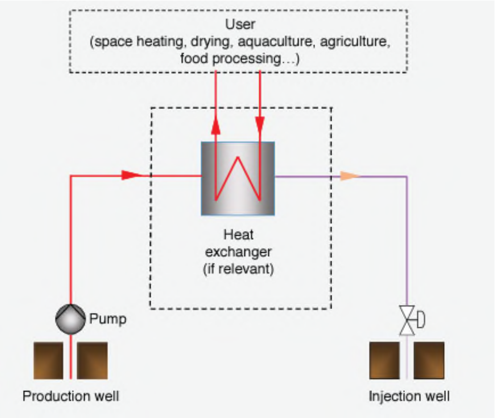
Technology R&D and focus areas for innovation

- **Emerging district heating and cooling** may incorporate distributed heat pumps and thermal energy storage to allow **cooler temperatures** to be used in H&C distribution grids, increasing efficiency. While little progress has been made in modernizing district H&C since the 1990s, the topic is receiving increasing attention due to its potential to decrease CO_2 emissions in the heating sector.
- **Deep direct use**: Deep direct use involves accessing deeper geothermal resources than conventionally used for direct use applications. An example is the **Eden Geothermal project**, which began delivering heat to the Eden Project campus in the UK in 2023 from a 4,871 m well. The delivered heat is ~85°C, coming from a single co-axial well system which makes use of enhanced geothermal (EGS) technology.
- Another example is **Cornell University**, which received a USD 7.2 million DOE grant to test a direct heating system on its campus, which is not located near conventional geothermal resources. An observation well was drilled in 2022 to 3 km. If successful, Cornell intends to create a direct heating system on campus, which will use a heat pump to provide up to 95% of annual campus heating demand.

1. As of the end of 2019, including district heating as well as and other space heating use.

Sources: Akar, S. et al. , 2023, Techno-Economic Analysis for a Potential Geothermal District Heating System in Tuttle, Oklahoma; Belliardi, M. et. al., 2023, An innovative application of 5GDHC: A techno-economic assessment of shallow geothermal systems potential in different European climates, Energy; Fulton, P. et. al., 2024, Subsurface Insights from the Cornell University Borehole Observatory (CUBO): A 3km Deep Exploratory Well for Advancing Earth Source Heat Deep Direct-Use Geothermal for District Heating; Lund, J. W. and Toth, A. N., 2021, Direct utilization of geothermal energy 2020 worldwide review, Geothermics; Robins, J. C. et. al, 2021, 2021 US Geothermal Power Production and District Heating Market Report; Kearney Energy Transition Institute analysis.

Direct use: FactCard



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity[1]	17,000	MW_{th}	●
Average plant capacity	0.1-1.000	MW_{th}	●
Resource temperature	10-170	°C	○
Resource depth[2]	0-3	km	○
Lifetime	~30	years	◕
Upfront investment	Unknown	USD/kW_{th}	-
LCOH	0.02-0.10	USD/kWh	○
CF[3]	19-61	%	◑
Geothermal resource	Hot water or steam		

Heat provision

Return to main-deck slide

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Description

- Direct use refers to the use of heat from geothermal resources, either using the geothermal resource itself to deliver heat, or using a heat exchanger to deliver heat via a working fluid. Some examples of direct use include heating for greenhouses (40-150°C), aquaculture (10-50°C), pools and spas (40-150°C), and various industrial processes[4].
- Direct use is the oldest method of using geothermal resources. Where resources are readily accessible, it provides a cost-competitive option for heating applications such as spas, aquaculture, greenhouses, etc.
- At shallow depths, direct use is not very scalable because only certain geographies have relatively accessible geothermal resources at a sufficient temperature.
- The greatest challenges in increasing deployment include poor data on geothermal resources and current demand for heating applications, little awareness, and lacking financing frameworks and policies.
- In the case of deeper and hotter geothermal resources, direct use competes with electricity generation, which is more profitable.
- **Combined heat and power** (CHP) systems can be designed which find direct use applications for lower-temperature working fluids exiting an electricity-generation cycle.

Technology R&D and focus areas for innovation

- **Mapping:** Improve mapping of geothermal resources, heating application demand, and identify overlap for potential project development.
- **CHP and cascading applications**: By combining various direct heat provision applications with electricity generation, the business case for direct use can be improved.

1. Including all reported uses of geothermal utilization in Lund and Toth (2021) less geothermal heat pumps and space heating; 2. Direct use is most often developed at shallow depths of < 300 m. Emerging direct use applications use deeper resources; 3. Capacity factor depends on use case, ranging from 18.9% for cooling/snow melting to 61.0% for industrial uses; 4. Geothermal heat pump and district heating and cooling applications are covered separately on following FactCards.
Sources: Ciucci, M., 2023, Innovative technologies in the development of geothermal energy in Europe; ESMAP, 2022, Direct Utilization of Geothermal Resources, The World Bank Group; Lund, J. W. and Toth, A. N., 2021, Direct utilization of geothermal energy 2020 worldwide review, Geothermics; Kearney Energy Transition Institute analysis.

Geothermal resources can serve as a sustainable energy source for heating and cooling applications

Overview and working principle

- Geothermal resources can be used for a variety of heating applications. Resources can be used directly for heating, or they can be used to heat a working fluid via heat exchange. **Heat pumps** can concentrate geothermal heat and raise the final temperature provided. In all cases, a mechanical system (piping, heat exchangers, pumps, controls) delivers the heat for its intended use.
- At the end of 2019, there were approximately **107,700 MWth** of installed geothermal heat provision capacity worldwide. The largest category of heat provision was **geothermal heat pumps** (GHP), making up 58.8% of total heating applications.
- **Low-medium temperature resources are typically used for heat provision**, as drilling for deeper and hotter resources, due to the cost, is more lucrative for electricity generation.
- **Direct use technologies often build on each other**. For example, a GHP can concentrate heat from a low-temperature geothermal resource before use. A district heating and cooling network may use a large GHP in central facilities, and incorporate seasonal energy storage, waste heat from nearby industrial facilities, and distributed heat pumps at individual buildings. The exact arrangements differ significantly between individual projects based on what energy sources and features are available nearby.
- Heat provision applications include residential heating and cooling, agri-food applications, bathing and swimming, industrial processes, and district heating and cooling.

Pros

- Established technology that has been used in its simplest form for millennia.
- Sustainable solution for heating technologies that would otherwise emit CO_2.
- Ground-source heat pumps are more efficient than air-source heat pumps.

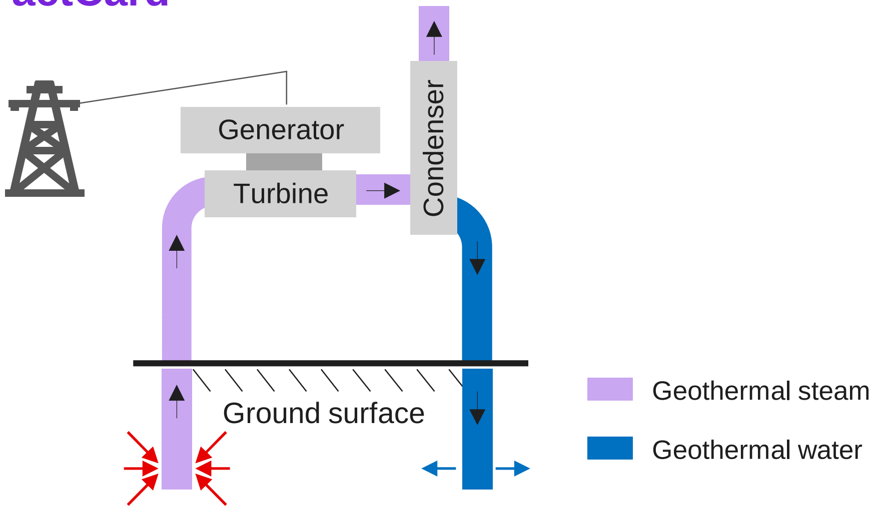
Cons

- Limited to applications that use lower-medium temperatures or are near suitable shallow geothermal resources.
- Effectiveness depends on the temperature difference between the geothermal resource and ambient temperature, making the technology less effective in cold climates.

Heat provision

Sources: Ciucci, M., 2023, Innovative technologies in the development of geothermal energy in Europe; Lund, J. W. and Toth, A. N., 2021, Direct utilization of geothermal energy 2020 worldwide review, Geothermics; Nardini, I., 2022, Geothermal Power Generation, The Palgrave Handbook of International Energy Economics; Kearney Energy Transition Institute analysis.

Dry steam: FactCard



Key data

Global installed capacity	2,900	MW_e	◕
Average plant capacity	48	MW_e	◑
Resource temperature	180-374	°C	◑
Resource depth	< 3.50	km	◔
Lifetime	25	years	◑
Upfront investment	1,500-4,000	USD/kW_e	◔
LCOE	0.05-0.08	USD/kWh	○
CF	60	%	◕
Geothermal resource	Dry steam		

Electricity generation Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Return to main-deck slide

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Description

– Dry steam is the oldest kind of geothermal electricity generation technology, with the experimental generator entering operation in 1904 in Larderello, Italy.

– A **high-quality dry steam geothermal resource** is required. The steam is piped directly from underground wells to the power plant where it goes through a cleaning system before being directed into a turbine/generator unit. Then, the steam is cooled and condensed and is typically reinjected back into the reservoir. Dry steam power generation has a greater efficiency than other conventional geothermal generating technologies.

– Dry steam resources are limited to a few locations across the globe. The geysers in the United States and Larderello, Italy have the largest dry steam geothermal generation in the world with a capacity of ~835 and 800 MW, respectively. Other countries with large dry steam geothermal power capacity are Indonesia, New Zealand, and Japan.

Technology R&D and focus areas for innovation

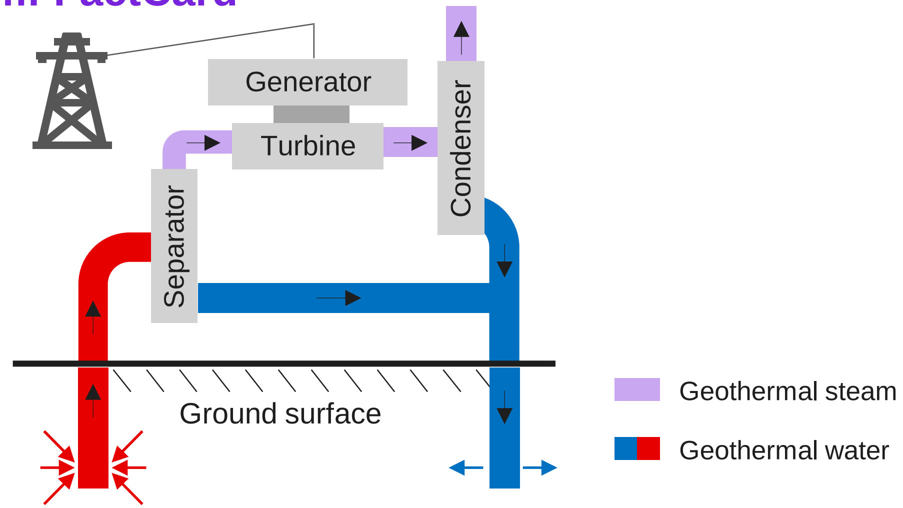
– Overall, dry steam cycles are a mature technology.

– **Efficiency improvements:** System performance is determined by the performance of individual components (turbine, condenser, etc.). The performance can be analyzed (and subsequently improved) with exergy analysis[1] to better understand the performance of each component. Specific steam consumption (the amount of steam required per kWh of electricity produced) can help evaluate the overall efficiency.

– **Sustainable reservoir management:** Over time, the geothermal resource reservoir may begin to run out, especially if it is not fully reinjected at the end of the cycle, causing the productivity of the plant to decrease. Reservoir management monitors the power output and ensures that the resource is used sustainably. For example, **additional wastewater can be injected to replace the original resource**.

Sources: Gutiérrez-Negrín, L. C. A., 2024, Evolution of worldwide geothermal power 2020–2023, Geothermal Energy; IRENA, 2017, Geothermal power technology brief; IRENA, 2023, Renewable Power Generation Costs in 2022; Moya, D., Akinsipe, O. C., Kaparaju, P., 2021, Chapter 1 - Various cycle configurations for geothermal power plants, Thermodynamic Analysis and Optimization of Geothermal Power Plants; Nardini, I., 2022, Geothermal power generation, The Palgrave Handbook of International Energy Economics; Kearney Energy Transition Institute analysis.

Flash steam: FactCard



Key data

Global installed capacity	8,600	MW_e	◕
Average plant capacity	35	MW_e	◑
Resource temperature	180-374	°C	◕
Resource depth	< 3.50	km	◔
Lifetime	25	years	◑
Upfront investment	1,500-5,000	USD/kW_e	◔
LCOE	0.05-0.09	USD/kWh	◔
CF	70	%	●
Geothermal resource	Pressurized water or steam		

Electricity generation Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Return to main-deck slide

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Description

– Flash steam geothermal plants are the most common geothermal electricity generation technology today, making up 52.7% of total installed capacity and 55.6% of total generation in 2021-2022. These can be single or dual-flash technologies. In the latter the flashing process is being done in two stages and their steams are used for high- and low-pressure turbines.

– Flash plants **require a hot pressurized geothermal fluid** resource of greater than 180°C from deep underground. When the fluid reaches the surface, due to a drop in pressure in a low-pressure separator, the fluid “flashes” into vapor. This vapor is used to generate electricity.

– Consecutive rounds of flashing can make the cycle more efficient. Flash plants **range from single to triple flash**, with single-flash plants having typically up to 80 MW capacity, and triple-flash having 60–150 MW capacity. A second flash may add an additional 20-30% of electricity output per well, while a third flash may add an additional 10%. Leftover water and condensed steam are injected back into the geothermal reservoir.

– Despite greater efficiency, single-flash systems are more economical on a per unit basis of electricity produced due to the lower capital investment.

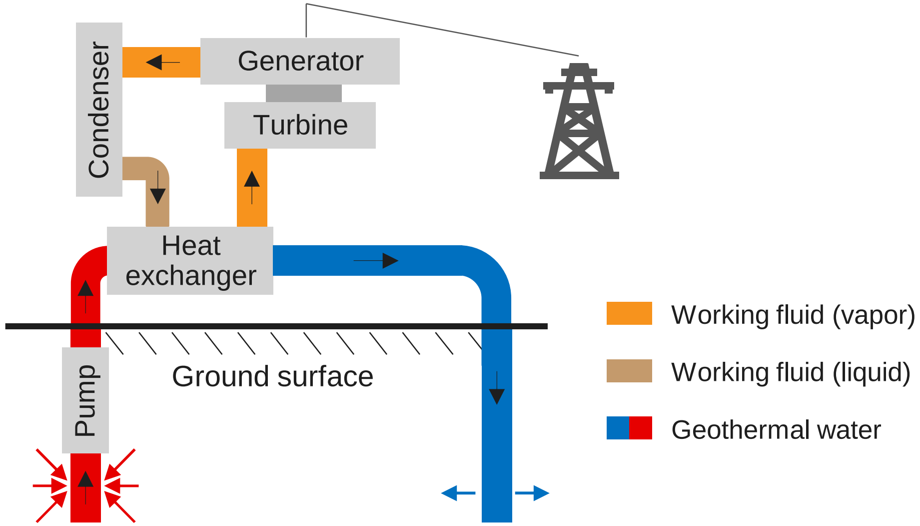
Technology R&D and focus areas for innovation

– Overall, flash plants are a mature technology. The same measures for maintaining and improving **efficiency** and **sustainable reservoir management** are taken for flash steam plants as for other conventional geothermal power plants.

– The greatest exergy loss during a flash cycle occurs during reinjection of the geothermal resource. As such, installations could be modified with a combined heat and power application (using the warm resource for a direct use purpose after the electricity generating cycle).

Sources: Bronicki, L. Y., 2016, Geothermal Power Conversion Technology, Renewable Energy Systems; Gutiérrez-Negrín, L. C. A., 2024, Evolution of worldwide geothermal power 2020–2023, Geothermal Energy; IRENA, 2017, Geothermal power technology brief; IRENA, 2017, Geothermal power technology brief; IRENA, 2023, Renewable Power Generation Costs in 2022; Moya, D., Akinsipe, O. C., Kaparaju, P., 2021, Chapter 1 - Various cycle configurations for geothermal power plants, Thermodynamic Analysis and Optimization of Geothermal Power Plants; Nardini, I., 2022, Geothermal power generation, The Palgrave Handbook of International Energy Economics; Kearney Energy Transition Institute analysis.

Binary cycle: FactCard



Key data

Global installed capacity[1]	4,100	MW_e
Average plant capacity	14	MW_e
Resource temperature	100-180	°C
Resource depth	< 3.50	km
Lifetime	25	years
Upfront investment	2,000-6,000	USD/kW_e
LCOE	0.05-0.09	USD/kWh
CF	65	%
Geothermal resource	Hot water or steam	

Electricity generation

Lower/shallower … Higher/deeper

Return to main-deck slide

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Description

- Conventional binary cycles are an established technology for electricity generation. They generate electricity **indirectly** from geothermal resources: heat from the geothermal resource is transferred to a working fluid in a heat exchanger. Then, the vaporized working fluid flows through the turbine, generating electricity.
- Because the working fluid has a lower boiling point than water, binary cycle technology can utilize geothermal resources at lower temperatures than direct technologies.
- While the typical minimum temperature of the geothermal resource for binary cycles is ~100°C, binary cycles as low as 70°C have been designed.
- The most common type of binary cycle is an **organic Rankine cycle** (ORC), which uses organic fluids or hydrocarbons. Another type is the **Kalina** cycle, which uses a water/ ammonia mixture as a working fluid but is limited in application.

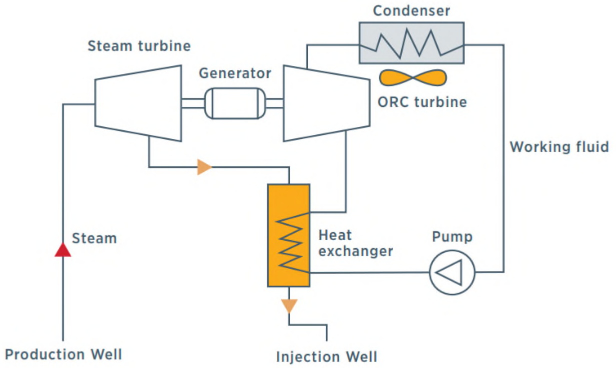
Technology R&D and focus areas for innovation

- Overall, binary cycles are a mature technology.
- **Working fluids**: The choice of working fluid depends on system parameters, environmental impacts, thermodynamic efficiency, and cost. As new fluids are developed, lower-temperature geothermal resources can be used.
- The same measures for maintaining and improving **efficiency** and **sustainable reservoir management** are taken for binary cycle plants as for dry steam plants.

1. Data from 2021-2022 presented at the 2023 World Geothermal Congress, specifically for binary ORC power plants.

Sources: Chowdhury, A. S., Ehsan, M. M., 2023, A Critical Overview of Working Fluids in Organic Rankine, Supercritical Rankine, and Supercritical Brayton Cycles Under Various Heat Grade Sources, International Journal of Thermofluids; Gutiérrez-Negrín, L. C. A., 2024, Evolution of worldwide geothermal power 2020–2023, Geothermal Energy; Herath, H. M. D. P. et. al. , 2020, Working fluid selection of Organic Rankine Cycles, Energy Reports; IRENA, 2017, Geothermal Power Technology Brief; IRENA, 2023, Renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis.

Combined cycle: FactCard



Key data

Global installed capacity[1]	560	MW_e	◑
Average plant capacity	11	MW_e	◔
Resource temperature	150-374	°C	◑
Resource depth	< 3.50	km	◔
Lifetime	25	years	◑
Upfront investment	~6,000	USD/kW_e	◑
LCOE	Unknown	USD/kWh	-
CF	75	%	●
Geothermal resource	Pressurized water or steam		

Electricity generation   Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Return to main-deck slide

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Description

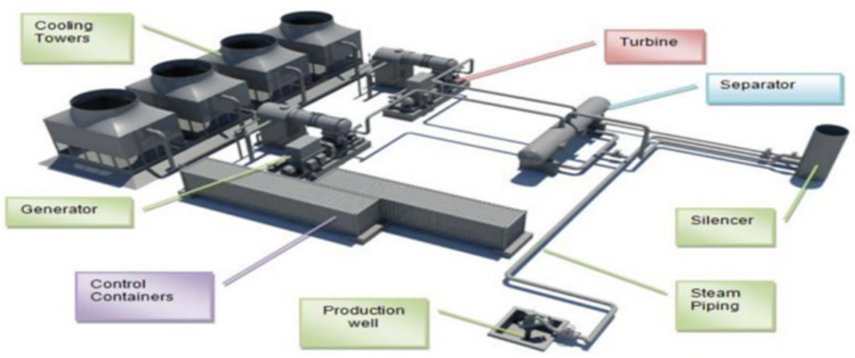
- A combined cycle combines a direct, high-temperature electricity production method with a lower-temperature binary cycle to increase the net efficiency. A combined cycle can increase the net electricity output by ~20%.
- This is also sometimes referred to as a **cascade** of applications, each step using the progressively cooled geothermal resource. A combined cycle can further be used for combined heat and power (CHP) by using the cooled geothermal resource for direct use following the binary cycle.
- Combined cycles are not a common geothermal power technology. As of 2021-2022, there were a total of 55 combined power plants in operation globally, making up less than 4% of total geothermal power capacity, concentrated in Türkiye, the Philippines, and the US.

Technology R&D and focus areas for innovation

- Overall, combined cycles are a mature technology.
- **Cascading applications**: based on output temperatures and local needs, combined cycle technologies can find diverse ways to use effluent heat available and create **hybrid** systems, such as combined heat and power.
- The same measures for maintaining and improving **efficiency** and **sustainable reservoir management** are taken for flash steam plants as for other conventional geothermal power plants.

1. Data from 2021-2022 presented at the 2023 World Geothermal Congress.
Sources: Gong, Y. et. al., 2010, Thermodynamic Analysis of Geothermal Power Generation Combined Flash System with Binary Cycle, Proceedings World Geothermal Congress 2010; Gutiérrez-Negrín, L. C. A., 2024, Evolution of worldwide geothermal power 2020–2023, Geothermal Energy; IRENA, 2017, Geothermal Power Technology Brief; IRENA, 2023, Renewable Power Generation Costs in 2022; Kearney Energy Transition Institute analysis.

Wellhead generator: FactCard



Key data

Global installed capacity[1]	130	MW_e	◑
Average plant capacity	5.50	MW_e	○
Resource temperature	150-374	°C	◑
Resource depth	< 3.50	km	◔
Lifetime	25	years	◑
Upfront investment	1,500-1,700	USD/kW_e	○
LCOE	Unknown	USD/kWh	-
CF[1]	10	%	○
Geothermal resource	Pressurized water or steam		

Electricity generation Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Return to main-deck slide

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Description

– Wellhead power generating technology is a **modular** technology that produces electricity from a **single geothermal well**. Wellhead generators can be constructed directly on the well pad of a production well and are generally only **100 kW to 15 MW** in capacity.

– The electricity generation of the wellhead generator is done with proven technology, such as direct generation from the geothermal resource or an indirect binary cycle. However, due to the simple modular structure, the **cooled geothermal resource is not reinjected at the end of the cycle**.

– Due to the lack of scale, wellhead plants are less efficient than a full-sized power plant. However, they require shorter installation periods and can reduce certain investment barriers of geothermal projects by enabling earlier electricity generation and revenue before a larger plant is constructed. They also allow the early collection of reservoir performance data.

– A direct electricity-generating technology used primarily for wellhead generation is **backpressure geothermal power plants**. This generation technology has the lowest investment cost because it does not include condensers or cooling towers, making it easy to install as a modular technology. It is the least efficient of all geothermal power technologies.

– Wellhead generators have notably been deployed in Eastern Africa, such as Kenya where 81 MW of wellhead generators were installed as of 2019.

Technology R&D and focus areas for innovation

– Overall, wellhead generators are a mature technology. However, by better understanding how wellhead generators can complement longer development periods of geothermal powerplants, or how they can be adopted for small-scale or off-grid needs, **economic business models** can be developed that increase the use of wellhead generators.

1. Data from 2021-2022 presented at the 2023 World Geothermal Congress, specifically for backpressure power plants.

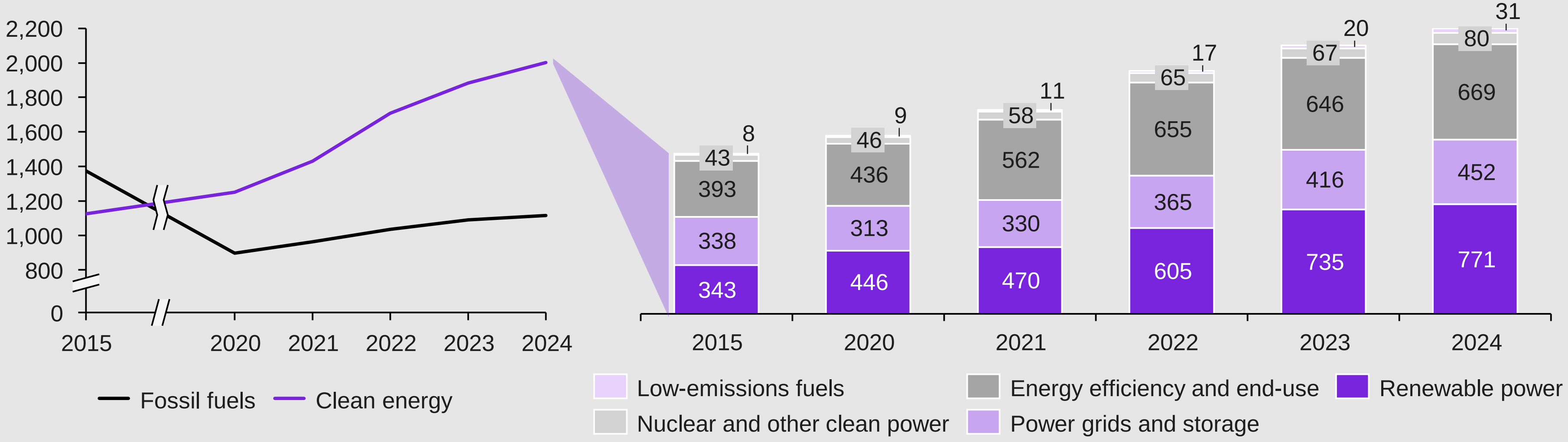
Sources: Córdova Geirdal, C. A., Gudjonsdottir, M. S., Jensson, P., 2015, Economic comparison of a well-head geothermal power plant and a traditional one, Geothermics; Gutiérrez-Negrín, L. C. A., 2024, Evolution of worldwide geothermal power 2020–2023, Geothermal Energy; IRENA, 2023, Global Geothermal Market and Technology Assessment; Kabeyi, M.J.B. and Olanrewaju, O.A., 2022, Geothermal wellhead technology power plants in grid electricity generation: A review, Energy Strategy Reviews; Olanrewaju, O. and Kabeyi, M. J. B., Application of Geothermal Wellhead Generators in Sustainable Power Generation, Geothermal Resources Council; Kearney Energy Transition Institute analysis.

Appendix of Section 4: Past and projected geothermal energy market growth

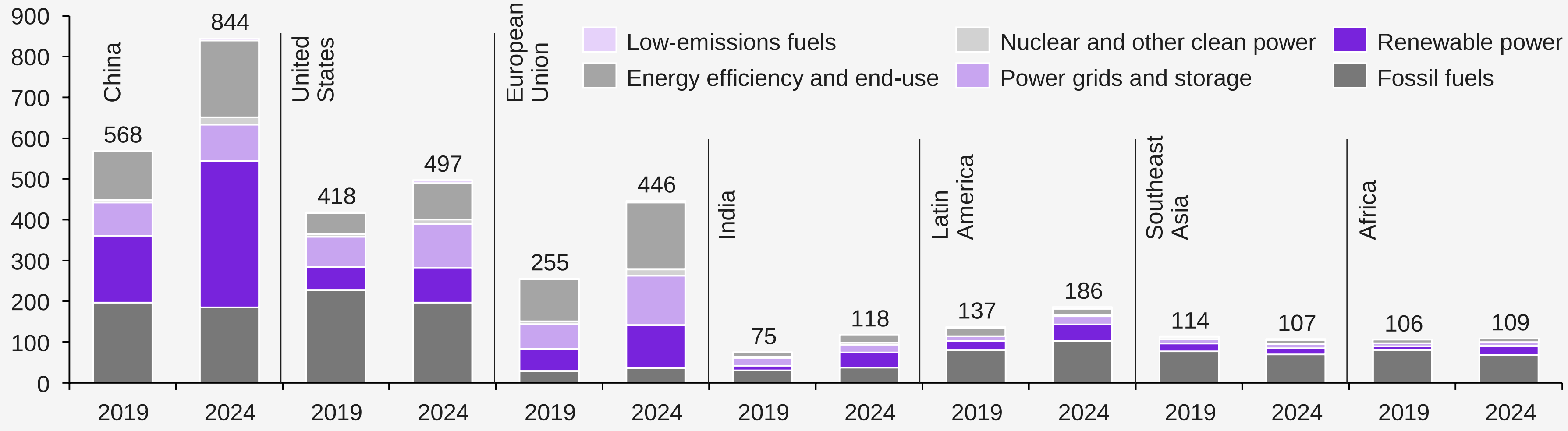
Global investment in clean energy is set to reach USD 2 trillion in 2024, nearly double that of fossil fuels, but major imbalances exist between China, the United States, the EU and the rest of the world

Emerging markets and developed economies outside China account for only ~15% of global clean energy spending.

Global investment in clean energy and fossil fuels
USD billion, 2015-2024e



Annual investment in clean energy by selected country and region
Billion USD (2023, MER), 2019-2024e



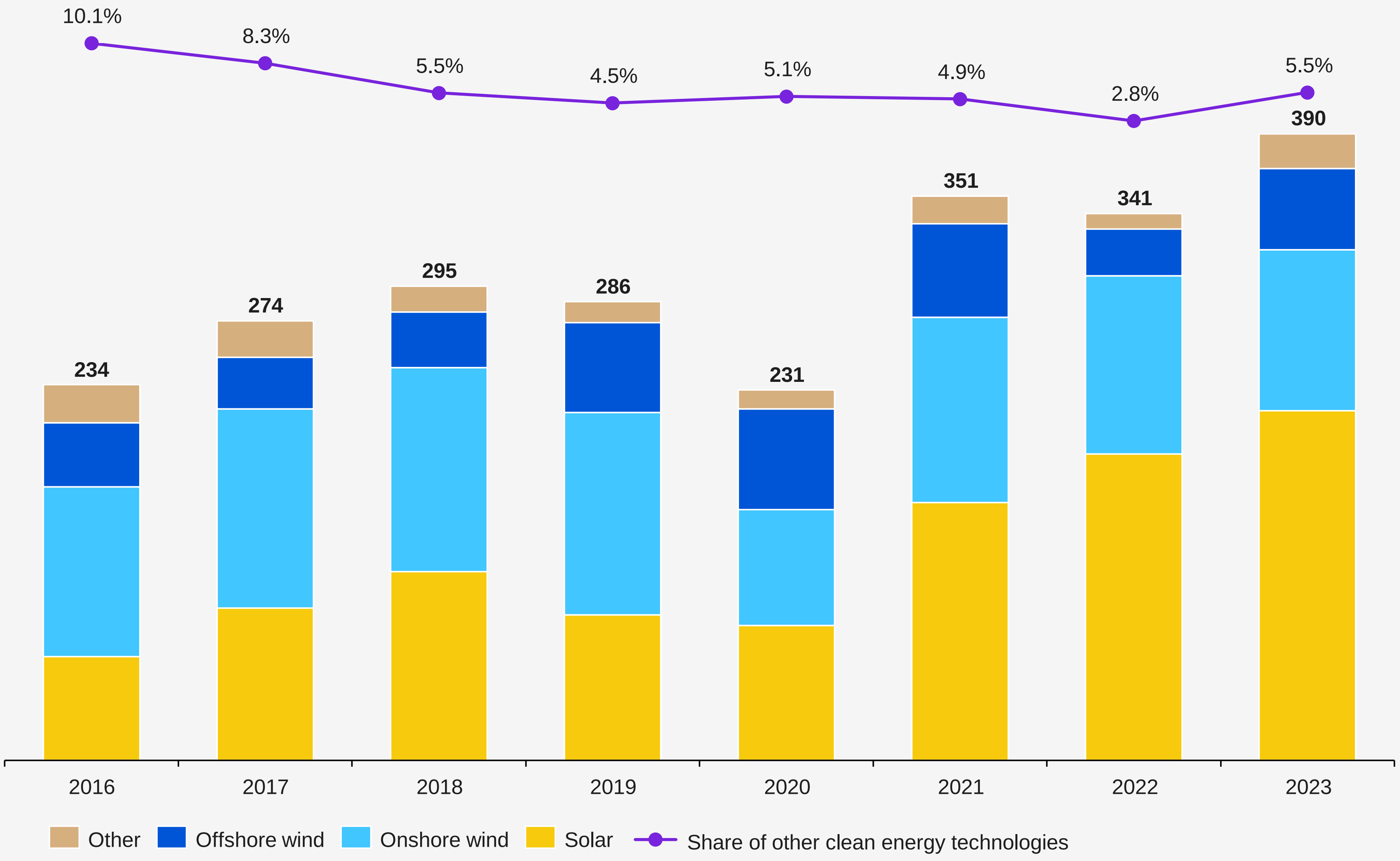
Source: IEA, 2024, World Energy Investment 2024; Kearney Energy Transition Institute analysis.

DRAFT

Geothermal together with other clean energy technologies plants represent less than 5.5% of final investment decisions (FIDs) for utility-scale renewable plants in 2023

Continued growth in solar and a rebound in offshore wind lifted FIDs for utility-scale renewables to an all-time high in 2023

Utility-scale renewable energy projects at FID
USD billion, 2016-2023



Note: Excludes large hydropower. “Other” includes biomass, waste-to-energy, geothermal, small hydro and marine.
Source: IEA, 2024, World Energy Investment 2024; Kearney Energy Transition Institute analysis.

Appendix of Section 6: Business models for geothermal energy

Grangemouth energy project aimed to harness geothermal heat, but faced challenges due to stakeholder complexity and competition from other energy projects

Example

1 Business model of HPA with external heat producer

2 Business model of HPA without external heat producer

3 Business model of local thermal energy provider

4 Business model of local thermal energy community

Project description

The Grangemouth area, Scotland's largest industrial site, was identified as a prime location for a large-scale geothermal district heating system, **leveraging mine water and potentially waste heat from nearby industrial plants like a refinery and chemical facilities.** The project aimed to provide heat to public and private housing, currently dominated by gas boilers.

The commercial model involved a council or third-party financed geothermal heat network, designed to compete with the existing gas network and **attract domestic customers based on price.**

The project did not move forward due to:

- System complexity in connecting heat customers and sourcing sufficient waste heat,
- Lack of response from major industrial stakeholders,
- Insufficient local authority support, and
- Competition from other energy projects, such as a biomass CHP plant.

Key characteristics

Study completed	December 2015
Resource	Flooded coal mine
Depth	580 m
Source temperature	22°C
Flow rate	100 l/s
Capacity	5.72 MW_{th}
CO_2 savings	5,600 tCO_2 / year
Capex	£38.9 million
NPV	£5 million (25-year project life)
IRR	7% (25-year project life)
Payback	13 years

Key partners

- Synergie Environ Ltd
- Mace Group Ltd
- Low Carbon Infrastructure Programme
- Scottish Enterprise

Return to main deck

Sources: Townsend, D.H. et al., 2020, "On the Rocks" – Exploring Business Models for Geothermal Heat in the Land of Scotch, Proceedings World Geothermal Congress; Kearney Energy Transition Institute analysis.

L'Oréal reduces gas usage and boosts efficiency with a thermo-frigo-pump for heating and cooling at its Creuzier-le-Vieux plant

Example

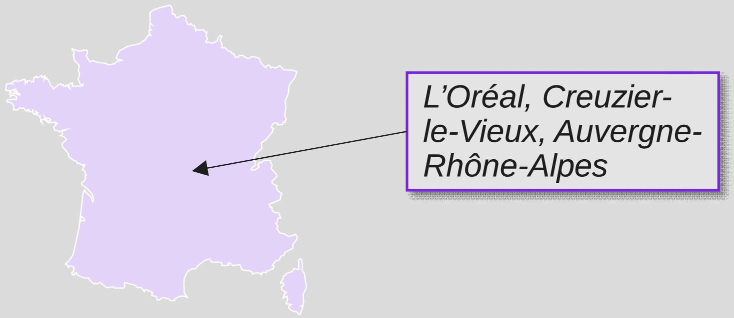
1 Business model of HPA with external heat producer

2 Business model of HPA without external heat producer

3 Business model of local thermal energy provider

4 Business model of local thermal energy community

Project description



This project integrates a **thermo-frigo-pump** to produce both heating and cooling for L'Oréal's cosmetic production plant. The system allows the company to reduce gas usage and operate more efficiently. **The energy system uses gas for heating and electricity for cooling.**

The annual requirements of the systems are the following:

– **6.41 GWh for cooling (20% geothermal)**, producing 45,000 m^3 of water at 6 ^oC, and

– Recovered waster energy generates **14.38 GWh of heat (15% geothermal)** for space heating, preheating 47,000 m^3 of wash water, and 6,000 m^3,of demineralized water.

Key characteristics

Construction completed in 2010	45,000 m^2
Geothermal overinvestment	Leasing formula 233 k€/year
Annual operating cost	55.7 k€
Payback	10 years
Annual emissions reduction	547 tonnes of CO_2eq
Installation	COP: heating – 3.3, cooling – 2, and global – 5.3

Key partners

– EDF optimal solutions

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Sources: ADEME, BRGM, 2023, Géothermie de surface : une énergie performante et durable pour les entreprises; Kearney Energy Transition Institute analysis.

A Scottish University Campus project sought to develop a geothermal heat network, but was paused due to financial challenges and thermal yield uncertainties

Example

1. Business model of HPA with external heat producer
2. Business model of HPA without external heat producer
3. Business model of local thermal energy provider
4. Business model of local thermal energy community

Project description

Campus of one of the main Scottish universities

This project aimed to explore the potential for geothermal energy at a Scottish University's main campus as part of its low-carbon heat strategy. **The goal was to develop a campus-wide district heating system, leveraging** a hot sedimentary aquifer **resource located 1,500 to 2,000 meters below the site.**

The commercial model involved a university-financed geothermal heat network, **competing** with existing gas boilers and CHP units on campus **based on cost per kWh** and return on investment.

The project did not move forward due to:

- Financial challenges, and
- Uncertainties surrounding thermal yield.

Key characteristics

Study completed	April 2018
Resource	Aquifer
Depth	2000 m
Source temperature	53°C
Flow rate	15 l/s
Capacity	3.24 MW_{th}
CO_2 savings	2,826 tCO_2 / year
Capex	£6.5 million
NPV	£7.6 million (20-year project life)
IRR	12.3% (20-year project life)
Payback	9 years

Key partners

- University
- Scottish government's low carbon infrastructure transition programme

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Sources: Townsend, D.H. et al., 2020, "On the Rocks" – Exploring Business Models for Geothermal Heat in the Land of Scotch, Proceedings World Geothermal Congress; Kearney Energy Transition Institute analysis.

Airbus uses a temperate water loop to deliver year-round heating and cooling, fully powered by geothermal energy

Example

1. Business model of HPA with external heat producer
2. Business model of HPA without external heat producer
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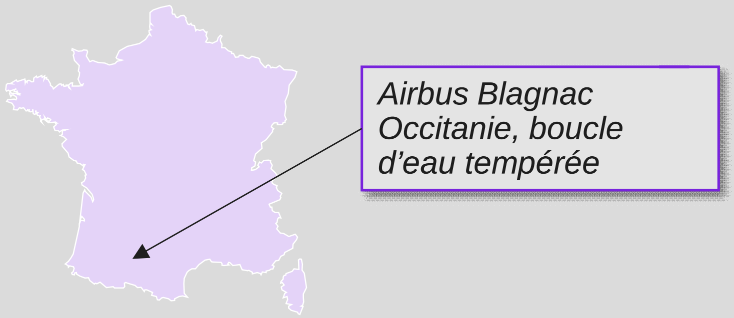
Project description



This project consists of a temperate water loop, **with water circulating between 5°C and 30°C**, supplying both heating and cooling through decentralized heat pumps in each building. This flexible, shared system can integrate with other renewable energies and adapt to urban planning needs.

At Airbus, this system provides year-round energy for both hot- and cold-water networks, meeting the site's thermal needs:

- **1,483.5 MWh for heating**
- **933.2 MWh for cooling,**
- **With 100% coverage by geothermal energy.**

Key characteristics

Construction completed in 2016	36,250 m²
Geothermal investment	4 M€, out of which 450 k€ for studies and design
Co-financing	1 M€, fonds for heat and new emerging technologies
Annual electricity consumption	506 MWh or 64 k€
Payback	7 years
Annual emissions reduction	384 tonnes of CO_2eq
Installation	103 tubes between 93-97m depth, and global – 5.4

Key partners

- Ginger Burgeap
- Mino
- Waterkotte
- Engie
- Accenta

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Sources: ADEME, BRGM, 2023, Géothermie de surface : une énergie performante et durable pour les entreprises; Kearney Energy Transition Institute analysis.

Fortissat heat network aimed to serve a proof of concept for other UK geothermal schemes, but was paused due to financial challenges and low heat density network

Example

1 Business model of HPA with external heat producer

2 Business model of HPA without external heat producer

3 Business model of local thermal energy provider

4 Business model of local thermal energy community

Project description

This project aimed to develop Scotland's first mine water geothermal district heating system in 15 years in a semi-rural, socially deprived area. **It focused on reducing fuel poverty and carbon emissions by providing a community heating system for existing mixed-tenure housing** and serving as a proof of concept for future UK geothermal schemes.

The commercial model involved a council or third-party-financed geothermal heat network, which would **compete** with existing gas networks and **boilers based solely on heat price** to attract domestic customers.

The project did not move forward due to:

- Low estimated return on investment, and
- Low heat density of the network, as most heat customers were semi-detached houses already connected to the gas grid.

Key characteristics

Study completed	February 2016
Resource	Flooded coal mine
Depth	380 m
Source temperature	18°C
Flow rate	50 l/s
Capacity	2.3 MW_{th}
CO_2 savings	782 tCO_2 / year
Capex	£10.8 million
NPV	£3.4 million (25-year project life)
IRR	1.7% (25-year project life)
Payback	-

Key partners

- TownRock Energy
- Scottish government's geothermal energy challenge fund

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Sources: Townsend, D.H. et al., 2020, "On the Rocks" – Exploring Business Models for Geothermal Heat in the Land of Scotch, Proceedings World Geothermal Congress; Kearney Energy Transition Institute analysis.

The Nice Meridia project optimizes energy use with geothermal and smart grids, providing up to 82% renewable energy for heating and 78% for cooling

Example

1. Business model of HPA with external heat producer
2. Business model of HPA without external heat producer
3. Business model of local thermal energy provider
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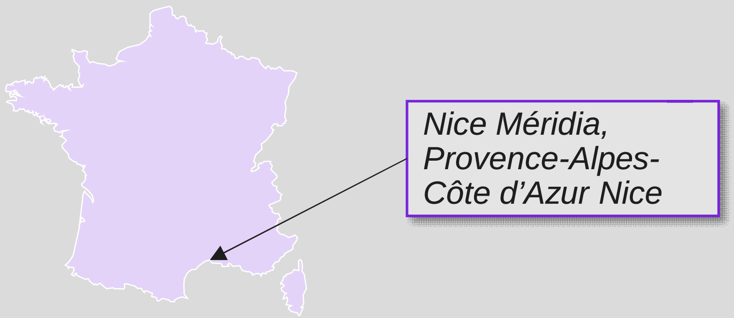
Project description



The Nice Meridia project focuses on integrating renewable energy, **primarily geothermal energy, to power district heating and cooling** in the urban area of Nice.

It leverages the geothermal potential of the Var aquifer and incorporates advanced energy management technologies through smart grids to optimize energy use, ensuring a high percentage of renewable energy in the overall system.

The Meridia Smart Energie geothermal plant supports the PCAET[1] plan, which aims to cut GHG[2] emissions by 22% by 2026 and 55% by 2030, **providing 82% renewable energy for heating and 78% for cooling.**

Key characteristics

Inauguration	December 2021
Total cost	18.8 M€
ADEME financing	3.639 M€
Production capacity	8 MW (heating) and 11 MW (cooling)
Emissions reduction	5,000 tonnes of CO_2eq
Buildings served	550,000 m^2

Key partners

– Direction régionale de l' ADEME en Provence-Alpes-Côte d'Azur
– Région Provence-Alpes-Côte d'Azur
– Méridia Smart Energie (IDEX)

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1. Plan Climat Air Energie Territorial; 2. Greenhouse gases
Sources: ADEME, 2023, Réalisation d'un réseau de chaleur et de froid alimenté par géothermie pour l'écoquartier Nice Méridia; Kearney Energy Transition Institute analysis.

Dollar community project aims to demonstrate that geothermal can be value-generating for heating and cooling new-built housing

Project description

This project, commissioned by a landowner in Clackmannanshire, aimed to assess the potential for a **mine water geothermal system to supply heating and cooling to a new housing development of 34 houses, with plans to expand to 200 homes.**

The proposed model is a joint venture energy service company that supports the community, competing with other new-built alternatives such as gas grid connections or biomass heat networks.

Once complete, the project will demonstrate that carbon-neutral, non-gas housing developments can be straightforward and value-generating, supporting the 2025 UK and 2024 Scotland requirements for no new-build housing with gas boilers.

Key characteristics

Study completed	November 2018
Resource	Flooded coal mine
Depth	55 m
Source temperature	11°C
Flow rate	5 l/s
Capacity	0.23 MW_{th}
CO2 savings	23.2 tCO_2 / year
Capex	£0.23 million
NPV	- (not estimated)
IRR	- (not estimated)
Payback	7 years

Key partners

– Scottish Government’s Low Carbon Infrastructure Transition Programme
– Energy Technology Partnership
– Zero Waste Scotland

Example

1 Business model of HPA with external heat producer

2 Business model of HPA without external heat producer

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Sources: Townsend, D.H. et al., 2020, “On the Rocks” – Exploring Business Models for Geothermal Heat in the Land of Scotch, Proceedings World Geothermal Congress; Kearney Energy Transition Institute analysis.

Indonesia lacks scalable geothermal heating and cooling business models despite policy development

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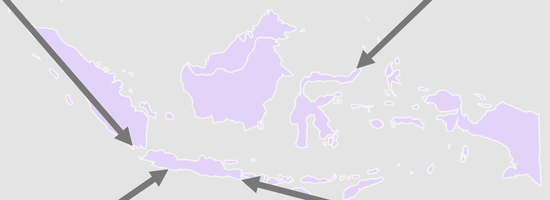
Example

Indonesia, located in the Pacific Ring of Fire, has significant geothermal potential due to its tectonic activity and volcanic landscapes, with reserves estimated at around 23 GW.

Indonesian geothermal heating and cooling projects

Lampung:
1. *Catfish growing – Ulubelu (local farmer) – GM*
2. *Coconut drying – Way Ratal (BPPT) – GM*

North Sulawesi:
1. *Palm sugar processing – Lahendong (PGE & Masarang) – GPP*
2. *Geothermal education park – Lahendong (PGE) – GPP*



West Java:
1. *Mushroom cultivation – Kamojang (PGE) – GPP*
2. *Darajat Pass – Darajat (Local comunities) – GPP*
3. *Coffee drying – Ibun, Bandung (PGE) – GPP*
4. *Tea weathering and drying – Wayang Windu (BPPT & PGE) - GPP*

East Java:
Natural park and geopark – Blawan, Ijen (Local communities) – GM

Established facility
Ongoing development
Pilot plant

In Indonesia, **the majority of geothermal heating and cooling projects is based on the CSR business model**, with companies undertaking projects as part of their social responsibility rather than as a core business venture.

Key enablers

Indonesia has focused on geothermal heating and cooling, **enacting laws to streamline permitting and licensing:**

– Republic of Indonesia Law No. 21 of 2014
– Government Law No. 11 of 2020
– Government Regulation No. 5 of 2021
– Minister of Energy and Mineral Resources Regulation No. 5 of 2021

Key partners

– Indonesian Agency for the Assessment and Application of Technology (BPPT)
– Pertamina Geothermal Energy (PGE)
– Masarang
– Local communities
– Local farmers

Corporate social responsibility
Government-led
Private investment
Community ownership
Green financing and impact investing
Hybrid / public-private partnerships
Energy service company

Note: GM – From Geothermal Manifestations; GPP – From Geothermal Power Plant
Sources: Al Asy'ari, M.R. et al., 2024, Beyond Electricity: Geothermal Direct Use Business Models and Potential Applications in Indonesia; Bagaskara et al., 2023, Exploring New Ideas to Promote and Improve Geothermal Direct Use in Indonesia; Kearney Energy Transition Institute analysis.

Ohaaki geothermal project is the first commissioned sustainable large-scale recovery plant for geothermal brine

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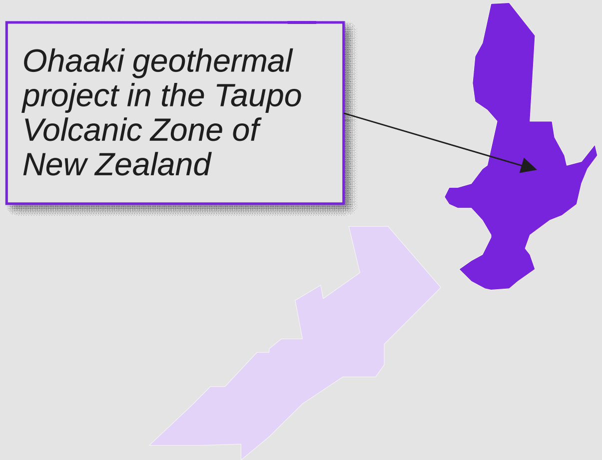
Example

Silica recovery in Ohaaki geothermal project



The Ohaaki electric power station is located in the Taupo Volcanic Zone of New Zealand. In 2021, the Ohaaki project was the world's first commissioned large-scale recovery plant for geothermal brine.

Silica recovery before reinjection provides an added benefit to Ohaaki's geothermal electricity production, as it **prevents silica scaling in the pipes and wells, which can reduce electricity output over time.** In 2019, near-battery-grade geothermal **lithium was extracted at the silica demonstration plant.**

Key characteristics

Commissioning year	2021
Project total cost	USD 17 million
Power generation	110 MW
Temperature of geothermal water	300ºC
Silica production	5,000 t/year

Key partners

– Geo40 Limited

– New Zealand government though Regional Strategic Partnership Fund

Corporate social responsibility
Government-led
Private investment
Community ownership
Hybrid / public-private partnerships
Energy service company
Green financing and impact investing

Sources: IRENA and IGA, 2023, Global geothermal market and technology assessment; Kearney Energy Transition Institute analysis.

Tu De-Kah geothermal project is one of the first in Canada to explore a commercial-scale geothermal development

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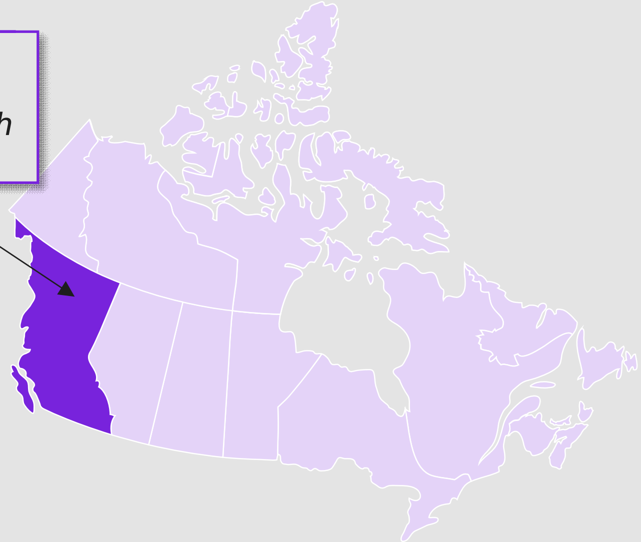
Example

Agriculture opportunities through Tu De-Kah geothermal project



The Tu De-Kah geothermal project is located in Fort Nelson, in northeast British Columbia and is owned by the Fort Nelson First Nation. The project will increase the energy sources of the local community and provide potential for food production. It aims to reduce dependency on fossil fuels while achieving consistent baseload power.

More than USD 50 million in financial support have come from the federal and provincial governments, while the local community is working with the Infrastructure Bank of Canada to complete the financing.

Key characteristics

Commissioning year	2028
Project total cost	USD 100 million
Power generation	7-15 MW
Temperature of geothermal water	120°C

Key partners

- Tu De-Kah local community
- Infrastructure Bank of Canada
- Federal government
- Provincial government
- Versaidez & Associates

Corporate social responsibility
Government-led
Private investment
Community ownership
Hybrid / public-private partnerships
Energy service company
Green financing and impact investing

Sources: IRENA and IGA, 2023, Global geothermal market and technology assessment; Kearney Energy Transition Institute analysis.

Ball State University's geothermal heat pump system is the largest in the United States

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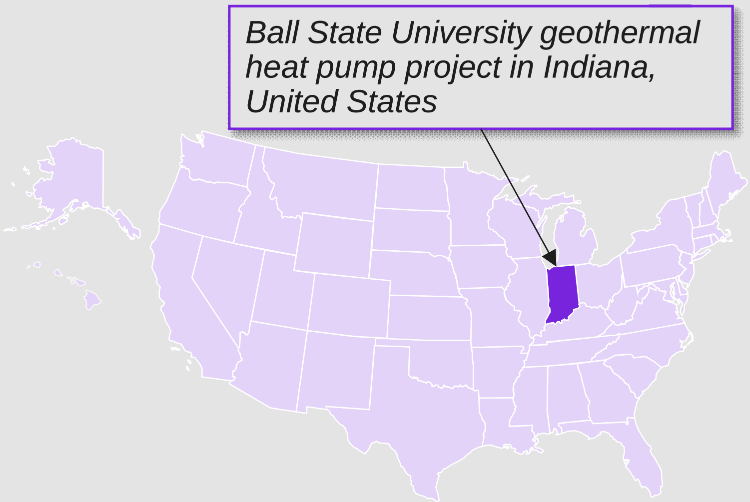
Example

In the US, the largest application of geothermal energy in direct use is GHPs, which account for 98% of the installed capacity. About 40% of GHP installations serve residential use, while the remaining capacity is for institutional and commercial purposes.

Ball State University geothermal heat pump project



Ball State University, in Indiana, has the largest geothermal heat pump installation in the United States. **It heats 20 buildings and cools 47 buildings.**

The geothermal closed-loop system enables Ball State University to decrease its dependence on four outdated coal-fired boilers. It has generated employment for several hundred contractors and suppliers, potentially creating around 2,300 direct and indirect jobs. **To develop the system, Ball State is drilling about 3,600 boreholes across various fields on campus.**

Key characteristics

Commissioning year	2012
Project total cost	USD 83 million
Annual savings	USD 2.2 – 2.5 million
Annual water savings	170 million liters
Annual energy savings	2,638 TJ
Temperature of cold water (cooling / heating)	6/66ºC

Key partners

- Ball State University
- State of Indiana
- United States Department of Energy
- Others

Corporate social responsibility
Government-led
Private investment
Community ownership
Hybrid / public-private partnerships
Energy service company
Green financing and impact investing

Note: GHPs – Geothermal heat pumps
Sources: IRENA and IGA, 2023, Global geothermal market and technology assessment; Kearney Energy Transition Institute analysis.

Türkiye has seen geothermal energy in industrial uses grow at an annual rate of 4-7% during the past 20 years

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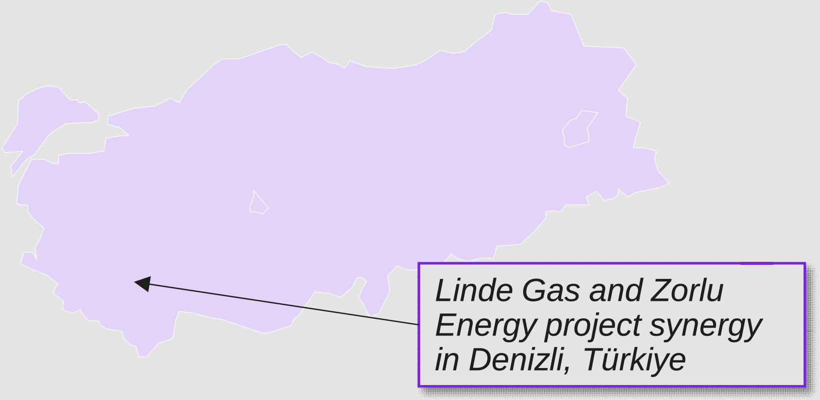
Example

Geothermal CO_2 emissions use in industrial applications in Denzili



Linde Gas operates a facility in Denizli with a **daily capacity of 240 metric tons of gas**. It **utilizes CO_2 from Zorlu Energy's geothermal power plants**, purifying and liquefying it for storage.

Linde is also delivering CO_2 to the Sarayköy's geothermal agricultural area, where it is used in greenhouses to boost production. Liquid CO_2 is also utilized in greenhouses and carbonated beverages.

Key characteristics

Commissioning year	2015
Project total cost	USD 15 million
CO_2 production capacity	240 t/day

Key partners

- Linde Gas
- Zorlu Energy

Corporate social responsibility
Government-led
Private investment
Community ownership
Hybrid / public-private partnerships
Energy service company
Green financing and impact investing

Sources: World Bank Group and ESMAP, 2022, Opportunities for Direct Uses of Geothermal Energy in Türkiye; IRENA and IGA, 2023, Global geothermal market and technology assessment; Kearney Energy Transition Institute analysis.

Green hydrogen production could enhance geothermal use, particularly in countries with small electricity markets

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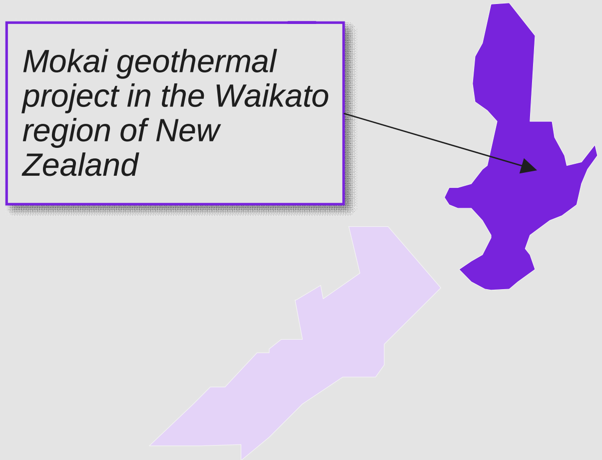
Example

Japan and New Zealand are pioneering the production of green hydrogen using geothermal energy.

Hydrogen production in Mokai geothermal project



The Mokai Geothermal System is located within the Waikato Region, 20 km north of Taupo. It covers an area of about 12 to 16 km². The field has some of the hottest geothermal wells in New Zealand with recorded downhole temperatures of up to 326°C.

Multiple cascade applications - **including a milk-processing plant, a greenhouse complex, and a plant nursery** - make use of geothermal heat from Mokai field.

Key characteristics

Commissioning year	2021
Project total cost	USD 17 million
Power generation	112 MW
Temperature of geothermal water	<326°C
Hydrogen production	180 t/year

Key partners

- Mercury NZ Ltd
- Tuaropaki Trust
- Halcyon Power

Corporate social responsibility
Government-led
Private investment
Community ownership
Hybrid / public-private partnerships
Energy service company
Green financing and impact investing

Sources: IRENA and IGA, 2023, Global geothermal market and technology assessment; Kearney Energy Transition Institute analysis.

Appendix of Section 8: Policy intervention for geothermal energy

EU Parliament calls for a geothermal framework

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Non-exhaustive; example

In January 2024, The European Parliament adopted a resolution on geothermal energy, calling on the European Commission to create a unified strategy for geothermal energy deployment.

Existing use and support for geothermal energy

Europe already has a fair amount of **geothermal district heating and cooling** (particularly in Iceland, Türkiye, France, and Germany). The 2022 energy crisis created new incentive for expanding the use of geothermal energy to increase energy independence.

- 2022 **REPowerEU Plan** targets a doubling of heat pump deployment rates.
- 2023 **updated Renewable Energy Directive** (RED III) targets deployment of renewable energy, such as instructing member states to accelerate permitting and remove barriers to renewable energy power and heating and cooling projects.
- 2023 **Net-Zero Industry Act** includes geothermal energy and heat pumps as key technologies.

The EU has **supported emerging geothermal technologies** with various funding grants.

- EUR 208 million total granted from **Horizon 2020** to 54 geothermal-related projects (2014-2020).
- EUR 4.5 million from the **Innovation Fund** for CCGeo to develop a closed-loop geothermal powerplant in Croatia (2021).
- EUR 91 million from the **Innovation Fund** for Eavor Technologies to demonstrate a closed-loop geothermal system (2023).
- EUR 34 million total from **Horizon Europe** funding for six projects as of August 2023.

Suggested contents of the geothermal framework

A unified geothermal framework would set guidance for EU member states on deploying geothermal energy. The resolution in particular highlights the following solutions for geothermal deployment in the EU:

- **Data availability**: Encourage collection and sharing of geological data. Use government funding for resource mapping and exploratory drilling if data is insufficient.
- **Financing schemes**: Create incentives for heat pump and geothermal heating and cooling. Design new business models for district heating.
- **Risk mitigation**: Adopt risk mitigation schemes to catalyze early-stage investment into geothermal projects.
- **Regulatory issues**: Adjust regulation and permitting frameworks to geothermal resource use. Create one-stop shops for permitting.
- **Technology development**: Fund geothermal R&D projects.
- **Institutional knowledge**: Cooperate internationally to further geothermal knowledge. Increase workforce training for geothermal installations and engineering.
- **Public acceptance**: Develop best practices for communication between industry, local authorities, and communities. Focus geothermal development in regions that historically rely on the fossil fuel industry.

Sources: Dulian, M., 2023, Geothermal Energy in the EU, European Parliament Research Service; European Commission Joint Research Centre, 2023, Deep Geothermal Heat and Power in the European Union; European Parliament, 2024, European Parliament resolution of 18 January 2024 on geothermal energy; IRENA, 2023, Global Geothermal Market and Technology Assessment; Kearney Energy Transition Institute analysis.

France

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Non-exhaustive; example

France's geothermal development was spurred by two energy crises in the 1980s. Heat pumps and district heating make up the majority of geothermal capacity, with new targets introduced in 2023.

Summary and current developments

Power (MW_e, 2023)	**16**
Direct use (MW_{th}, 2020)	**2,597.6**
Heat pumps	77.6%
District heating	19.6%
Other	2.8%

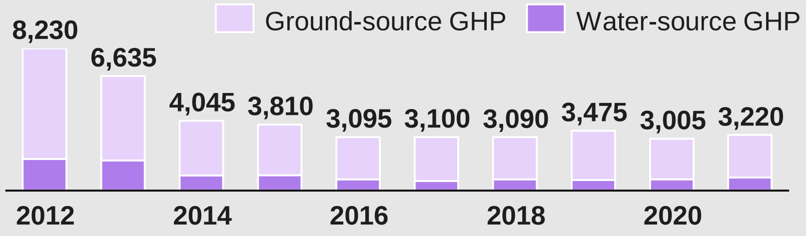
France had 78 deep geothermal installations at year-end 2022; 47 were linked to district heating networks. Geothermal is also used for direct heating needs in industry, agriculture, and recreation.

While **geothermal heat pumps** (GHP) constitute the majority of geothermal direct use, they make up the minority of heat pumps sold. In 2021, 3,220 GHP were sold vs. 253,000 air-source heat pumps. The growth in GHP sales has stagnated in the past 10 years.

France currently has two geothermal power plants in Alsace and one in Guadeloupe.

A **Geothermal Action Plan** was released in 2023.

Annual GHP sales in France



Key enabling policies

1976: The French Geological Survey (BRGM) leads its first district heating project.

1978: Decree 74-498 defines "Geothermal prospecting and exploitation licenses."

1978-1984: BRGM conducts geothermal research and feasibility studies.

1983: ADEME[1] and BRGM create **Aquapac**, a fund to cover short-term exploration and drilling risks and long-term operational risks of geothermal energy in aquifers.

1987: BRGM partners with Britain and Germany to research deep drilling at Soultz-sous-Forêts.

2009: Fonds Chaleur created by ADEME to provide funding and support renewable heating.

2021: BRGM and ADEME publish a data inventory of targets for deep geothermal exploration and exploitation.

2023: Geothermal Action Plan targets a **40% increase in deep geothermal** projects by 2030 and a **doubling of GHP sales** by 2025.

1. ADEME is the French Agency for Ecological Transition in Paris.

Sources: BRGM, n.d., History of the BRGM, the French geological survey, BRGM History; EGEC, 2023, French national geothermal energy action plan to boost geothermal energy; France Ministry of Energy Transition, 2023, Géothermie : un plan d'action pour accélérer; Guadeloupe Energie, 2024, Geothermal Energy Powering Regional Strategy; IEA Geothermal, 2022, France; IRENA, 2024, Renewable Energy Capacity Statistics 2024; Lund, J. W. and Toth, A. N., 2021, Direct Utilization of Geothermal Energy 2020 Worldwide Review; Kearney Energy Transition Institute analysis.

Iceland

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Non-exhaustive example

Iceland is a world leader in geothermal energy, in particular district heating, after decades of government support. Iceland is at the forefront of technological development, leading research on supercritical geothermal resources and co-developing synergistic industries.

Summary and current developments

Power (MW_e, 2023)	**756**
Direct use (MW_{th}, 2020)	**2,373**
District heating	69.5%
Snow melting	11%
Bathing/swimming	8.9%
Fish farming	4.6%
Industrial	3.4%
Greenhouse heating	2.4%
Heat pumps	0.2%

Large-scale space heating began in 1930 in Reykjavík, while Iceland's first geothermal power plant began operating in 1969.

Presently, geothermal heat provides 90% of heating for the capital city, 28 district heating systems, and 200 rural direct use systems. Geothermal power is competitive with hydro and is not subsidized.

Orkustofnun, the National Energy Authority, is responsible for initiating exploration of geothermal resources and granting required licenses, even if the geothermal resource is located on private land.

Iceland has initiated projects co-developing geothermal with green hydrogen, mineral recovery, and carbon capture and storage.

Key enabling policies

1940s: State Electricity Authority explores geothermal resources for space heating and drills exploratory wells.

1961: National Geothermal Fund established to provide risk mitigation via loans, loaning up to 60% of drilling costs, which are converted to a grant if drilling is not successful.

1980s: China and Iceland geothermal cooperation - since the 1980s, Iceland has cooperated with China on geothermal initiatives, such as technical training, joint ventures (2006), and creating a geothermal working group (2018).

1998: Resources Act (No. 57/1998) set out a framework for exploration of geothermal resources, granting Orkustofnun administrative and regulatory authority. Orkustofnun's role was further clarified in **Act No. 87/2003**.

1999-2003: First Master Plan for geothermal energy proposed, ranking potential geothermal developments based on economic as well as environmental-cultural heritage criteria.

2000: Iceland Deep Drilling Project begins, aiming to drill and research supercritical geothermal resources over several decades.

2011: Updated Master Plan act requires Master Plan to be updated every four years.

Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; IRENA, 2024, Renewable Capacity Statistics 2024; Ketilsson, J. et. al., 2021, Legal Framework and National Policy for Geothermal Development in Iceland; Lund, J. W. and Toth, A. N., 2021, Direct Utilization of Geothermal Energy 2020 Worldwide Review; Kearney Energy Transition Institute analysis.

United States

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Non-exhaustive; example

Risk reduction and financial incentives encouraged geothermal power, direct use, and heat pump industry development. Recent funding targets deployment of enhanced geothermal systems.

Summary and current developments

Power (MW_e, 2023)	**2,674**
Direct use (MW_{th}, 2020)	**20,712**
Geothermal heat pumps	97.67%
Other	2.33%

After initially leading geothermal exploration, the US government created a variety of risk reduction and financing mechanisms in the 1970s to support private development of the geothermal industry. Federal initiatives were complemented by **state-level incentives and policies**, such as tax incentives and renewable portfolio standards.

More recently, the **Enhanced Geothermal Shot** (2022) aims to develop enhanced geothermal systems (EGS), reducing cost to USD 45/MWh by 2035. However, funding for geothermal energy in the Bipartisan Infrastructure Law (BIL, 2021) and Inflation Reduction Act (IRA, 2022), **USD 80 million**, is much smaller than for other technology areas (e.g., 118x less than that for hydrogen).

Power purchase agreements (PPAs) with private and public entities **totaling 545 MW** had been signed as of the end of 2023. Disclosed prices were 67-99 USD/kWh. In 2024, Fervo Energy announced two PPAs with utility Southern California Edison for a total of 320 MW from its 400 MW EGS facility in Utah, which is anticipated to be operational in 2026-2028.

Key enabling policies

- **1960s:** Government-led geothermal exploration begins.
- **1970: Federal Geothermal Steam Act** defines geothermal resources and lease conditions.
- **1975:** Risk-reduction programs are implemented via the **Geothermal Loan Guarantee Program**.
- **1975: Geo-Heat Center** at Oregon Institute of Technology funded to conduct research and provide information and technical services.
- **1978: Federal Energy Security Act** creates investment tax credits applicable to geothermal.
- **1979: Public Utilities Regulatory Act** allow private developers to develop power projects.
- **2004/2005: Production tax credits** extended to geothermal projects.
- **2008:** DOE[1] begins providing tax credits for residential and commercial heat pumps.
- **2009: American Recovery and Reinvestment Act** allocates USD 368 million to geothermal projects.
- **2021/2022: IRA** and **BIL** allocate USD 80 million for enhanced geothermal projects.

1. Department of Energy

Sources: IRENA, 2024, Renewable Capacity Statistics 2024; Lund, J. W. and Bloomquist, R. G., 2012, Development of Geothermal Policy in the United States – What Works and What Doesn't Work; Lund, J. W. and Toth, A. N., 2021, Direct Utilization of Geothermal Energy 2020 Worldwide Review; Stevens, H., 2024, How fracking could unlock a clean energy future, The Washington Post; US Department of Energy, 2024, Pathways to Commercial Liftoff: Next-Generation Geothermal Power; Kearney Energy Transition Institute analysis.

Türkiye

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Non-exhaustive; example

Türkiye is one of the leading countries in the world for geothermal direct use as well as power. Past development was assisted by a favorable feed-in tariff for private sector involvement. The most recent FIT has decreased financial support.

Summary and current developments

Power (MW_e, 2023)	**1,691**
Direct use (MW_{th}, 2020)	**3,488**
Bathing/swimming	34.55%
District heating	29.62%
Greenhouse/agriculture	23.55%
Individual space heat	12%
Heat pumps	0.24%
Air conditioning	0.01%

Türkiye geothermal energy industry has been under development for decades. The first pilot power plant began operating in 1974, and the first district heating system entered operation in 1987. Geothermal heat is used directly, notably for district heating, bathing and swimming, and agriculture.

While initial development of geothermal resources was state-led, the 2007 **Law on Geothermal Resources** and consequent **feed-in tariffs** (FITs) incentivized private sector participation. Türkiye met its target of 1,000 MW of geothermal electricity by 2023 ahead of schedule.

The **2035 National Energy Plan** targets a combined 5,100 MW from geothermal and biomass power by 2035.

Key enabling policies

1960s: General Directorate of Mineral Research and Exploration begins state-sponsored exploration of geothermal resources.

2007: Law on Geothermal Resources and Natural Mineral Waters created a framework for geothermal energy development; clarified permitting process.

2010: Renewable Energy Support Scheme (YEKDEM) set a 10-year FIT of USD 105/MWh, with additional 5-year USD 27/MWh for a local content bonus. Awarded in USD to plants entering operation between 2010 and 2021.

2017: Risk Sharing Mechanism (RSM) co-launched by Türkiye and the World Bank Geothermal Development Project. Combined USD 355 million of loans and grants to provide partial coverage of exploration drilling costs of projects.

2020: Turkish Geothermal Energy Association founded by companies to further geothermal industry and improve stakeholder relations.

2021: Updated YEKDEM set a 10-year FIT for projects put into service before 2026. Capped at USD 86/MWh. Eligible for a 5-year local content bonus. Awarded in Turkish Lyra (less attractive to international investors than previous FIT).

2023: Geothermal exploration schemes announced by the General Directorate of Mineral Research and Exploration in Sivas and Adana Provinces.

Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; IRENA, 2024, Renewable Capacity Statistics 2024; World Bank Group, 2022, Opportunities for Direct Uses of Geothermal Energy in Türkiye; Lund, J. W. and Toth, A. N., 2021, Direct Utilization of Geothermal Energy 2020 Worldwide Review; Müstecaplıoğlu, M., 2021, New Presidential Decision on YEKDEM Feed-in Rates, Norton Rose Fulbright; Türkiye Ministry of Energy and Natural Resources, 2022, Türkiye National Energy Plan; UNESCO, 2021, How Türkiye became a role model for geothermal energy within a decade; World Bank Group, 2021, Türkiye to Scale-up Renewable Geothermal Energy Generation with World Bank Support; Kearney Energy Transition Institute analysis based on desktop research.

Indonesia

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Non-exhaustive; example

Indonesia has the second-greatest geothermal power capacity after the US. However, it is set to miss its original 2014 target of ~7,000 MW of geothermal power by 2025. Recent legislation focuses on accelerating geothermal deployment for power as well as heating and cooling.

Summary and current developments

Power (MW_e, 2023)	**2,418**
Direct use (MW_{th}, 2020)[1]	**2.3**
Bathing/swimming	100%

Geothermal hot springs have been used for centuries for activities like cleaning, washing, and cooking. Power generation began in the 1980s with assistance from New Zealand. Currently, Indonesia is the leading country for installed geothermal power in the APAC region.

The main challenges to geothermal development include early development risks, uncompetitive electricity tariffs, requirements to sell electricity to the national power company, PLN, under-developed infrastructure, local opposition, and lengthy permitting.

Presidential Regulation 112 **Acceleration of Renewable Energy Development for Power Supply** supports renewable energy targets, such as **3.3 GW** of geothermal capacity by 2030. It is still unclear whether the **proposed geothermal tariff** (ranging from USD 0.065/kWh to USD 0.107/kWh) will catalyze development.

Since 2020, rules and regulations have been announced for developing geothermal heating and cooling. Updated targets are ambitious, aiming for more than 5,000 MW_e by 2030.

Key enabling policies

1974: Presidential Decree no. 16 authorized state-owned Pertamina Geothermal Energy (PGE) to carry out geothermal exploration.

2000: Presidential Decree no. 76 repealed PGE's monopoly over exploration of geothermal resources.

2010/2011: Rulings by the PMK[2] created financial incentives, such as reduced income taxes, VAT exemption, and power purchase guarantees.

2012: PMK 03/2012 created a Geothermal Sector Infrastructure Financing Fund (PISP) for early geothermal exploration.

2014: Geothermal Law separated geothermal activities from mining activities, easing development restrictions.

2020: Geothermal Resource Risk Mitigation Project in Indonesia launched by the World Bank.

2022: PMK 08/2022 amended PISP to cover both public and private drilling risks and expanded the types of risks covered. **Presidential Regulation 112** created a **new tariff structure** to accelerate renewables deployment.

2024: Indonesia-New Zealand Partnership 2025-2029 outlined intentions to collaborate on geothermal knowledge sharing.

1. While there are various examples of agricultural and aquacultural uses of geothermal energy and brine in Indonesia, estimates for capacity used are not available.
2. PMK stands for the Ministry of Finance Regulation in Indonesia. PMK regulations cover a wide range of fiscal and financial matters.

Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; IRENA, 2024, Renewable Capacity Statistics 2024; Lund, J. W. and Toth, A. N., 2021, Direct Utilization of Geothermal Energy 2020 Worldwide Review; Nakaayi, A. and Nyakabwa-Atwoki, R. K. B., 2024, International Outlook on Policy, Legal and Regulatory Aspects and Risk Mitigation Facilities for Geothermal Resource Development; Kearney Energy Transition Institute analysis.

Kenya

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Non-exhaustive; example

Kenya's geothermal power development was successfully led by the public sector. Later, public-private partnerships became more common. Recent projects have proceeded despite pricing uncertainty from PPA moratoriums due to high electricity tariff prices.

Summary and current developments

Power (MW_e, 2023)	**984**
Direct use (MW_{th}, 2020)	**18.5**
Bathing/swimming	47%
Greenhouse/agriculture	30%
Other	23%

Most of Kenya's geothermal resources are in the Great Rift Valley, estimated to have 7,000-10,000 MWth of geothermal capacity.

Development of geothermal energy commenced in the 1950s but only gained traction in the 1970s and 1980s under the state-owned **Kenya Electricity Generating Company (KenGen)**.

Geothermal power capacity increased from 15% of total electricity generation in 2010 to more than 40% in 2021. This rapid increase was due to **public financing**, **risk mitigation**, and **policies for incentives and private sector investment**. While projects by independent producers have been announced as recently as 2024, some uncertainty in geothermal power purchase agreements (PPA) remains due to PPA moratoriums.

Kenya has targeted **1.6 GW of geothermal power by 2030**. While power is the primary use case, direct use is gaining popularity for greenhouses and fish farming.

Key enabling policies

1982: Geothermal Resources Act vested rights to geothermal resources with the government and defined a framework for resource development.

1999: Electric Power Act created a development framework for the electric power sector.

1999: Environmental Management and Coordination Act set standards for environmental impact assessments for the power sector.

2008: State-owned **Geothermal Development Company** (GDC) created to lead geothermal development. Its tasks are resource exploration and assessment; well drilling; development and management of steam-fields; early generation[1] and sale of steam to power producers; and promoting direct use.

2010: Geothermal feed in tariff (FIT) introduced for plants < 70 MW, of USD 8.5 cents/kWh.

2013: Public Private Partnership Act created frameworks for public private partnerships.

2019: Energy Act consolidated various energy laws, redefined the geothermal development framework, and defined fiscal incentives for project developers.

2021-2025: Geothermal Risk Transfer Facility established by development agency FSD Africa to provide insurance for early drilling activity of geothermal projects in Kenya and Ethiopia.

1. Early generation is achieved via wellhead generators, which can be installed on individual wells before a full geothermal powerplant is constructed.

Sources: IRENA, 2023, Global Geothermal Market and Technology Assessment; IRENA, 2024, Renewable Capacity Statistics 2024; Lund, J. W. and Toth, A. N., 2021, Direct Utilization of Geothermal Energy 2020 Worldwide Review; Mwawughanga, F. M., 2005, Regulatory Framework for Geothermal in Kenya; Nakaayi, A. and Nyakabwa-Atwoki, R. K. B., 2024, International Outlook on Policy, Legal and Regulatory Aspects and Risk Mitigation Facilities for Geothermal Resource Development; Kearney Energy Transition Institute analysis.

Japan

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Non-exhaustive; example

Early development of geothermal was encouraged with government support. After a 20-year standstill, recent **research and subsidies** are encouraging geothermal power development. **Hot springs** remain the largest direct heating application.

Summary and current developments

Power (MW_e, 2023)	**428**[1]
Direct use (MW_{th}, 2020)	**2,570.46**
Bathing/swimming	77.8%
GHP[2]	6.4%
Snow melting	5.8%
District heating	4.3%
Other	5.7%

Government resource development and cost-sharing incentivized initial geothermal power projects in Japan. However, project development stalled after 1995.

The 2011 Fukushima accident catalyzed renewed interest. A **feed-in tariff** (FIT) incentivized development of **small binary power plants**, but total capacity increase has not yet matched earlier development rates.

The Japan Organization of Metals and Energy Security (JOGMEC) currently has three mechanisms supporting geothermal power projects: grant subsidies, equity capital investments, and loan liability guarantees. However, geothermal power development has historically faced pushback from the hot springs (onsen) industry.

The primary use case for geothermal heating is bathing and swimming at onsen. GHP use is also expected to grow due to government incentives.

Key enabling policies

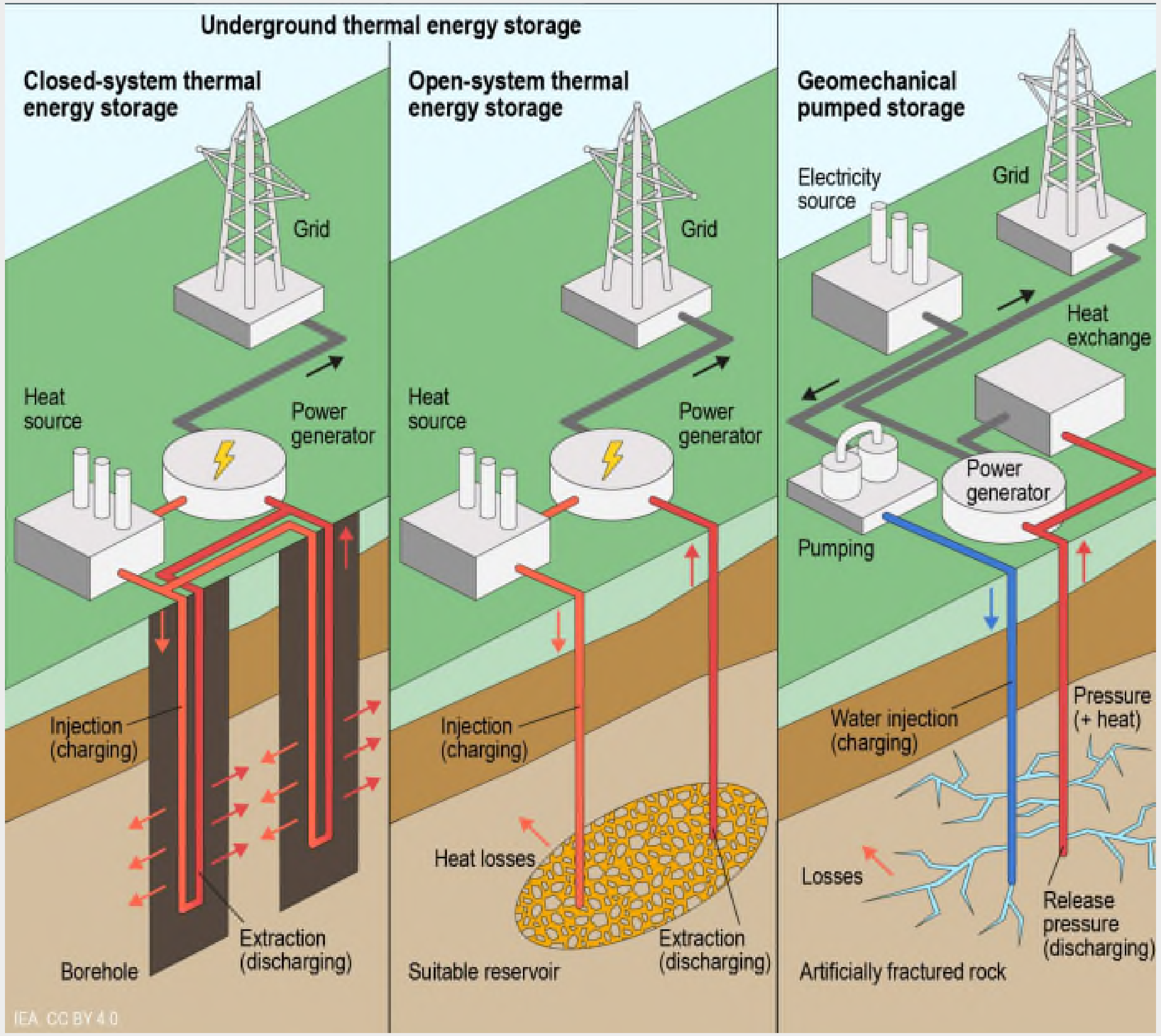
- **1974:** Government serves as a geothermal resource developer
- **1980:** Introduced cost-sharing program: government covers up to 40% of exploration well costs and 20% of production and injection well costs. Program ended in 2002.
- **2013: JOGMEC** begins survey program to gather and publish geothermal data.
- **2012: FIT** introduced for 15-year contracts; currently JPY 40/kWh (USD 0.35) for plants < 15 MW and JPY 26/kWh (USD 0.23) for larger projects.
- **2017:** Research project launched on supercritical geothermal resources in line with national energy strategy for 2050.
- **2021:** Introduced deregulation measures to accelerate operation start dates.
- **2024:** Ministry of Economy, Trade, and Industry announced subsidies for six projects to **promote public awareness of geothermal**.
- **2024:** JOGMEC awarded subsidies to six projects through its **Geothermal Resource Survey Subsidy Program**.

1. Estimates range up to 499.4 MW (Yasukawa 2023). 2. Geothermal heat pump. 3. New Energy and Industrial Technology Development Organization. 4. Enhanced (engineered) geothermal systems.
Sources: ESMAP, 2016, Comparative Analysis of Approaches to Geothermal Resource Risk Mitigation; IRENA, 2023, Global Geothermal Market and Technology Assessment; IRENA, 2024, Renewable Capacity Statistics 2024; Lund, J. W. and Toth, A. N., 2021, Direct Utilization of Geothermal Energy 2020 Worldwide Review; Yasukawa, K., 2024, 2023 Japan Country Report, IEA Geothermal; Kearney Energy Transition Institute analysis.

Appendix on geothermal energy storage

Underground rock formation can store energy in different ways

Overview of geothermal energy storage



Sources: IEA, 2024, The future of geothermal energy; Kearney Energy Transition Institute analysis

Underground thermal energy storage (UTES):

- Corresponds to systems designed to **store heat or cold.**
- Can be used as **seasonal storage** or for **district heating** applications.
- Can be achieved through **closed- or open-loop** designs.
- Requires **suitable geological conditions**, such as **natural aquifers**, **abandoned mines**, or **created boreholes**.

Mechanical underground energy storage, or geomechanical pumped storage:

- Corresponds to systems using excess electricity to **pump water into underground reservoirs** created by hydraulic fracking.
- Utilizes the **elasticity of underground rock formations to store and recover energy**.
- **Stored energy is retrieved by releasing the pressurized water**, which generates electricity as it flows back to the surface.

Geothermal energy storage

Geothermal energy storage systems features and performance

Feature	Unit	UTES[1]	Geomechanical pumped storage
Global installed capacity	**($MW_{e(th)}$)**	2,900	0-3
Average plant capacity	**($MW_{e(th)}$)**	1-10	1-10
Operating temperature	**(°C)**	20-95	100-250
Operating depth	**(km)**	0.02-2	2-3
Lifetime	**(years)**	50	Unknown
Upfront investment	**($USD/kW_{e(th)}$)**	Unknown	Unknown
LCOS[2]	**($USD/kW_{e(t)}$)**	0.02-0.40	0.02-0.10
Geothermal resource	**-**	Aquifers or subsurface	Deep geothermal reservoirs and hot dry rocks

Geothermal energy storage

Pros and cons of geothermal energy storage

Advantages	Disadvantages
– **Supports energy security** by storing excess energy – **Reduces curtailment** – **Balances intermittent renewables**	– **High upfront investment** – **Limited to specific geographies** with suitable and accessible geothermal resources – Yet to be delivered at scale

Innovation, research, and development

Underground thermal energy storage

- **Design parameters:** Improve system size and insulation materials to reduce LCOH[3] and enhance storage capability.
- **Depth:** Deeper systems may offer better round-trip storage efficiency.
- **Data reporting:** Standardized data reporting will aid policymaking for UTES.

Geomechanical pumped storage

- **Underground rock formation:** Transforming underground rock formations into elastic storage systems, e.g., *QuidNet Energy*, to bypass the geographic limitations of traditional energy storage methods.
- **Renewables:** Combining energy storage with renewable generation technologies; e.g., *Sage Geosystems' EarthStore* storage facility in Texas alongside solar PV.
- **Depth:** Greater depths to reach higher temperatures; e.g., *Fervo Energy* project at ~2.4 km deep and ~190°C.

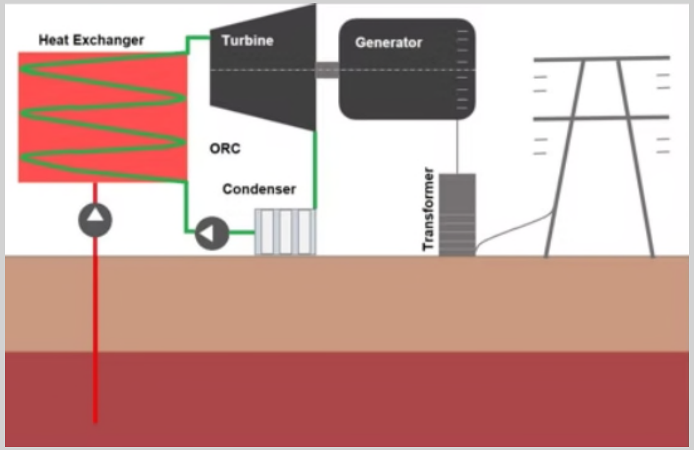
1. Underground thermal energy storage; 2. LCOS denote levelized cost of storage. 3. LCOH denote levelized cost of heat.
Sources: Kearney Energy Transition Institute analysis based on desktop research

Underground thermal storage can be combined with existing infrastructure from renewables, oil and gas, and mines

Recovery heat from heavy oil reservoirs

Heavy oil reservoirs can be used as **long-term underground thermal storage** by **injecting heated water or steam into the heavy oil reservoir**, which will be slowly—in the range of months/years—**displacing the oil** by gravity, or by reducing the oil viscosity. The injected steam or water can be heated at the surface through electricity or burning natural gas.

- A couple of Canadian companies (C-FER and ABClean Energy) are planning to design this type of recovery plan, though the feasibility of such systems is still to be proven.

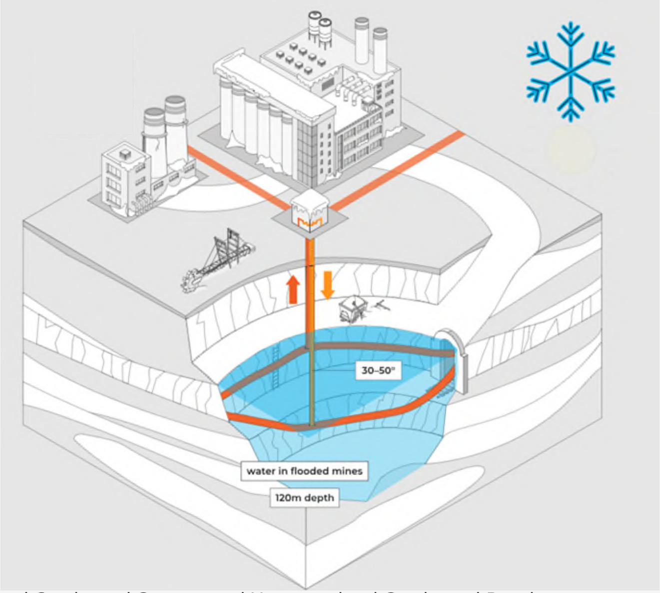


Seasonal storage with closed mines

When operating as storage, the system **uses the insulating properties** of the subsurface.

Mine thermal energy storage (MTES) allows **seasonal storage** by injecting hot water into the mine during summer and extracting it in winter through a heat pump. The water can be heated with the excess of electricity from renewable energy or through waste heat recovery from industrial processes.

This type of system is considered fifth-generation district heating and cooling, as it integrates different energy sources. MTES **technology is under development; there are currently very few systems operational globally** (United Downs in the UK, Bochum in Germany, Minjwater in Heerlen).



Sources: Geothermal rising, accessed 2024, Geothermal in hybrid renewable systems; Khodayar, M. and Björnsson, S., 2024, Conventional Geothermal Systems and Unconventional Geothermal Developments: An Overview, Open Journal of Geology; PUSH-IT, accessed September 2024, Piloting Underground Storage of Heat in Geothermal Reservoirs; Kearney Energy Transition Institute analysis.

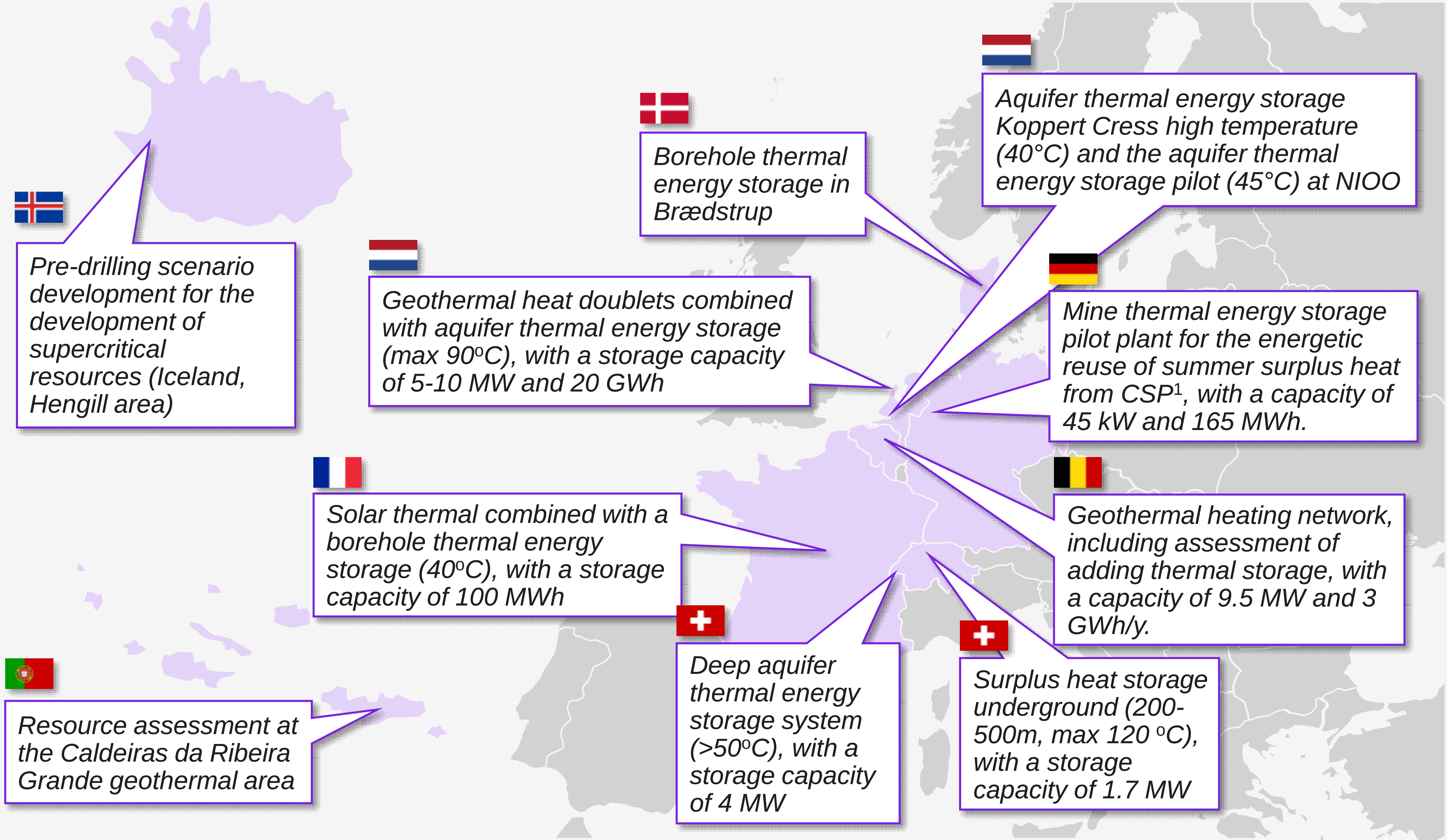
Storing energy through geothermal technologies is mostly found in Europe and at early demonstration phase

Energy storage using geothermal technologies is primarily concentrated in Europe and remains at early demonstration stage.

Geothermal energy storage

Geothermal energy storage projects

2023



1. Concentrated solar thermal

Sources: Koornneef et al., 2021, HEATSTORE Project Update: High Temperature Underground Thermal Energy Storage, IGA; Kearney Energy Transition Institute analysis

While geothermal energy storage is a mature technology, it is not widely commercialized

Non-exhaustive

Interest in underground thermal energy storage is growing due to heating and cooling **decarbonization goals.** Synergies between geomechanical pumped storage and **emerging geothermal technologies** are being addressed by start-ups.

Geothermal energy storage

UTES is a solution for decarbonizing heating and cooling[1]

Interest in commercializing UTES has recently grown due to its potential role in sustainable energy systems, such as **district heating and cooling** (DHC) or **providing flexibility** to the electricity grid. However, widespread adoption of UTES **requires awareness building and technology development** adapted to these uses, particularly at medium-deep storage depths.

The **European Union** has sponsored multiple projects on UTES:

- The EU **HeatStore** project sponsored 6 UTES pilots (2018-2021).
- Horizon Europe funded **EUR 19.8 million** (2022) for the PUSH-IT project for pilot UTES in geothermal reservoirs.
- The 2023 Strategic Research and Innovation Agenda of ETIP-G[1] recommended **EUR 200 million** for 20 high-temperature UTES pilot projects in the next five years.

The potential of geomechanical pumped storage expands with the use of emerging geothermal technologies

Geomechanical pumped storage can create **flexibility and synergistic coupling** with geothermal power technologies. Policies can support research and start-ups that are developing **storage alongside enhanced geothermal systems** (EGS):

Fervo Energy – raised **USD 244 million** in 2024 for its EGS projects and received **USD 4.5 million** from the DOE (2022-2024) to develop its geothermal storage technology, **Fervo Flex**.

Sage Geosystems – raised **USD 17 million** in 2024 to fund its first-of-a-kind 3MW energy storage facility, EarthStore. The technology was demonstrated in 2023, producing 200 kW for > 18 hours and 1 MW for 30 minutes.

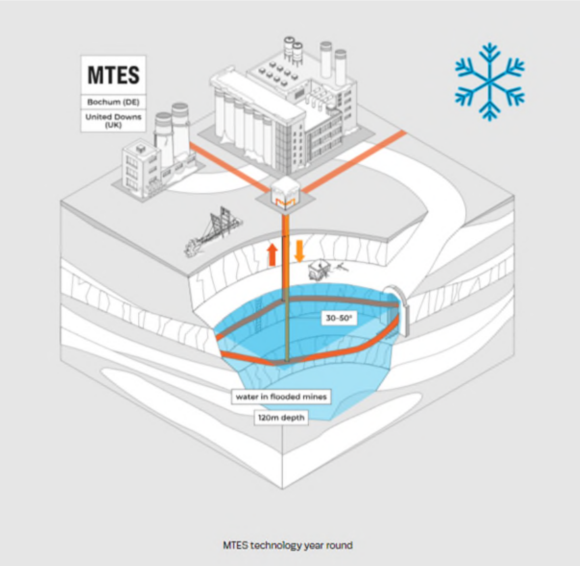
Key policies for UTES

- Support R&D grants for emerging storage technologies to reduce technology risks and improve performance.
- Sponsor early resource exploration to confirm resource suitability.
- Build awareness and technological skills to install UTES as part of decarbonized DHC systems and energy storage.
- Develop financing frameworks to incentivize project development, such as grants for early start-ups.
- Streamline development frameworks and permitting processes for installing DHC and thermal energy storage projects.
- Enact energy efficiency, and clean heating and cooling policies.

1. The European Technology and Innovation Platform on Geothermal

Sources: European Commission Joint Research Centre, 2023, Deep Geothermal Heat and Power in the European Union; Fervo Energy, 2024, Fervo Energy Raises $244 Million to Accelerate Deployment of Next-Generation Geothermal; GeoThermica, 2022, Final Report – Public Version HeatStore; IRENA, 2023, Global Geothermal Market and Technology Assessment; Sage Geosystems, 2024, Sage Geosystems Raises $17 Million in Series A, Announces World's First Commercial Geopressured Geothermal System (GGS) Facility; Kearney Energy Transition Institute analysis.

Geothermal resources can be used as thermal energy stores underground



Pros

- Reduce fossil fuel use in district heating.
- Provide flexibility to maximize use of renewable energy for heating and cooling.
- Balance seasonal heating and cooling demand with seasonal energy storage.
- Geomechanical pumped storage systems can provide flexible electricity on-demand.

Cons

- Limited to suitable geographies for certain storage systems (e.g. aquifer thermal energy storage).
- Limited to certain temperatures based on regulation and environmental safety (especially for ATES).
- Geomechanical pumped storage systems are still in R&D phases.

Overview and working principle

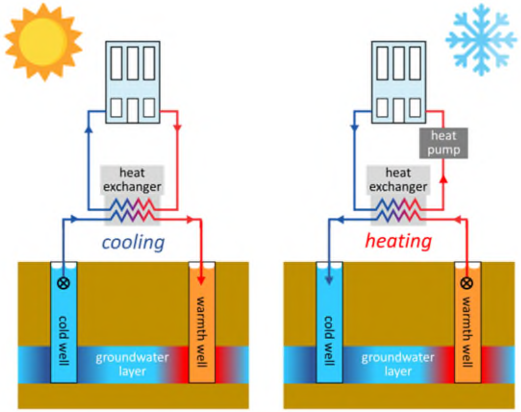
- Underground thermal energy storage injects warmed water or working fluid into the earth via boreholes (closed loop), or open-loop aquifers, flooded caves, and repurposed mines or oil and gas fields. Geomechanical pumped storage systems (> 100°C) can use deeper enhanced geothermal systems to inject working fluids and store energy.
- UTES technologies are mainly used for **seasonal energy storage for district heating and cooling**. The two main technologies used today are **aquifer thermal energy storage** (ATES) and **borehole thermal energy storage** (BTES).[1] Less common systems **repurpose old mining, oil, and gas sites**. For example, a flooded and abandoned coal mine has been used in Nova Scotia, Canada to provide heat seasonally for various consumers since 1989.
- UTES requires balancing the amount of thermal energy injected and extracted throughout the year. UTES is considered a mature technology.
- Emerging **geomechanical pumped storage systems** use deeper wells of enhanced geothermal systems and inject fluids into the geology. After fluid is injected, it is further heated and pressurized by the earth's temperature. Charge and discharge cycles control when the fluid is released.
- With the use of high-temperature resources, **geomechanical pumped storage systems** can not only provide heating solutions but could also be used to **generate electricity**. Several start-ups are experimenting with high-temperature storage.

Geothermal energy storage

1. While tank thermal energy storage (TTES) and pit thermal energy storage (PTES) are often cited alongside ATES and BTES, they store heat due to insulation from their external environments, and thus they do not involve purposeful heat exchange with geothermal energy.

Sources: : Baddour, D., 2024, How a technology similar to fracking can store renewable energy underground without lithium batteries, Inside Climate News; European Commission Joint Research Centre, 2023, Deep Geothermal Heat and Power in the European Union, EU Horizon Europe PUSH-IT, 2023, The Technologies; IRENA, 2020, Innovation Outlook: Thermal Energy Storage; Kearney Energy Transition Institute analysis.

Underground thermal energy storage (UTES): FactCard



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity[2]	2,900	MW_{th}	◕
Average plant capacity	1-10	MW_{th}	○
Resource temperature	20-95	°C	○
Resource depth	0.02-2	km	○
Lifetime	~50	Years	◕
Upfront investment	Unknown	USD/kW_{th}	-
LCOH	0.02-0.40	USD/kWh	●
Efficiency	50-90	%	●
Geothermal resource	Aquifers and subsurface		

Description

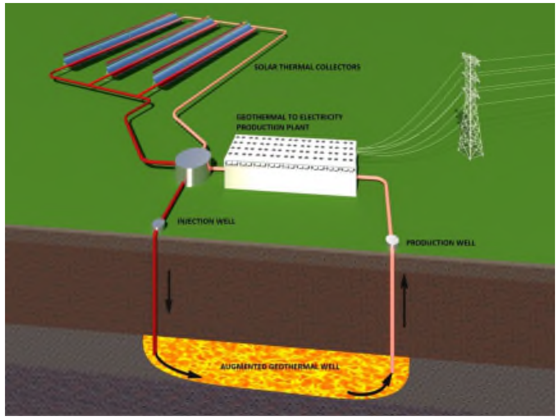
- While UTES[1] efficiency can be as high as 90%, most systems have a relatively low efficiency and are used with cheap thermal energy sources. System cost depends strongly on individual project conditions. UTES is often used with heat pumps.
- ATES systems are **open-loop**. They are mostly located in the Netherlands, Sweden, Belgium, and Denmark. ATES is typically deeper and larger capacity than BTES. ATES can either be a multi-well system (which laterally separates hot and cold water) or a mono-well system (which vertically separates hot and cold water). Injection temperatures are usually regulated to not surpass 25°C for environmental reasons. There are more than 3,000 ATES systems worldwide.
- BTES systems are **closed-loop**. Boreholes are used as a heat exchanger to store thermal energy in soil or bedrock at depths typically between 30-200m. BTES tends to be more expensive than ATES. Among seven BTES and three ATES thermal storage system levelized cost of heats reported by T. Yang et. Al. (2021), the average costs for ATES and BTES were 71 and 175 EUR/MWth, respectively. There are more than one million low-temperatures BTES systems worldwide.

Technology R&D and focus areas for innovation

- The EU **HEATSTORE** project (2019-2022) investigated UTES to **lower costs, reduce risk, and improve system performance**. The **PUSH-IT** project launched in 2023 to investigate temperature energy storage up to 90°C.
- **Design parameters** of UTES systems: The design parameters of UTES systems impact the efficiency and energy storage capability of the system. While the technology is mature, improvements can lead to lower levelized costs of heating.
- **Depth** of BTES systems: While typical BTES systems extend to several hundred meters, deeper systems may have better energy storage round trip efficiency.
- **Improving data reporting**: There is currently little standardized data on UTES systems. Data collection and reporting will assist policymaking to support UTES.
- In August 2024, the US DOE awarded USD 7.9 million for a pilot project developing geothermal reservoir **thermal energy storage for industrial process heat**.

1. Underground thermal energy storage; 2. Includes installed capacity of ATES and BTES in Sweden and the Netherlands.
Sources: Kallesøe, A. J., 2021, HEATSTORE – Underground Thermal Energy Storage (UTES) – State of the Art, Example Cases and Lessons Learned; EU Horizon Europe PUSH-IT, 2023, The Technologies; HEATSTORE, 2021, Roadmap for flexible energy systems with underground thermal energy storage towards 2050; IRENA, 2020, Innovation Outlook: Thermal Energy Storage; IRENA, 2023, Global Geothermal Market and Technology Assessment; IRENA, 2021, Low-temperature thermal energy storage; Yang, T. et. al., 2021, Seasonal thermal energy storage: A techno-economic literature review, Renewable and Sustainable Energy Reviews; Kearney Energy Transition Institute analysis.

Geomechanical pumped storage systems: FactCard



Key data

Lower/shallower ○ ◔ ◑ ◕ ● Higher/deeper

Global installed capacity	< 3	MW_{th}	○
Average plant capacity[1]	1-10	MW_{th}	○
Resource temperature	100-250	°C	◔
Resource depth	2-3	km	◑
Lifetime	Unknown	years	-
Upfront investment	Unknown	USD/kW_{th}	-
LCOH[2]	0.02-0.1	USD/kWh	○
Efficiency	~75	%	●
Geothermal resource	Deep geothermal reservoirs and hot dry rocks		

Description

– Geomechanical pumped storage systems use kilometers-deep wells that exceed 100°C to inject pressurized water for storage. The technology is also referred to as **geopressured geothermal systems,** or **compressed water energy**. Solar collectors can be used to heat the fluid.

– While the stored heated resource could be used for **heat provision**, the **high temperature and pressure allows it to be used for electricity generation**, which can occur on-demand to increase grid electricity supply.

– As an energy storage technology, the key metric to determine success of geomechanical pumped storage systems technology will be **how its LCOS[3] compares to other electricity storage**, such as lithium-ion batteries.

– Start-ups leading innovation are concentrated in Houston, Texas and build on oil and gas industry experience with fracking through using **enhanced geothermal systems**.

Technology R&D and focus areas for innovation

– **QuidNet Energy** (US) is developing a “geomechanical energy storage” system. They estimate their wells can provide 1-10 MW and store energy for 10+ hours.

– **Sage Geosystems** (US) is building its first commercial energy storage facility, **EarthStore**, in Texas alongside a solar photovoltaic installation. The 3 MW facility is estimated to provide 6-10 hours of storage capacity and is anticipated to be commissioned by the end of 2024. Pilot plant results in 2023 were cost competitive with pumped hydro energy storage.

– **Fervo Energy** demonstrated geothermal storage in its 2.4 km deep and ~190°C wells in 2023, though their first commercial plants are focused on electricity generation.

1. Based on QuidNet Energy projected capacity per well; 2. Based on Sage Geosystem’s estimates of pilot demonstration and new commercial project.; 3. Levelized cost of storage
Sources: Baddour, D., 2024, How a technology similar to fracking can store renewable energy underground without lithium batteries, Inside Climate News; European Commission Joint Research Centre, 2023, Deep Geothermal Heat and Power in the European Union; HEATSTORE, 2021, Roadmap for flexible energy systems with underground thermal energy storage towards 2050; Kearney Energy Transition Institute analysis based on desktop research.