



Energy  
Transitions  
Commission

# The role of geothermal in clean energy systems

Expert workshop  
December 2025

# Introducing the ETC's Nuclear & Geothermal workstream



## CONTEXT

- In many regions of the world, **wind and solar will be the most cost-competitive and scalable** new clean electricity generation sources
- But in some places, fast growing demand, limited land availability, or the high cost of balancing the power grid **could make other clean sources attractive**.



## ETC WORKSTREAM WILL EXPLORE

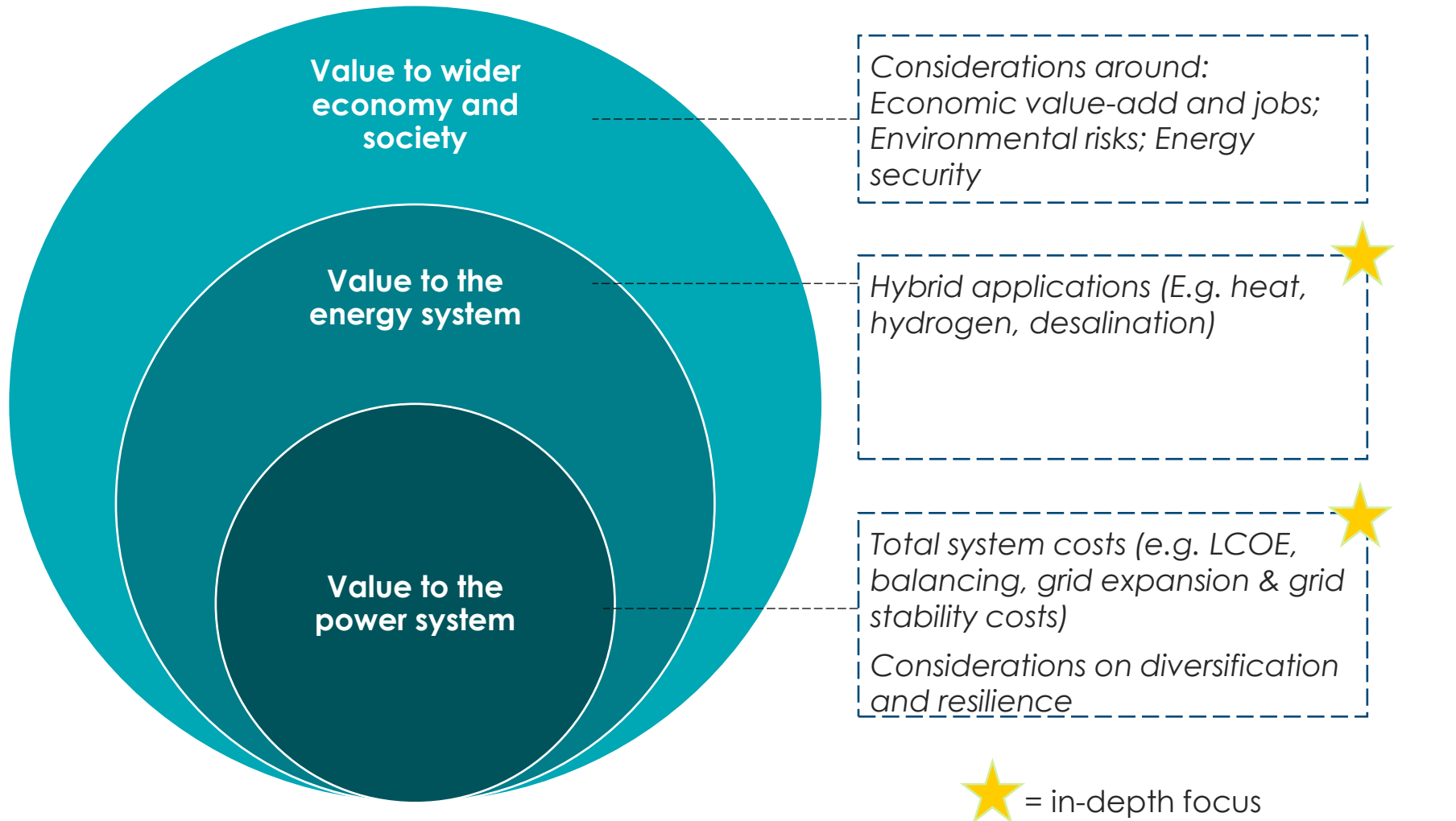
- **What is the role of nuclear and geothermal** electricity in future power systems, alongside wind and solar generation, in different regions of the world?
- Can they be delivered at low cost? Where needed, how can their deployment be scaled faster?

## WORKSHOP SCHEDULE

- Workshop 1 - The role of Nuclear** (2<sup>nd</sup> October 2025)
- Workshop 2 - The role of Geothermal** (3<sup>rd</sup> December 2025)
- Workshop 3 - Key enablers to scale Nuclear and Geothermal**



# Value of firm clean power should be assessed holistically against alternatives



**To understand how geothermal can complement a high renewable system**



# Agenda

- **Context: geothermal energy state of play**

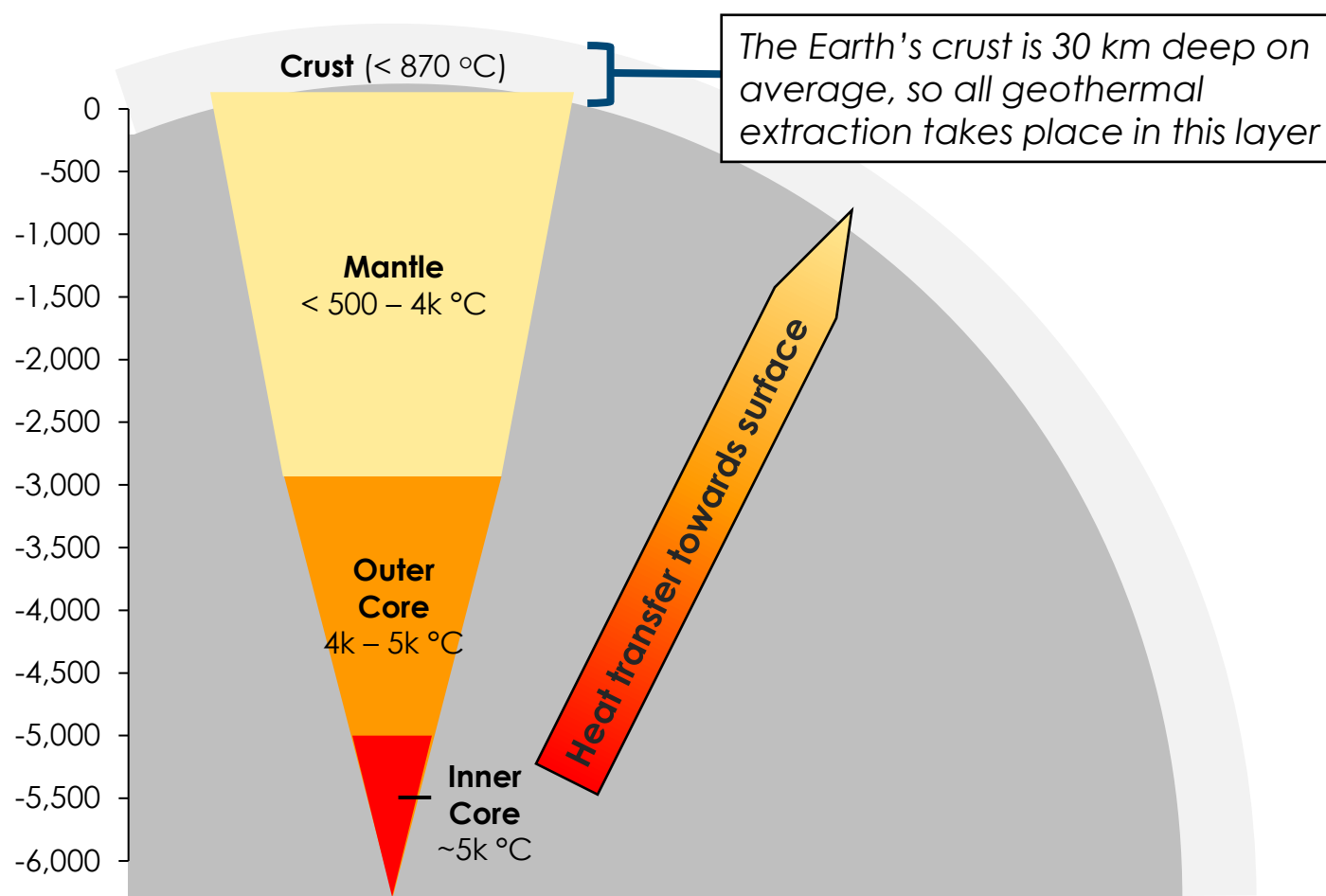
- Techno-economic deep dives: power, heat and storage
- System value considerations
- Wider considerations of geothermal development
- Emerging conclusions



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

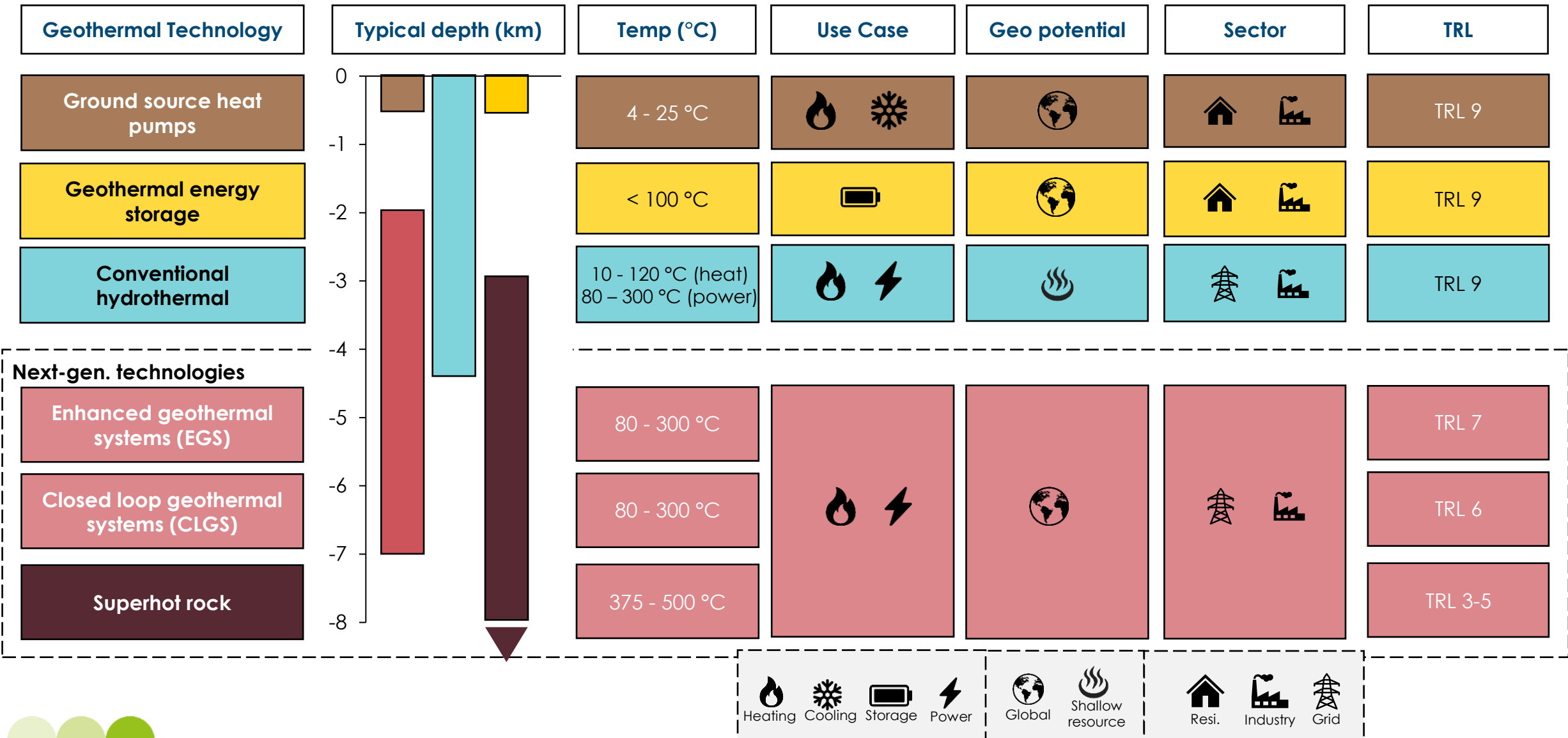
## Geothermal resource depth, temperature ranges and composition by layer (indicative)

Depth (km), temperature annotated in °C



- Geothermal energy primarily stems from the **heat stored in the Earth's core**. It is thermal energy stored in rock, soil and fluids beneath the earth's surface.
- There are several ways geothermal energy can be harnessed, and its viability depends on
  - **Subsurface conditions** (temperature gradient, depth, permeability)
  - **Surface conditions** (heat/electricity demand, infrastructure proximity)

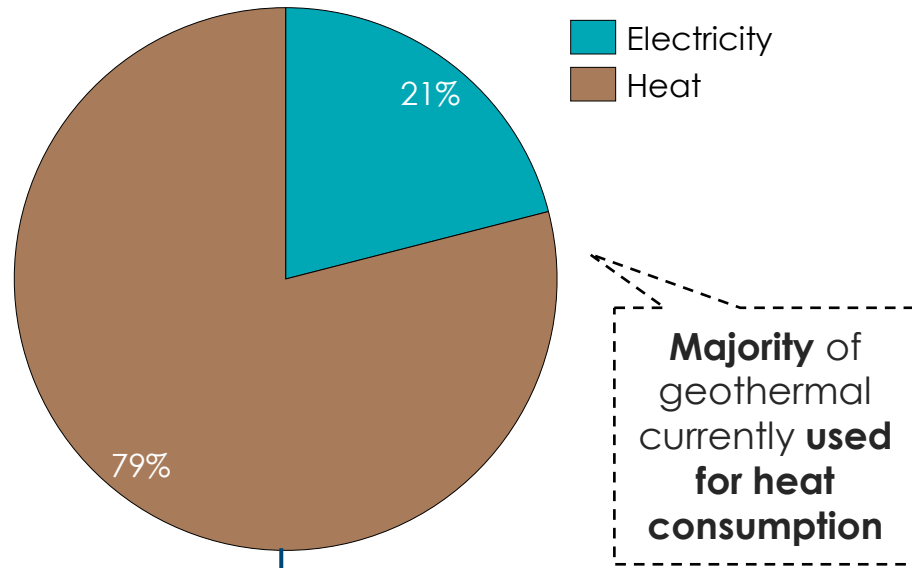
# Geothermal energy encompasses different resources and uses; power generation is currently geographically limited



Notes: Underground energy storage parameters refer to underground thermal energy storage (excluding more nascent options such as geothermal mechanical storage). Assumed TRL scale: TRL 1-3 = Research to Proof of Concept; TRL 4-6 = Lab to Pilot Demonstration; TRL 7-9 = Prototype Demonstration to FOAK / Full Commercial Deployment

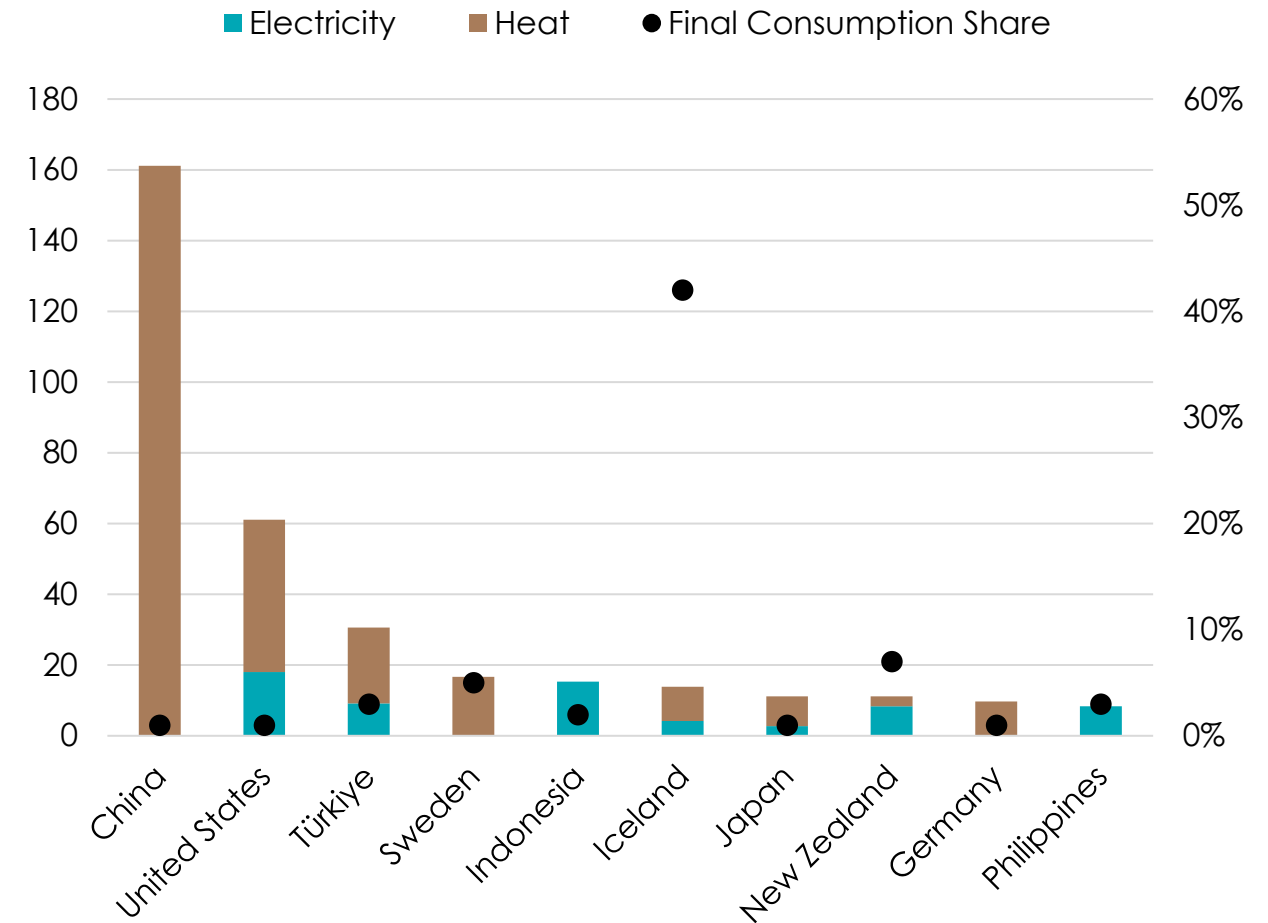
# Geothermal energy accounts for a small share of current final energy consumption, and is primarily used via shallow resource for heat

Total final geothermal energy consumption by application, world %



**Geothermal heat (via ground source heat pumps) provides space and district heating & cooling, industrial process heat, and agricultural heat**

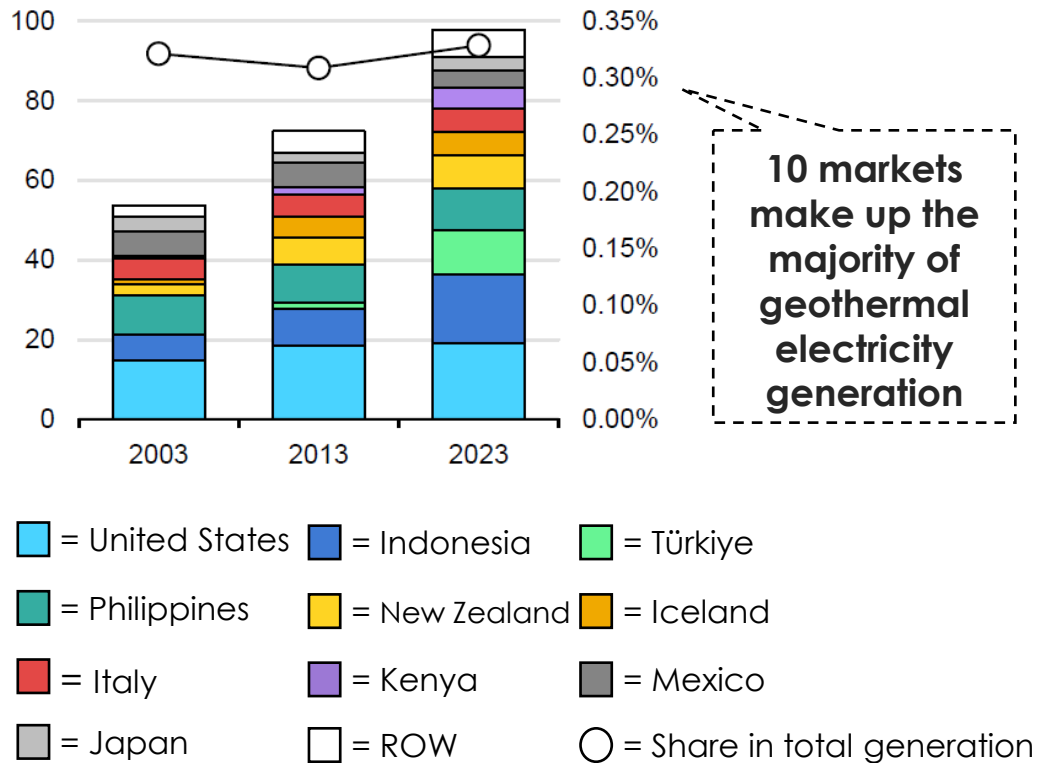
Final energy consumption by country (top ten consumers)  
GWh (LHS), % (RHS)



# Geothermal currently plays a small role in global electricity generation, and is primarily concentrated in a few countries

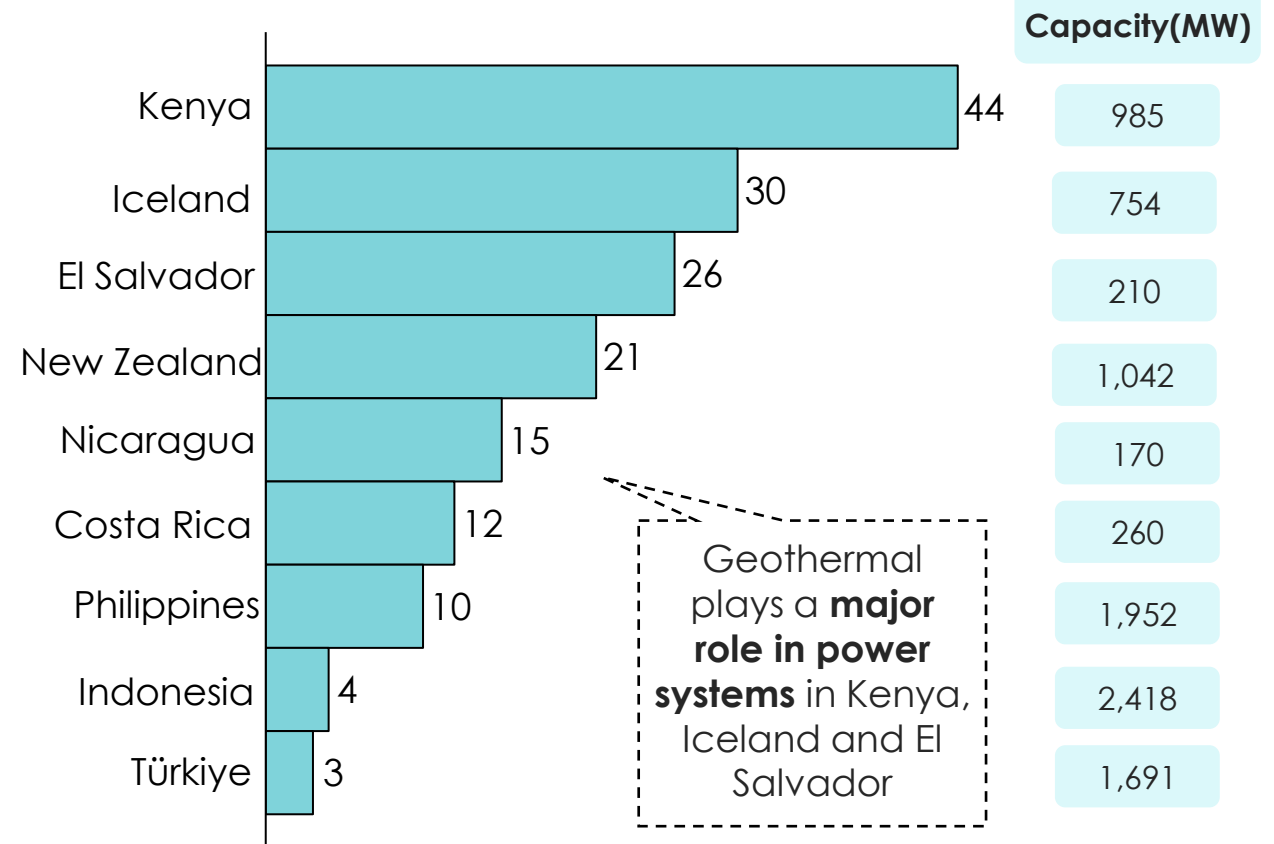
Global electricity generation from geothermal, % of global total

TWh



Share of total national electricity generation, 2023

%



Source: IEA (2024) The Future of Geothermal Energy; ThinkGeoEnergy (2025), ThinkGeoEnergy's Top 10 Geothermal Countries 2023: Power Generation Capacity; SIGET (2024), Capacidad instalada de generacion eectrica 2023; TheGlobalEconomy.com (2024), Nicaragua: Geothermal electricity capacity (MW); International Renewable Energy Agency (2024), Renewable Capacity Statistics 2024



# Next-generation technologies aim to significantly expand potential role of geothermal

**Conventional technologies** are constrained by resource availability...

## Conventional

### Ground source heat pumps / Hydrothermal

- Ground source heat pumps rely on widely available low-temperature thermal resource
- Hydrothermal relies on naturally-occurring fractures and thermal resources that only exist in niche locations
- Fluids circulate openly through naturally occurring fractures

**Next generation technologies** are aiming to grow the potential by...

- **Decoupling the need for natural resource availability**, via engineered systems
- **Leveraging transferrable** technology, supply chains, and workforces **from the oil & gas sector**

## Next-generation

### Enhanced geothermal systems (EGS)

- Heat accessed via engineered fractures in commonly found environments
- Fluids circulate openly within a well pair connected by fractures engineered with hydraulic fracturing & horizontal drilling

### Closed-loop geothermal systems (CLGS)

- Heat accessed via a closed-loop pipe running through rock
- Fluids circulate through a long series of closed wellbore loops permeating the subsurface

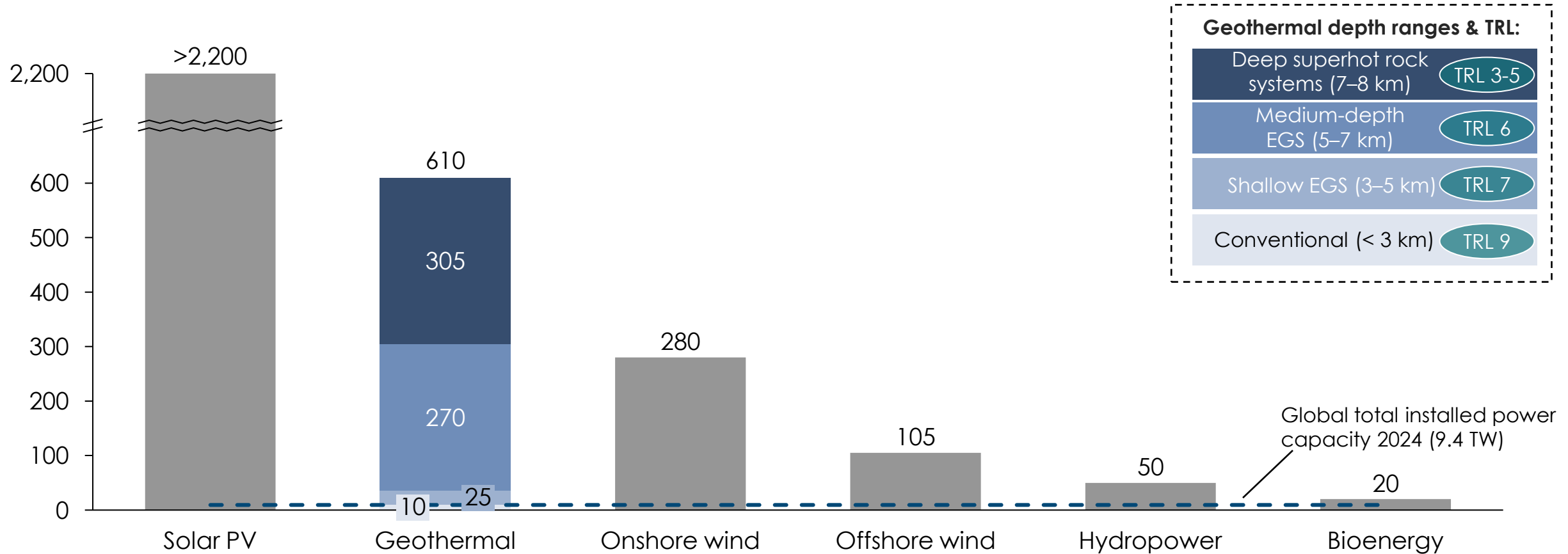
### Superhot rock

- Ultra-deep EGS accessing high-temperature resource in superhot crystalline rock
- Can require plasma, millimeter-wave, or spallation drilling techniques.

# By expanding available resource across geographies, next-generation technologies could unlock significant power generation potential

Technical potential of selected renewable energy technologies for electricity generation (IEA estimate)

TW

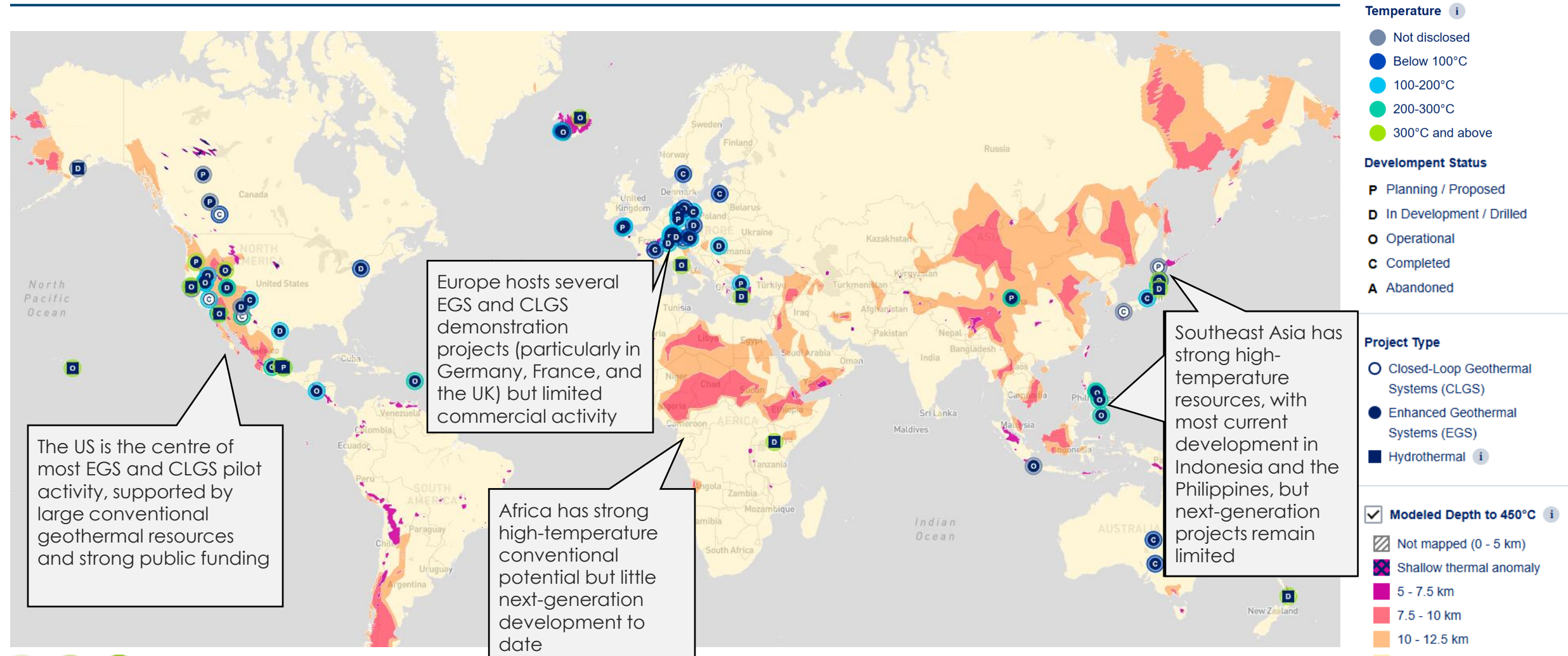


Source: IEA (2024) *The Future of Geothermal Energy: Geothermal: Project InnerSpace™ calculations for EGSs based on GeoMap™ data with a threshold of USD 300/MWh, in collaboration with IEA. Offshore wind: IEA (2019), Offshore Wind Outlook 2019. Hydropower: IEA TCP 2010. Bioenergy: IEA calculation based on the assumption that all sustainable bioenergy potential of 100 EJ is used for power generation. Onshore wind: Based on DTU-2027 study. Solar PV: Technical potential from various studies in de La Beaumelle N.A. et al. (2023), The Global Technical, Economic, and Feasible Potential of Renewable Electricity.*



# Next generation geothermal power project development is expanding, with activity concentrated in North America, Europe, and APAC

## Global geothermal project deployment map



Notes: APAC = Asia-Pacific. Shaded thermal regions indicate broad geothermal gradients, not specific next-generation resource requirements.  
 Sources: Clean Air Task Force (2025), The Next Generation of Geothermal Energy. Available at: <https://www.caff.us/shr-map/>

# Tech companies and governments are increasing interest in geothermal for power

## Industry / Big Tech

- **Google:**
  - In 2021, **agreement with NV Energy to purchase 115 MW<sub>e</sub> by 2030** from next-gen geothermal project developed by Fervo
  - In 2025, **10 MW<sub>e</sub> geothermal PPA** with Baseload Capital in Taiwan, commencing in 2029
- **Microsoft:** In 2024, **partnered with G42**, UAE-based AI company, to build a 1 GW<sub>e</sub> geothermal-powered data centre **in Kenya by 2027**.
- **XGS Energy and Meta have partnered on a 150 MW<sub>e</sub>** next-generation geothermal project in New Mexico, targeting operations in 2030

## Governments

- The **U.S. Department of Energy** found that **geothermal energy could provide up to 120 GW<sub>e</sub> (16% of generation)** across the US.
- The California Public Utilities Commission mandated procurement of 1 GW of clean firm power by 2026, resulting in **262 MW<sub>e</sub> of new geothermal PPAs**.
- **Kenya** has significant geothermal resources and aims to reach **5 GW<sub>e</sub> by 2030** (up from ~1 GW today).
- The **Indonesian** government aims to reach 7.8 GW by 2030 and **9.3 GW<sub>e</sub> by 2035** (up from 2.6 GW today)

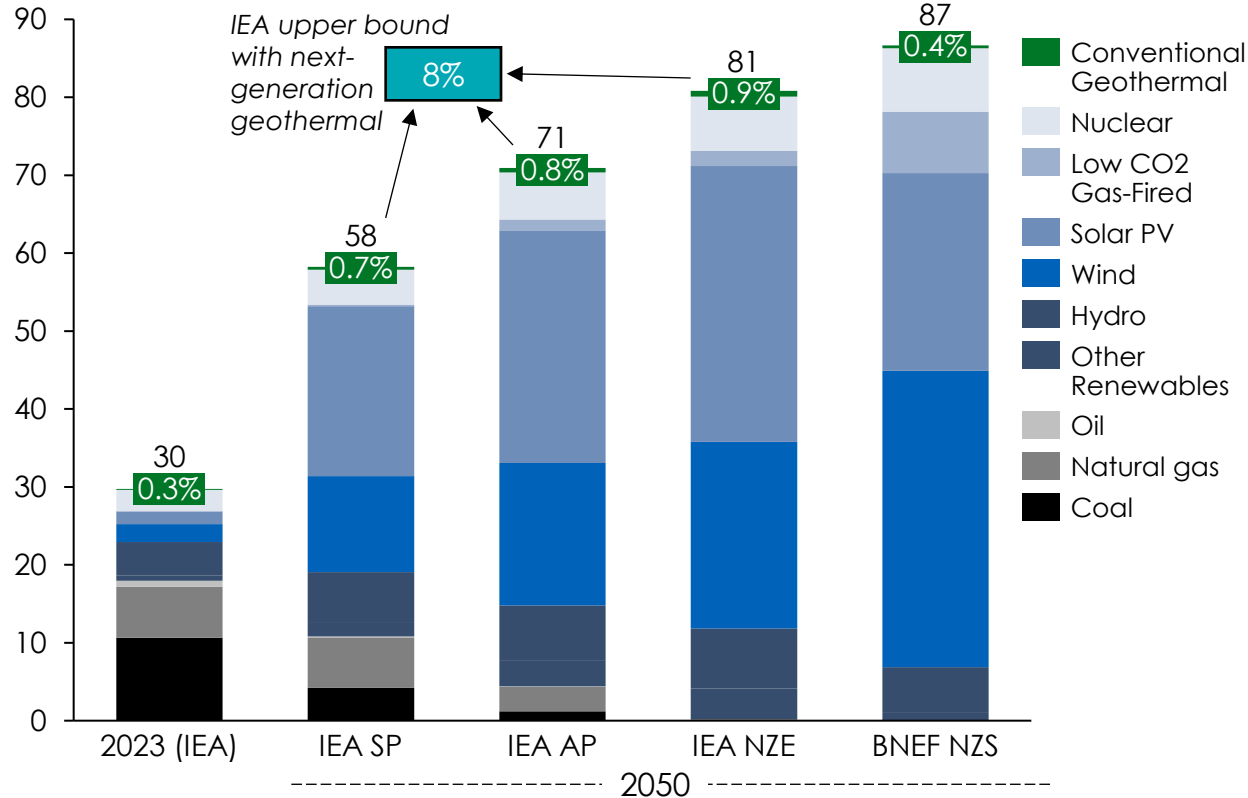


Source: Google (2023), *A first-of-its-kind geothermal project is now operational*; Financial Times (2025), *How geothermal energy could provide 'always on' supply*; Data Center Dynamics (2025), *Google signs 10 MW geothermal PPA with Baseload Capital in Taiwan*; Business Wire (2025), *XGS Energy and Meta to partner on 150 MW advanced geothermal project*; Think Geoenergy (2025), *How Kenya's energy policy is driving geothermal development*; Proceedings World Geothermal Congress 2023 (2023), *Country Update: Geothermal as The Backbone of Energy Security in Indonesia's Energy Transition*

# Future scenarios show geothermal could make up 1-8% of power generation, and 2-5% of heat in 2050, depending on next-generation scale up

Global geothermal share of electricity by scenario (2023 and 2050)

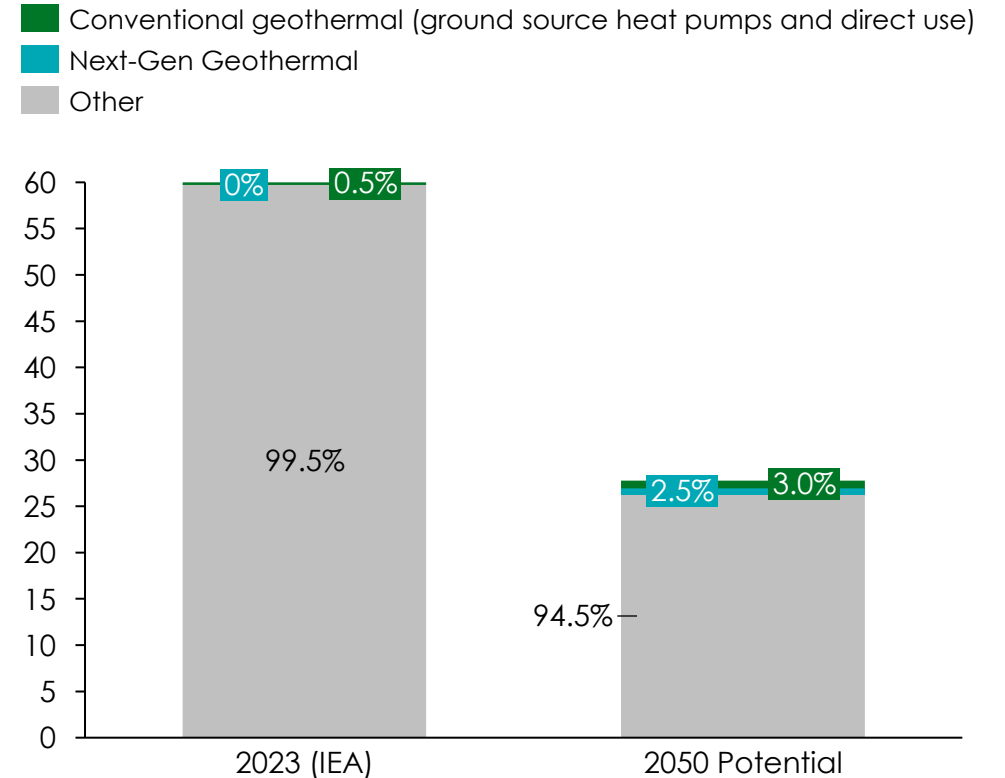
TWh<sub>e</sub>



Geothermal share of global electricity generation remains <1% across existing scenarios – next-generation technologies change this

Global geothermal share of heat by scenario (2023 and 2050)

TWh<sub>th</sub>



Geothermal share of global heat has potential growth opportunities which are expanding into cooling

Notes: SP = Stated Policies, AP = Announced Pledges, NZE = Net Zero Emissions, ETS = Economic Transition Scenario, NZS = Net Zero Scenario. Heat shares were estimated based on IEA Net Zero Scenario data and 2050 demand was estimated to be 100 EJ split between industry (60 EJ) and buildings (40 EJ). Sources: BNEF (2025), *New Energy Outlook 2025*; IEA (2024), *World Energy Outlook 2024*; IEA (2024) *The Future of Geothermal Energy*

## This workshop will explore the following key questions:

- 1) What role will geothermal play in clean power systems and to what extent will next-generation technologies significantly change the landscape?
- 2) What are the prospects for scaling geothermal heating and cooling systems, and the impact of next-generation technologies? What are key end use applications for geothermal heating and cooling?
- 3) What are the prospects for geothermal energy storage?
- 4) What are the system-level implications of geothermal scale-up pathways?
- 5) What are the wider considerations around the risks and benefits of geothermal?



# Agenda

- Context: geothermal energy state of play
- **Techno-economic deep dives: power, heat and storage**
- System value considerations
- Wider considerations of geothermal development
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# Technology overview



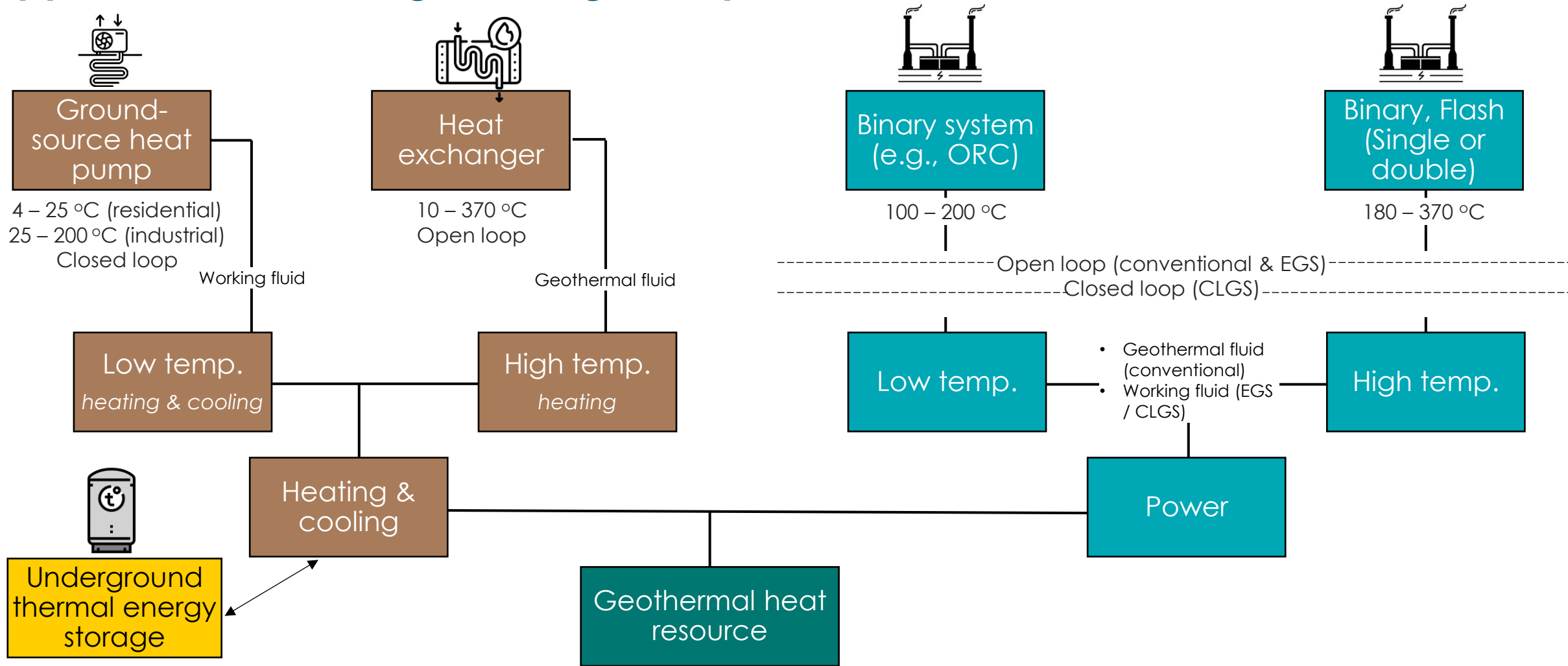
# Geothermal heat and power generation technologies range from high-maturity shallow geothermal to low-maturity ultra-deep superhot rock

	Conventional		Next-Generation		
	Ground source heat pumps	Hydrothermal	Enhanced geothermal systems (EGS)	Closed-loop geothermal systems (CLGS)	Superhot rock
Resource depth (km)	< 0.5	< 3.5	2 – 7	2 – 7	3 – 20
Application	Heat or cooling	Heat or power	Heat or power	Heat or power	Heat or power
Resource temp. (°C)	4 – 25	10 - 120 (heat) 80 - 300 (power)	80 – 300	70 – 400	375 – 500
Output per well (MW)	0.002 – 0.02 MW <sub>th</sub>	3 – 10 MW <sub>e</sub> 10 – 50 MW <sub>th</sub>	3 – 10 MW <sub>e</sub> 10 – 50 MW <sub>th</sub>	1 – 4 MW <sub>e</sub> 5 – 15 MW <sub>th</sub>	10 – 30 MW <sub>e</sub> 100 – 150 MW <sub>th</sub>
Market Leaders					
<div style="border: 1px solid green; padding: 5px; margin-bottom: 5px;">Natural reservoir</div> <div style="border: 1px solid blue; padding: 5px; margin-bottom: 5px;">Reservoir not required</div> <div style="border: 1px solid orange; padding: 5px;">Engineered reservoir</div>					
TRL (Technology readiness level)	9	9	7	6	3-5

Hybrid next-generation sites are also under development

Notes: Assumed TRL scale: TRL 1-3 = Research to Proof of Concept; TRL 4-6 = Lab to Pilot Demonstration; TRL 7-9 = Prototype Demonstration to FOAK / Full Commercial Deployment  
 Source: BNEF (2025), US Next-Generation Geothermal Makes Unsung Progress; US DoE (2024) Pathways to Commercial Liftoff: Next-Generation Geothermal Power Updated

# Geothermal energy surface technologies vary by temperature and application in heating, cooling, and power uses



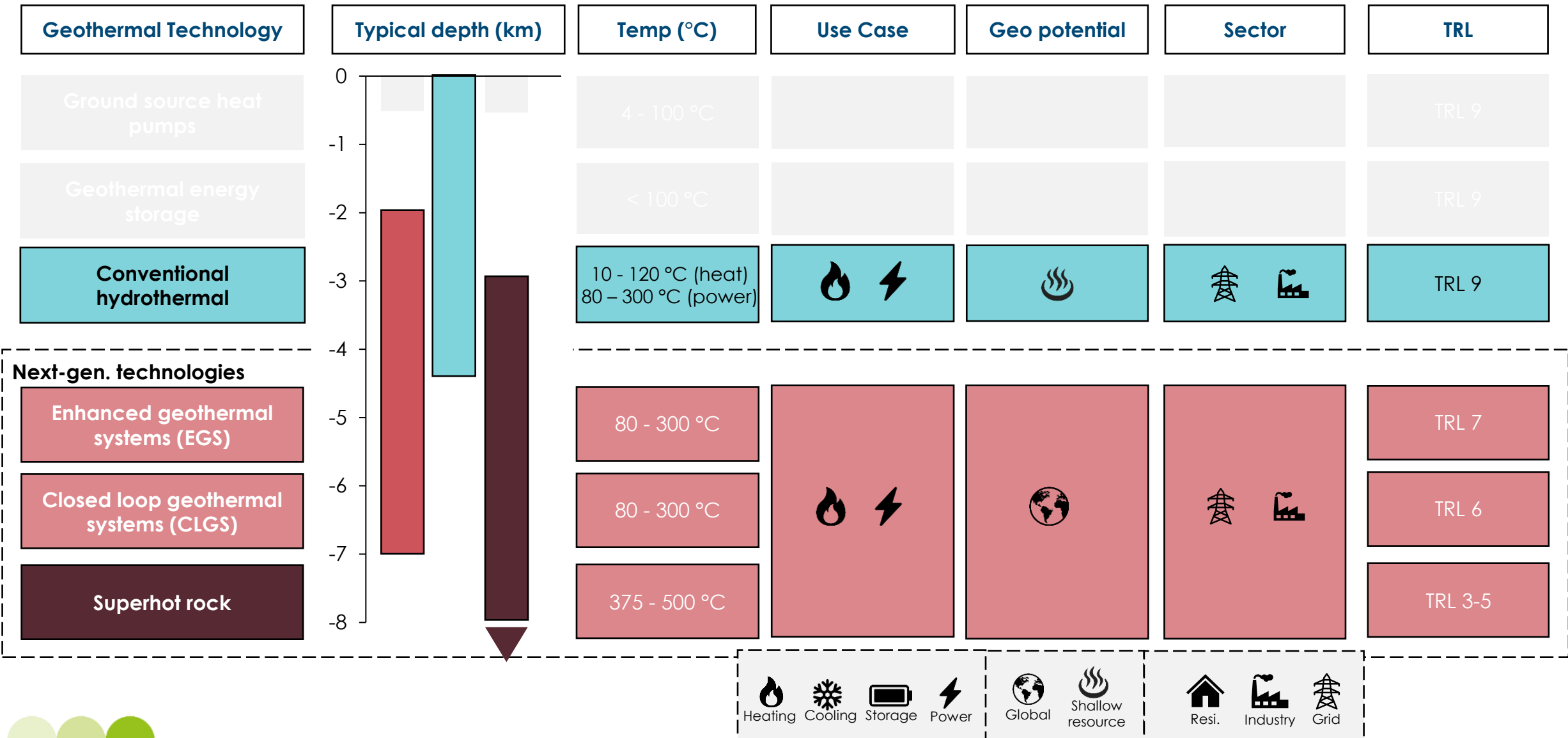
Next-generation geothermal systems (EGS and CLGS) can access higher temperatures or non-hydrothermal formations, expanding applicability across heat and power applications

Notes: ORC = Organic Rankine Cycle; EGS = Enhanced geothermal systems; CLGS = Closed-loop geothermal systems. High-temperature power systems can use binary, single flash (~180-260 °C), double flash (~180-370 °C), or a combination of both.  
Sources: KEARNEY ETI (2025), Geothermal energy, turning up the heat

# Power generation



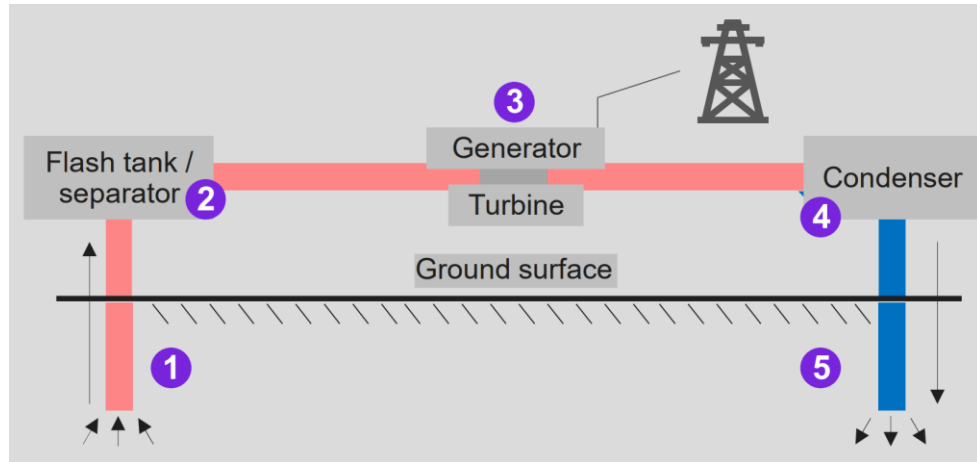
# Geothermal power generation today is based on conventional hydrothermal, but next-generation offers opportunities for scaling geographically



Notes: Geothermal energy storage parameters refer to underground thermal energy storage (excluding more nascent options such as geothermal mechanical storage). Assumed TRL scale: TRL 1-3 = Research to Proof of Concept; TRL 4-6 = Lab to Pilot Demonstration; TRL 7-9 = Prototype Demonstration to FOAK / Full Commercial Deployment

# The working principles of geothermal power production rely on heat extraction from deep resources

The working principle of geothermal power production (flash steam generator system)



- 1 When a well is drilled to access hot water reservoirs, **the water flows to the surface due to internal pressure (in conventional geothermal technology)**
- 2 **As the hot water rises to the surface, the pressure decreases and it turns into steam**
- 3 **The steam powers a turbine connected to a generator to produce electricity**
- 4 Excess steam is cooled and condensed to water in a cooling tower
- 5 **Condensed water is pumped back into the Earth, restarting the cycle**

## Potential risks (conventional & EGS):

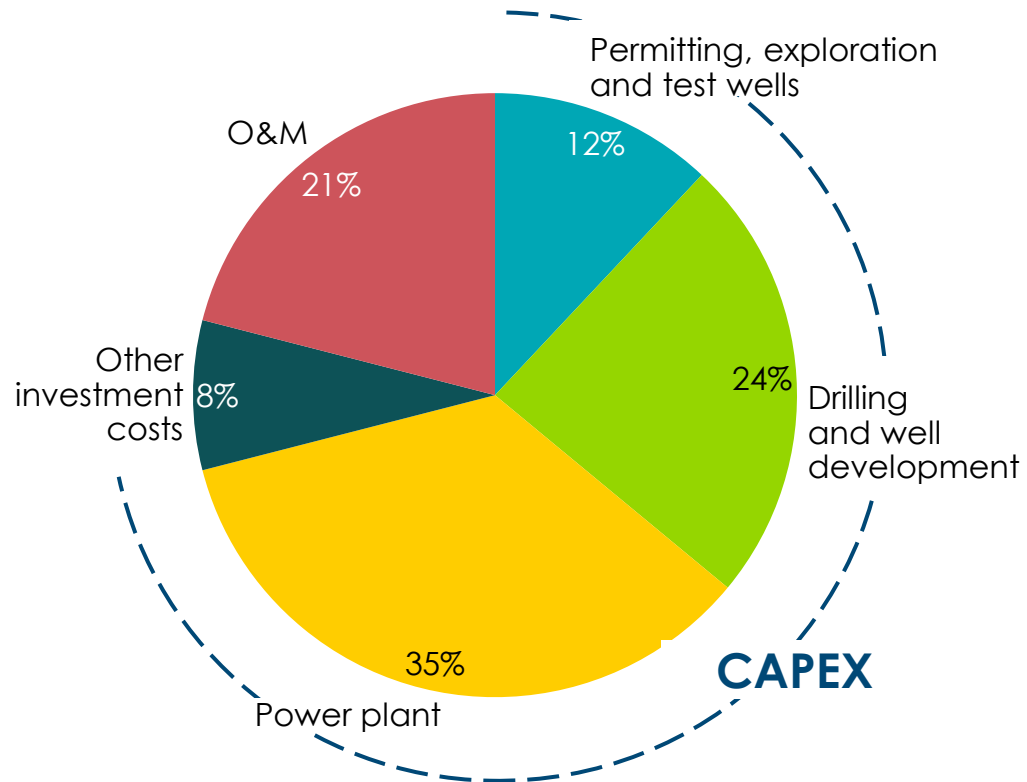
1. **Pressure decline** as fluids are extracted
2. **Temperature decrease** due to excessive heat extraction
3. **Thermal gradient depletion** due to high flow rates

## Next-generation differences:

Technology	Key difference
Enhanced Geothermal Systems (EGS)	Creates permeability via stimulation in hot, dry rock. Requires injection and production wells with engineered fractures to circulate fluid.
Closed-Loop Geothermal Systems (CLGS)	Uses a sealed pipe loop with no interaction with formation fluids. Does not rely on natural or stimulated permeability.

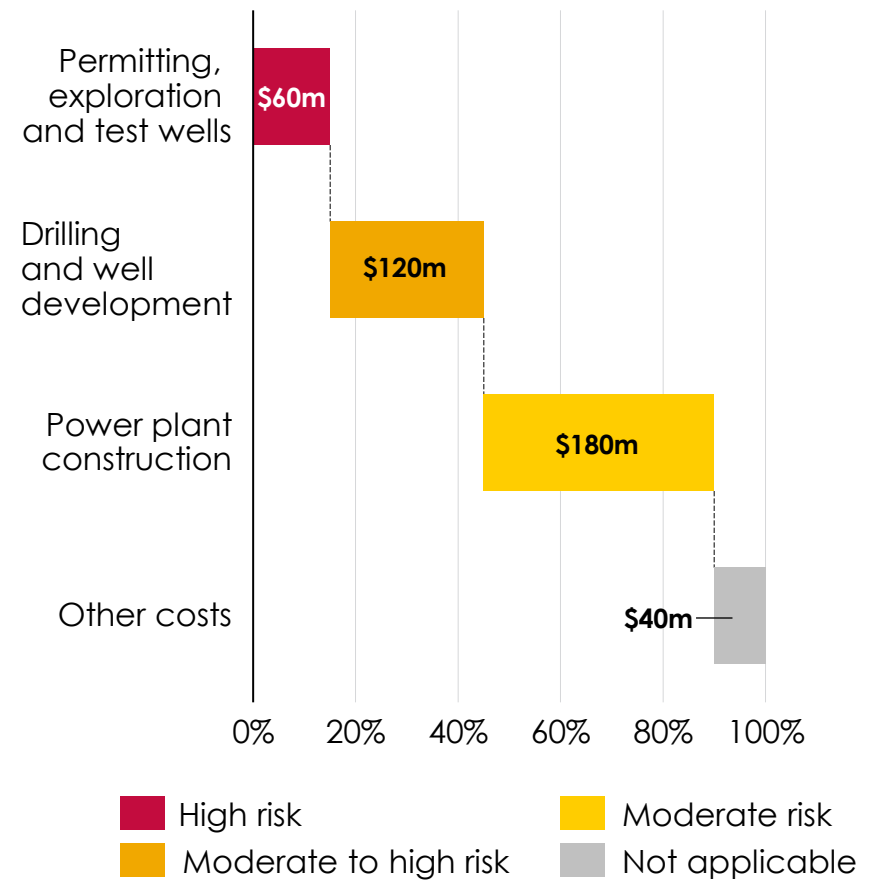
# Geothermal levelised cost of energy (LCOE) is dominated by capital expenditure (CAPEX) and can have high exploration risk, driving higher weighted average cost of capital (WACC)

Typical breakdown of conventional geothermal powerplant LCOE %



CAPEX shares and risks for plant development stages

%, indicative values for 100 MW project - \$m



Note: Development expenditure is combined with capital expenditure (CAPEX), O&M = operations and maintenance. Risk assessments account for the possibility of cost overruns and delays due to finding geothermal resources of insufficient quality, lengthy permitting and unforeseen technical challenges

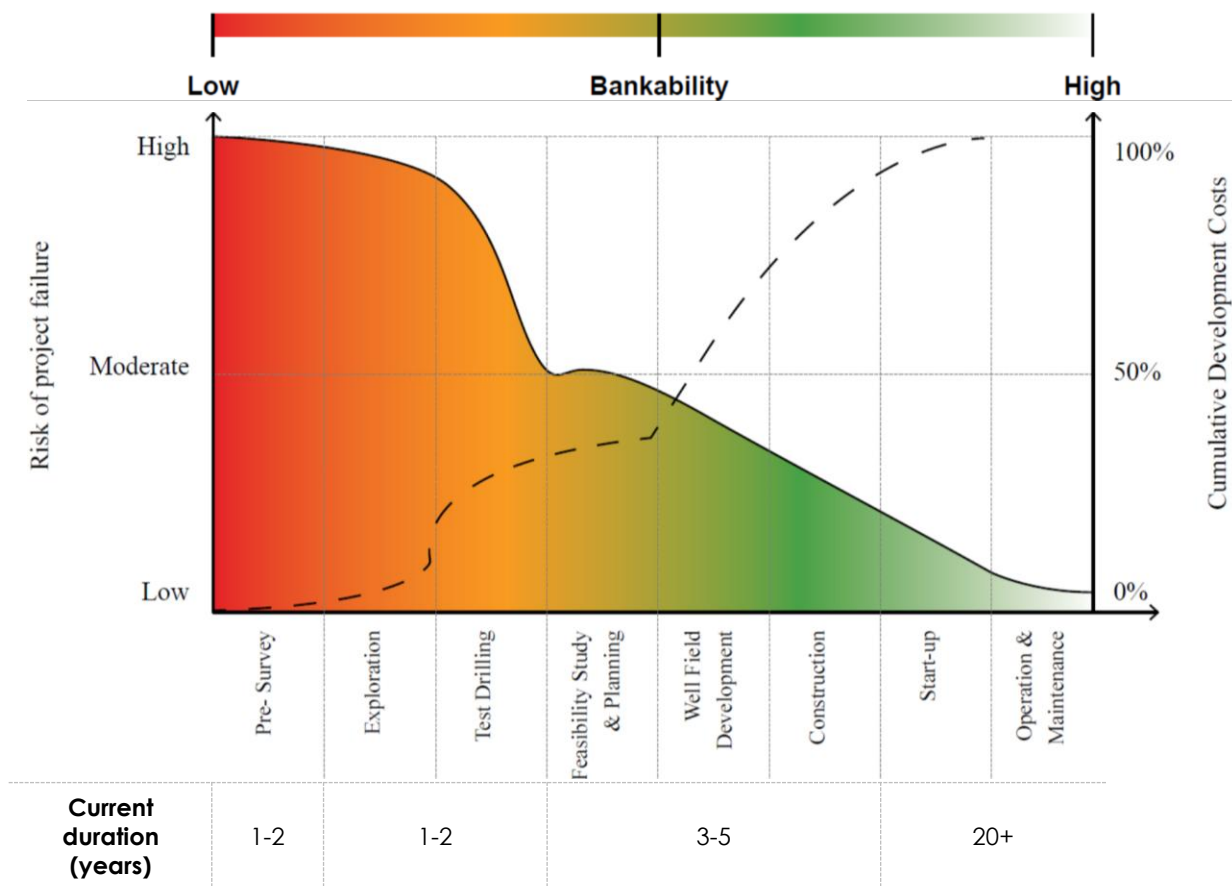
Source: IEA analysis based on data from IRENA, BNEF and NREL: IEA (2024) *The Future of Geothermal Energy*; Michael Barnard (2025), *Beyond the Hype: Geothermal in Context Separating viable heat solutions from speculative drilling dreams*



# Project risk typically remains high until around 20-40% of CAPEX has been spent, leading to high WACC

## Risk of project failure by project stage, bankability rating, and development cost share

LHS – Risk rating; RHS – Cumulative development cost share; colourbar – bankability



- **Risk of project failure decreases as surveys and exploration are completed and significantly drops once full-size commercial wells are drilled and tested**
- **Well field development and construction dominate development costs**, once the development is largely derisked
- The duration of survey / exploration stages and associated investment **vary based on the developer's risk appetite and level of public support**
- As a result of the high upfront cost and long development time:
  - Geothermal **levelised costs of electricity or heat are highly sensitive to WACC**
  - Development risk means that geothermal projects have **high WACC**

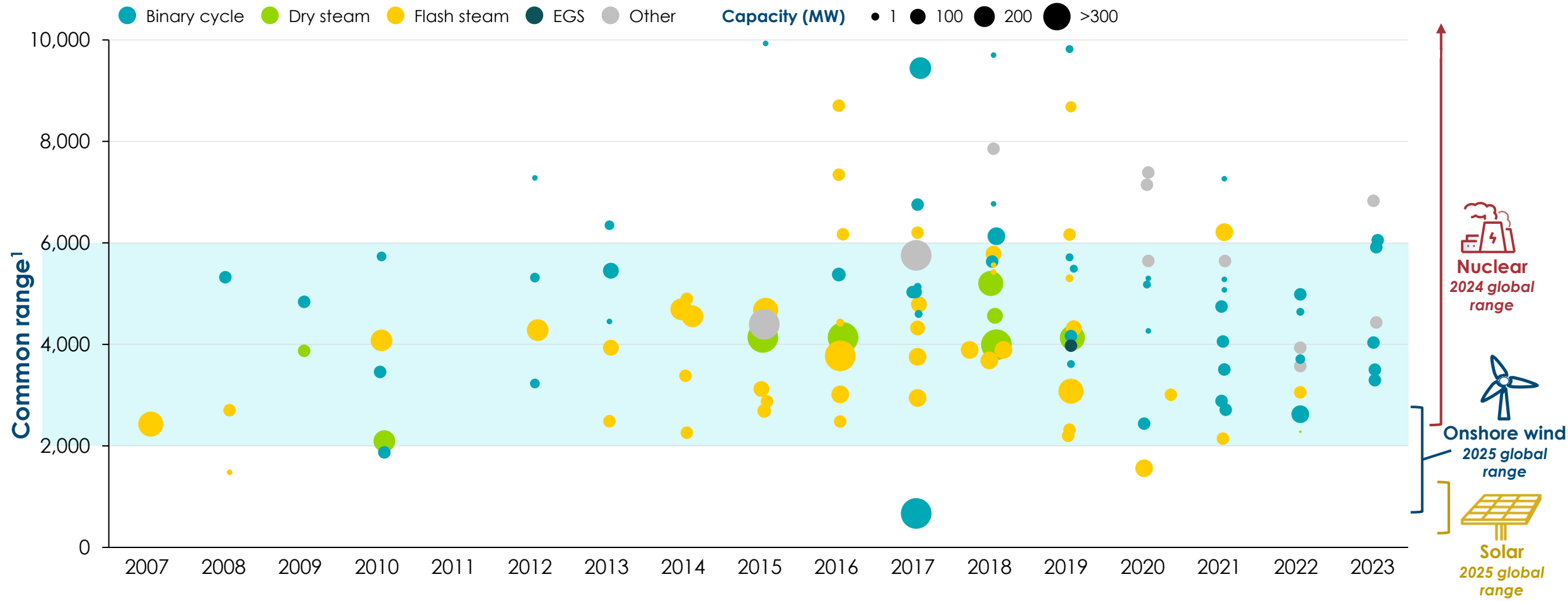


Source: British Geological Survey (2023), *Evidence report supporting the deep geothermal energy white paper: The case for deep geothermal energy - unlocking investment at scale in the UK*; Robins, J.C. et al. (2022). "2022 GETEM Geothermal Drilling Cost Curve Update." NREL/CP-5700-82771; Thunder Said Energy (NA), *Geothermal energy: costs and economics?*; CTVC (2022), *The heat beneath our feet*; Michael Barnard (2025), *Beyond the Hype: Geothermal in Context Separating viable heat solutions from speculative drilling dreams*

# CAPEX for a geothermal power project varies by technology and capacity, typically between \$2,000-6,000/kW

## Geothermal power upfront investment by project, technology, and capacity

USD/kW<sub>e</sub>, 2010-2023



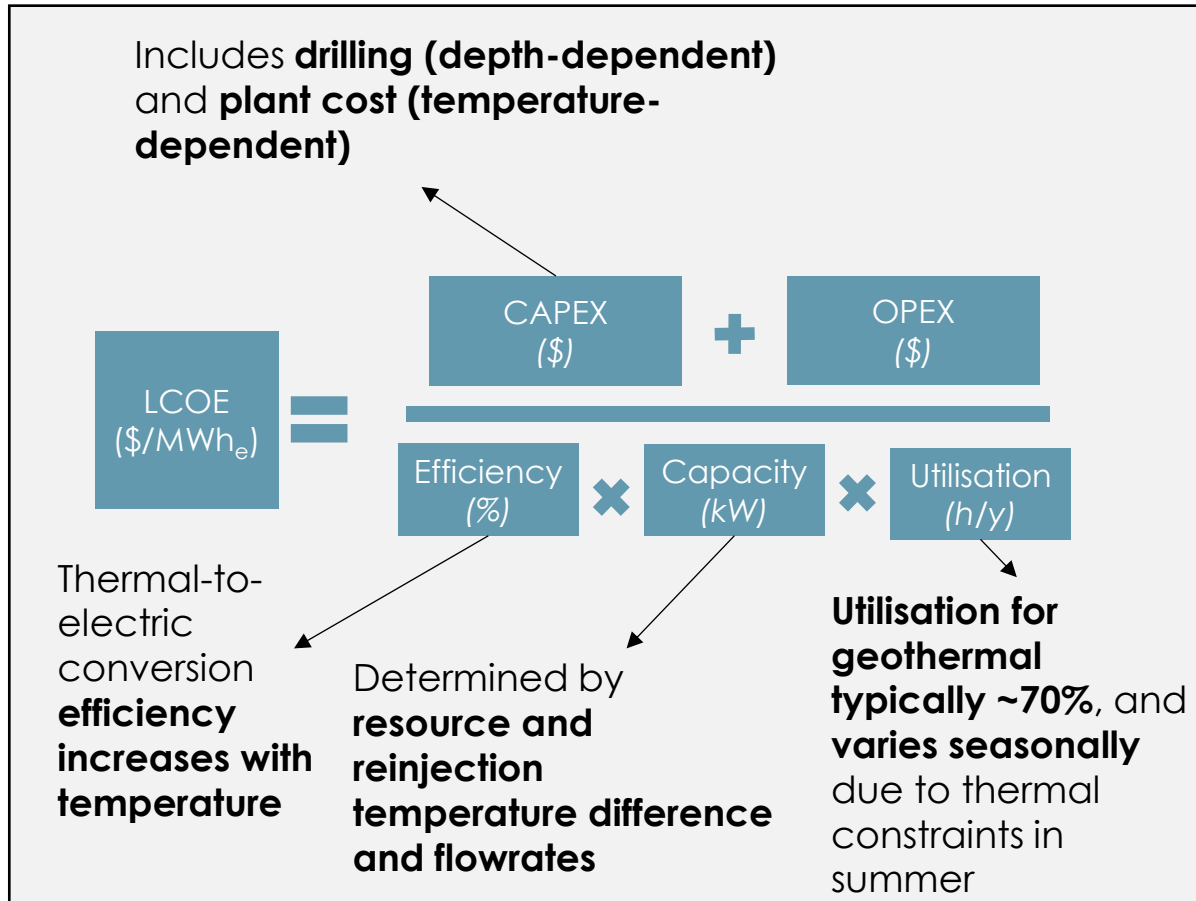
Notes: 1. Range excludes outlier projects, typically small and/or remotely located, and is representative of the norm

Source: KEARNEY ETI (2025), Geothermal energy, turning up the heat: <https://www.energy-transition-institute.com/documents/d/eti/kearney-eti-geothermal-factbook-2025-pdf>, IRENA, 2024, renewable Power Generation Costs in 2023; Kearney Energy Transition Institute analysis

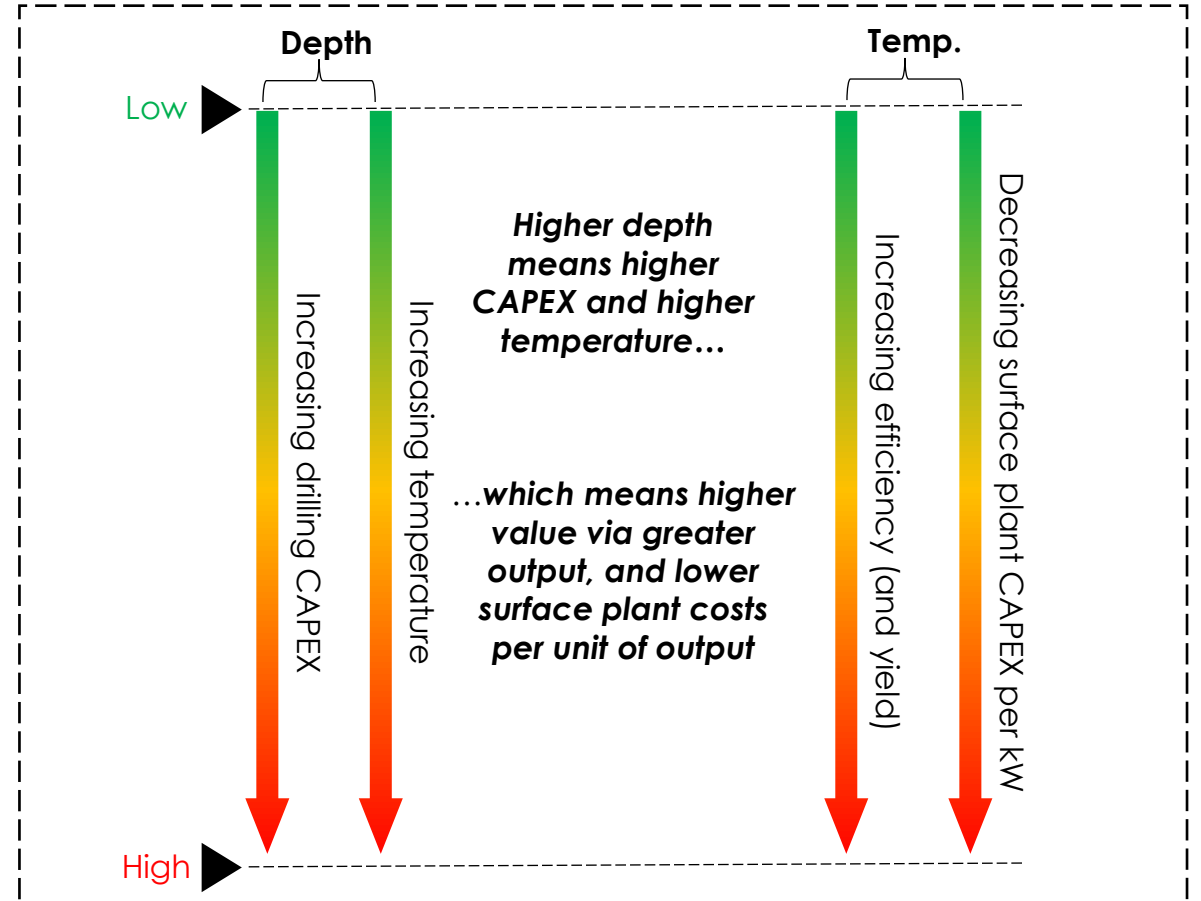


# Several key parameters determine geothermal cost competitiveness

## Geothermal levelised cost of energy (LCOE) drivers



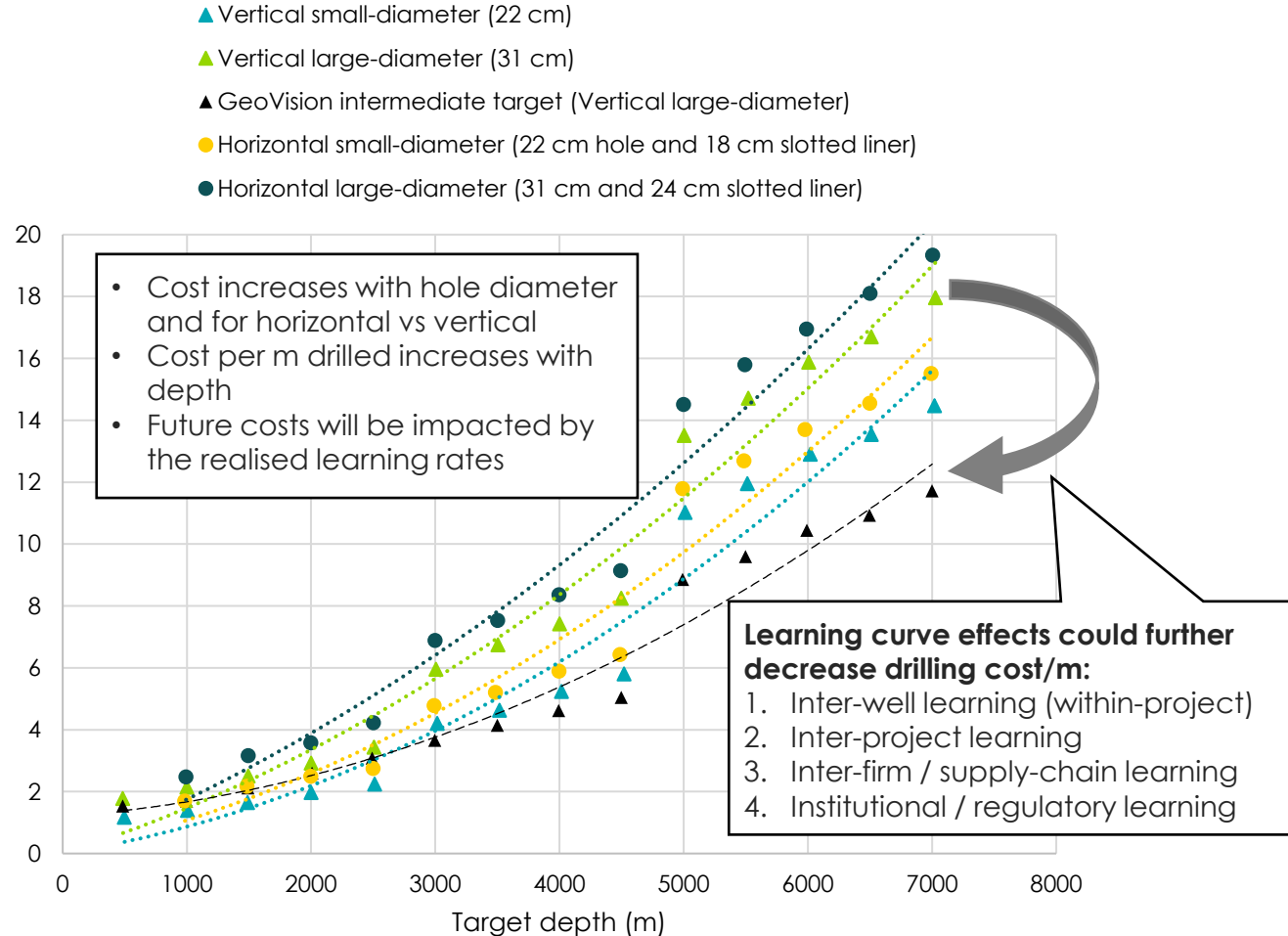
## Resource characteristics: Depth-temperature sweet spots define LCOE competitiveness



# Depth: Drilling costs are proportional to well diameter and depth; EGS drilling rates have significantly increased but further improvements could be limited

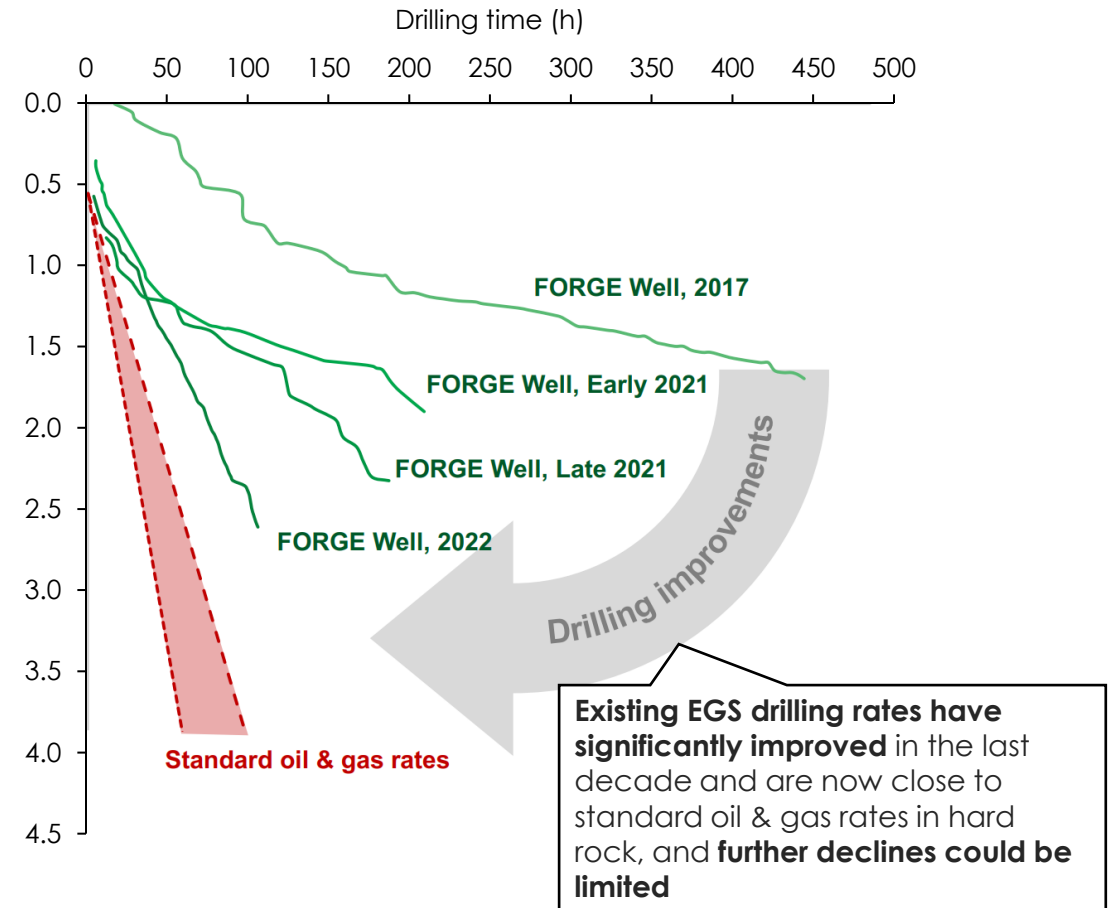
Total drilling cost per well by drilling category

Million \$



Drilling depth against time for the US DoE's Utah FORGE well vs oil & gas km

km

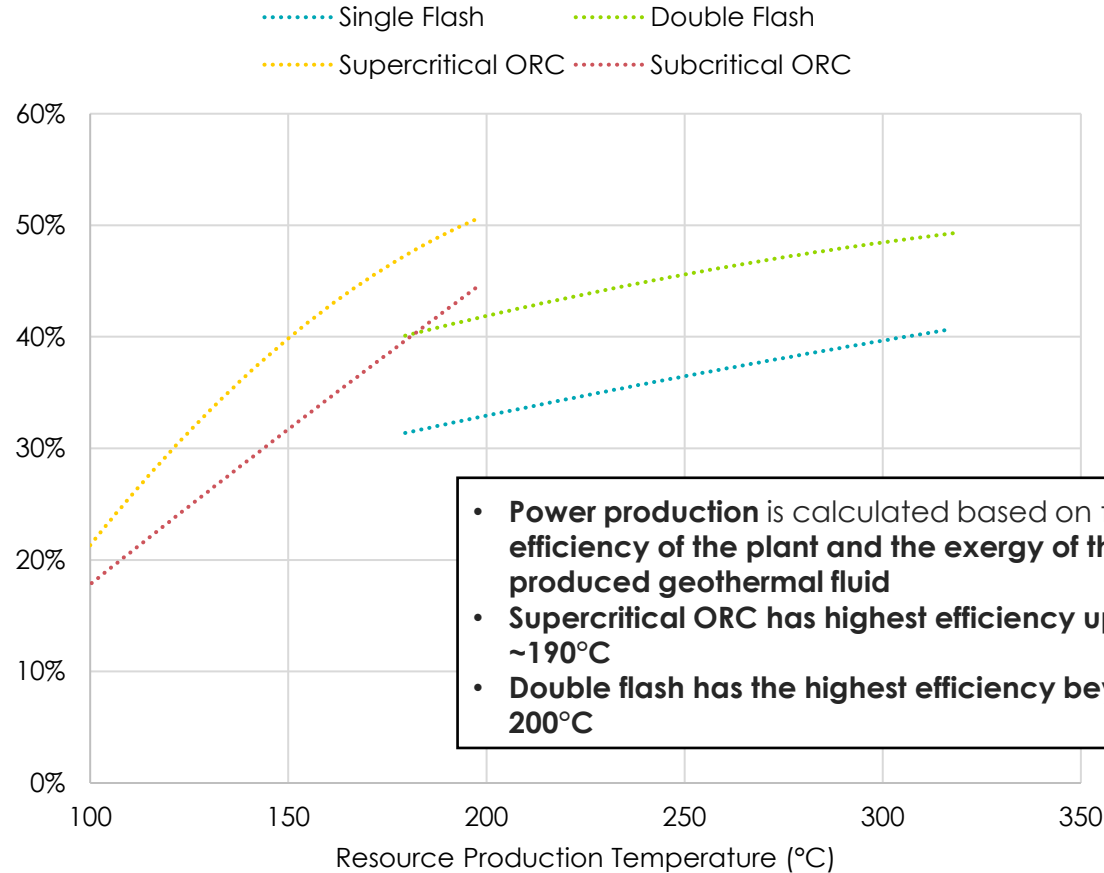


Notes: Slotted liners provide structural support for horizontal well sections and perforations along the liner's length allows geothermal fluid to flow from the formation into the wellbore while filtering entry of debris. The use of a liner also avoids the need to cement the horizontal interval. FORGE is the U.S. DOE's flagship Enhanced Geothermal System (EGS) field laboratory. Source: NREL (2025), 2025 Geothermal Drilling Cost Curves Update; US DoE (2024) Pathways to Commercial Liftoff: Next-Generation Geothermal Power Updated

# Temperature: Thermal-to-electric conversion efficiency increases with temperature, and the cost of the conversion facility falls

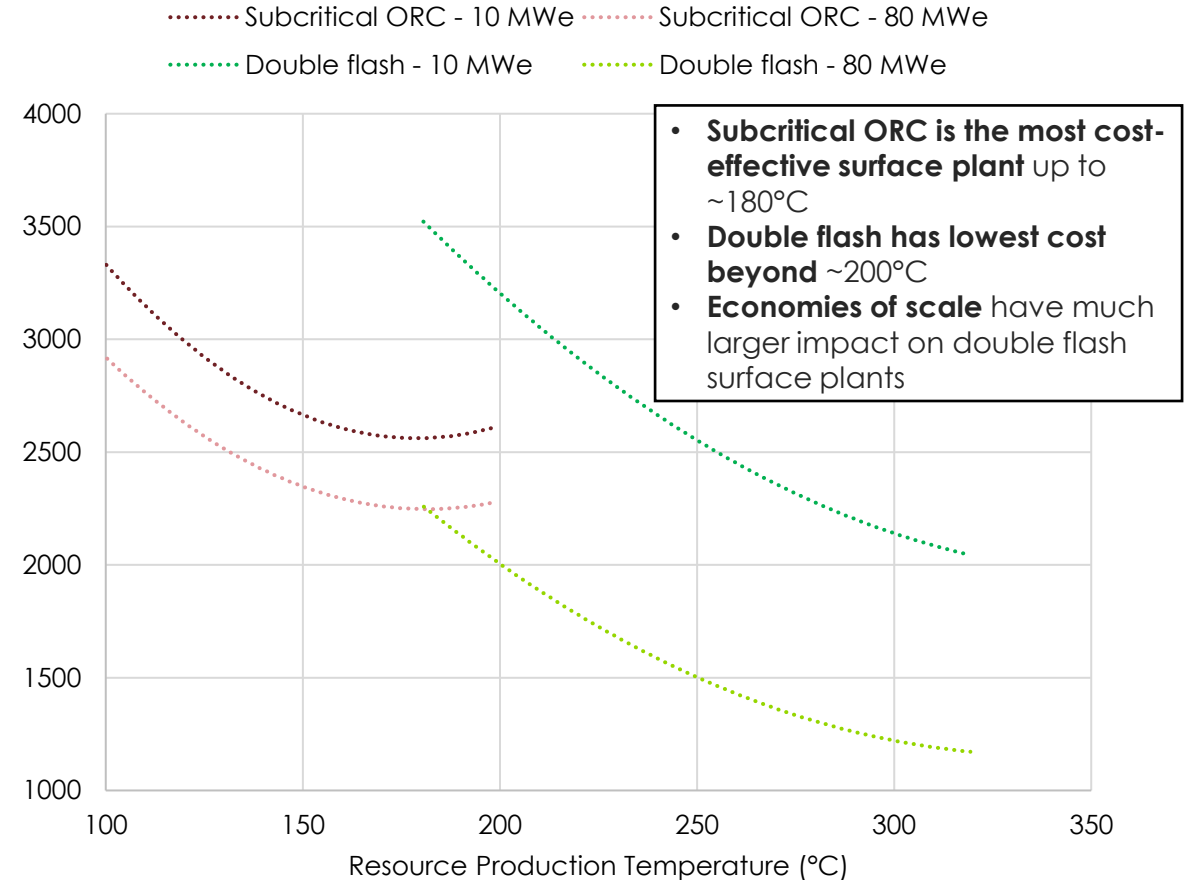
Efficiency (fluid exergy to electricity) vs production temperature at surface

%



Surface plant CAPEX vs production temperature at surface

\$/kW<sub>e</sub>



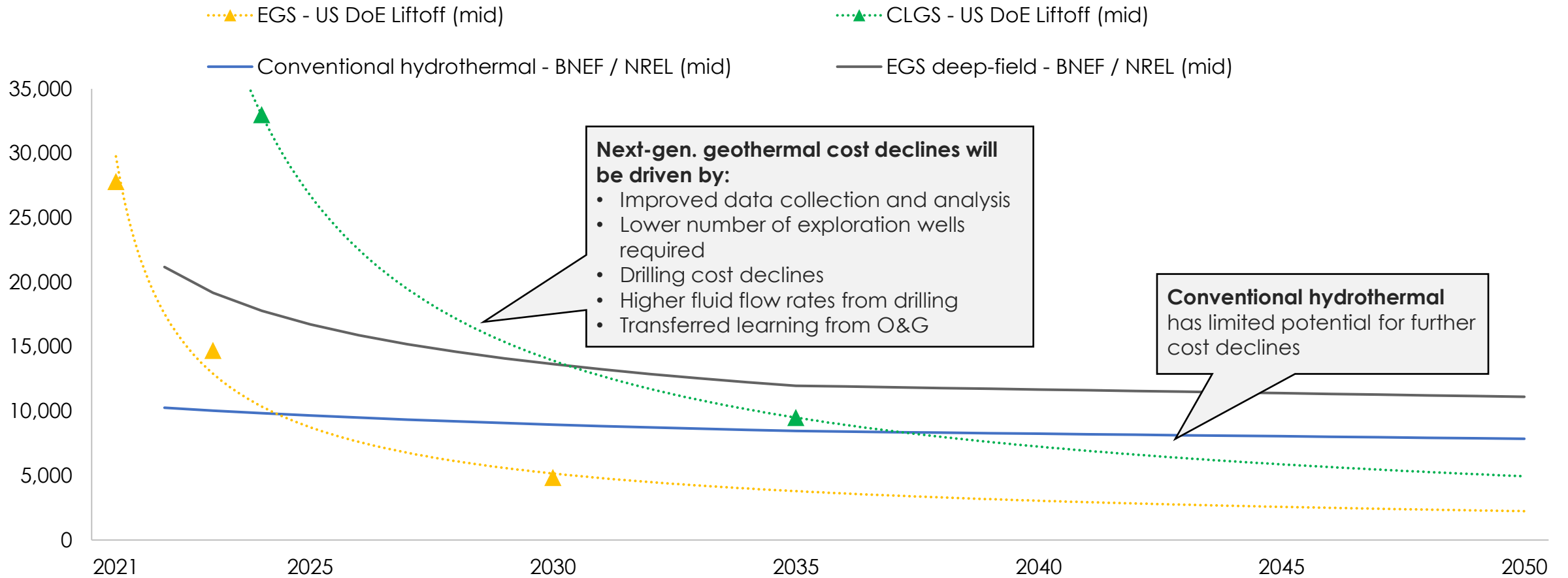
Notes: 15°C ambient temperature assumed. Exergy measures the maximum useful work a system can produce as it reaches equilibrium with its environment. ORC = Organic Rankine Cycle, where a low-boiling point organic fluid (e.g., isobutane or pentane) is vaporized by geothermal heat, drives a turbine, and is condensed and recycled (subcritical operates below critical pressure and supercritical operates at a supercritical pressure). A single flash steam system is where high-pressure geothermal water from the reservoir is depressurised ("flashed") to produce steam that drives a turbine. In a double flash system, after the first flash and turbine stage, the remaining liquid is flashed again at lower pressure, increasing energy extraction by about 15–25%. Source: Koenraad F. Beckers (2019), *GEOPHIRES v2.0: updated geothermal techno-economic simulation tool*



# CAPEX for next-generation geothermal technologies could significantly decline from today's levels...

## Next-generation geothermal (EGS and CLGS) CAPEX declines over time

\$/kW<sub>e</sub>, real 2024



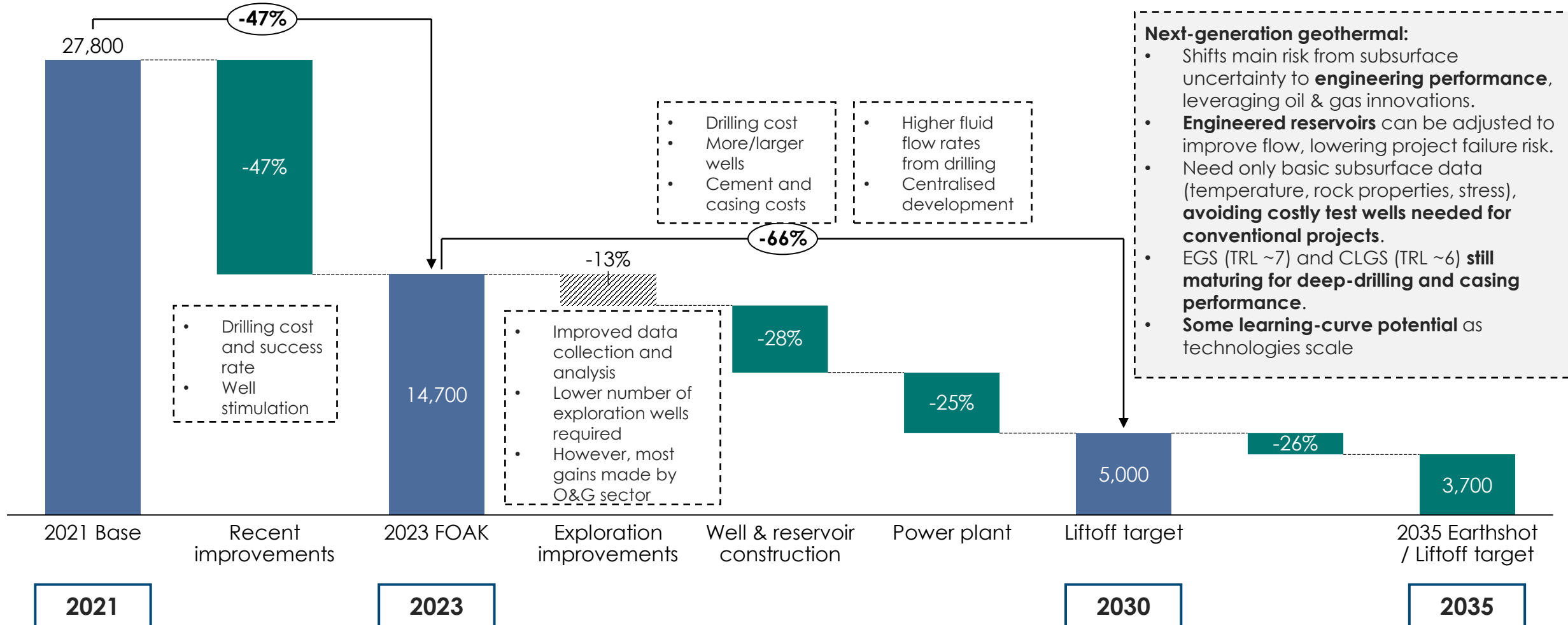
Source: US DoE (2024) *Pathways to Commercial Liftoff: Next-Generation Geothermal Power Updated*; BNEF (2025), *US Next-Generation Geothermal Makes Unsung Progress*



# ...however, this would require significant improvements in drilling and power plant cost declines

## EGS CAPEX decline drivers (based on US DoE data)

\$/kW<sub>e</sub>, real 2024

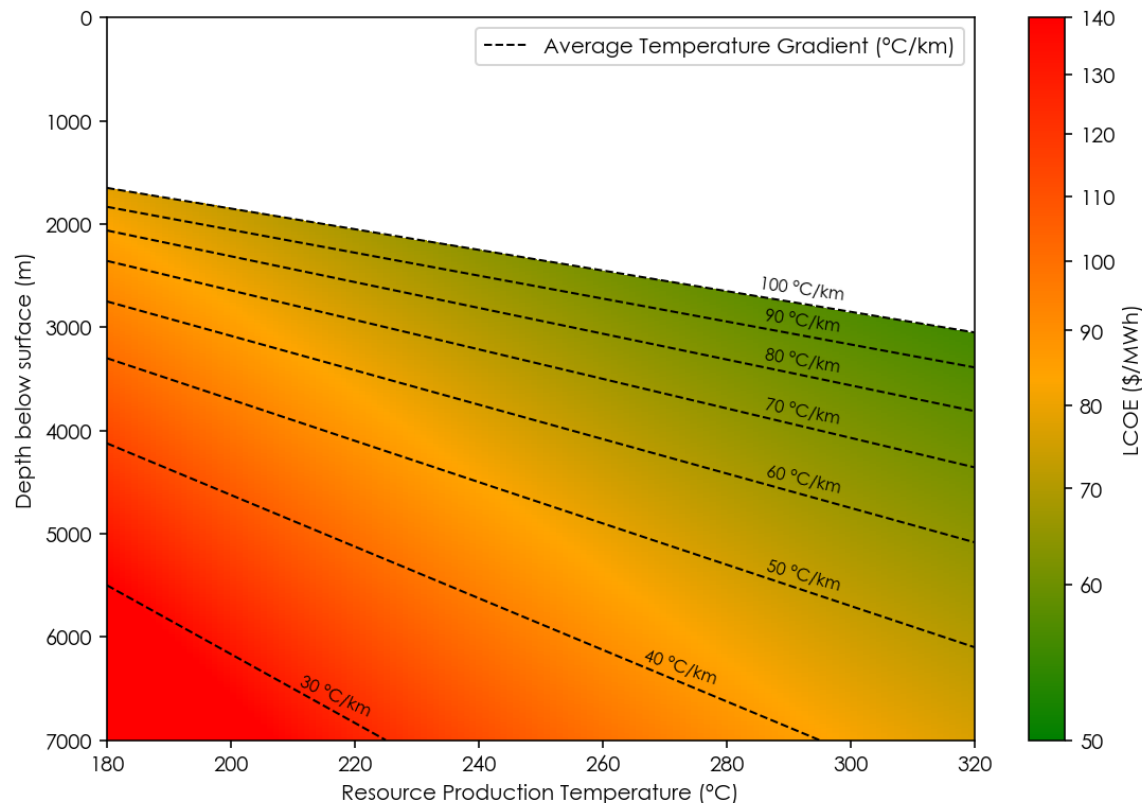


Notes: EGS = enhanced geothermal systems  
 Source: US DoE (2024) *Pathways to Commercial Liftoff: Next-Generation Geothermal Power Updated*

# Alongside physical site characteristics, next-generation geothermal development and operation risk will determine WACC and LCOE

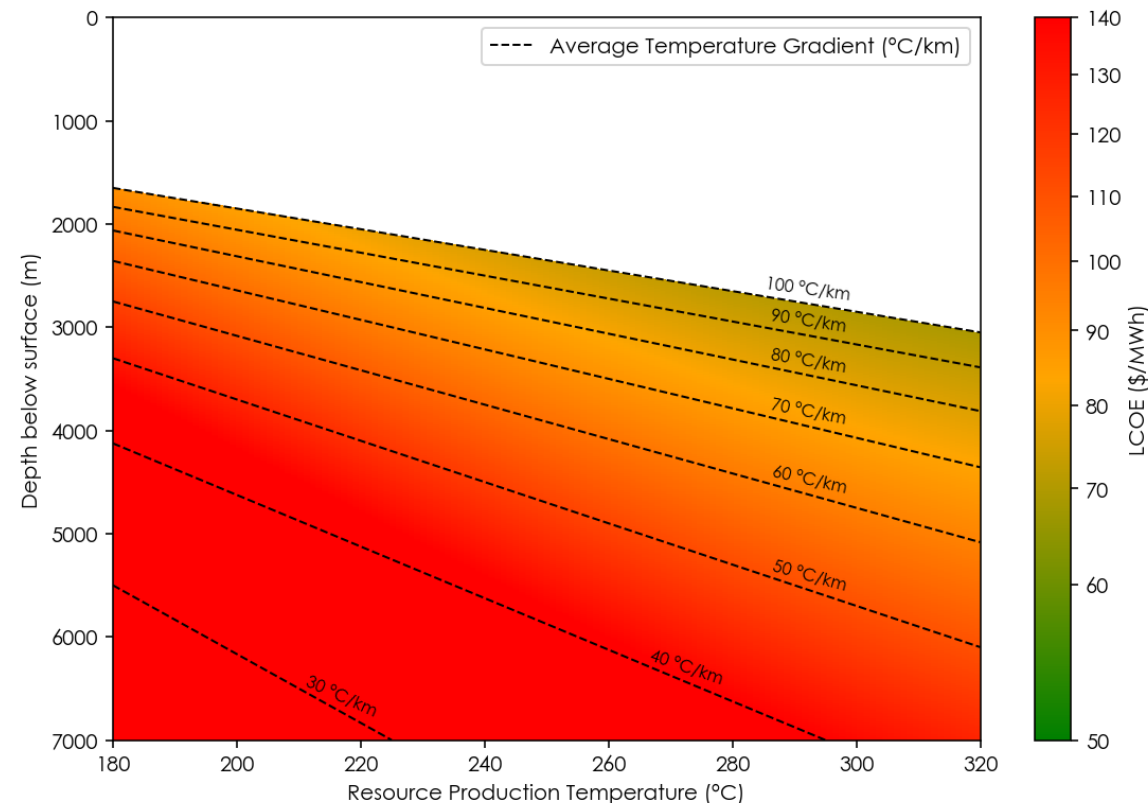
Illustrative EGS cost variation by depth and temperature (2035 costs, constant WACC)

Depth below surface – m; heatmap LCOE – \$/MWh, real 2024



Illustrative EGS cost variation by depth and temp. (2035 costs, escalating WACC: 1%/km)

Depth below surface – m; heatmap LCOE – \$/MWh, real 2024



Typical temperature gradients by region:

Low gradients: 15-30 °C/km	Moderate gradients: 30-45 °C/km	High gradients: 45-100+ °C/km
E.g., UK, Eastern US, Central/Eastern Europe, Brazil	E.g., Australia, Northern India, Northwest Africa, Northern Canada, Southwest UK	E.g., East African Rift, Iceland, Western US, New Zealand, Indonesia, Philippines, Central Andes (Chile, Bolivia, Argentina)

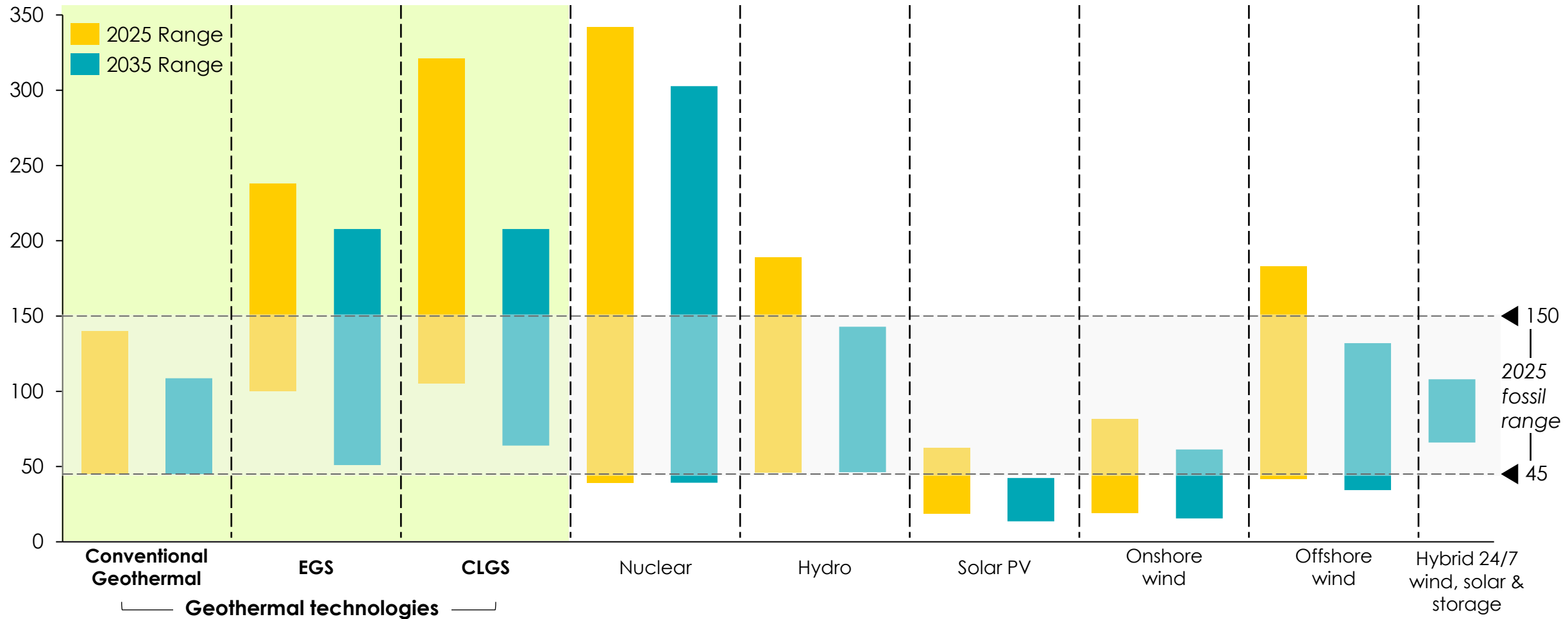
Notes: EGS = enhanced geothermal systems, WACC = weighted average cost of capital, LCOE = levelised cost of energy. "1%pt/km" = 1 percentage point per km. Source: Systemiq analysis for the ETC (2025); NREL (2025), 2025 Geothermal Drilling Cost Curves Update; Koenraad F. Beckers (2019), GEOPHIRES v2.0: updated geothermal techno-economic simulation tool; US DoE (2024) Pathways to Commercial Liftoff: Next-Generation Geothermal Power Updated; F. Kolawole (2023), Global distribution of geothermal gradients in sedimentary basins; J. Limberger (2017), Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization



# Next-generation geothermal could become competitive with clean firm alternatives including hybrid wind, solar and storage sites

Levelised cost of energy ranges in 2025 and 2035 for selected clean energy technologies

\$/MWh (real 2024)

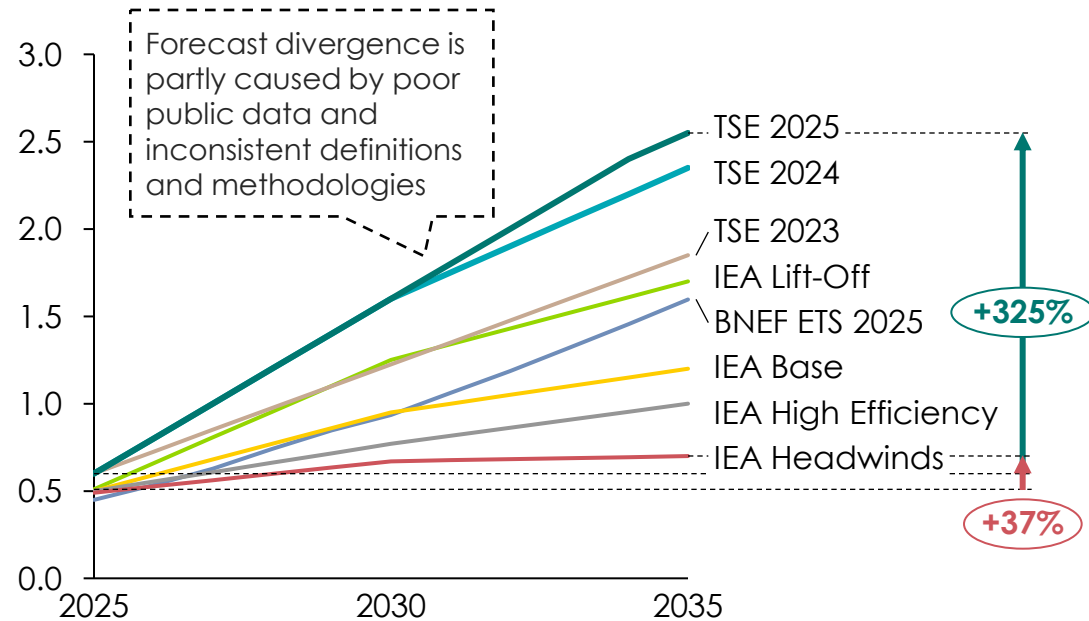


Notes: Hybrid 24/7 wind & solar based on IEA 2035 STEPS estimates from China (lower bound) to the EU (upper bound), with hybridized systems achieving ~95% availability. EGS = Enhanced geothermal systems; CLGS = Closed-loop geothermal systems. Source: BNEF (2025), LCOE Data Viewer; BNEF (2025), *US Next-Generation Geothermal Makes Unsung Progress*; IEA (2025), *World Energy Outlook 2025*

# Data centre demand could incentivise next-generation geothermal commercialisation; however, demand growth pathways are highly uncertain

## Global data centre annual demand projections by scenario

'000 TWh/year



### Key enabling characteristics for geothermal deployment in countries:

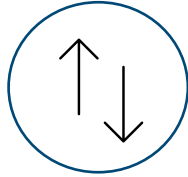
1. High data centre load growth (or other growth of high-load factor industry)
2. Existing oil and gas supply chain
3. Start-up ecosystem

Key geographies include the US and possibly Southeast Asia

- BNEF ETS expects **2% to 7% of 2035 global demand**
- **Unclear interaction between demand drivers** (e.g. digitalisation, demand growth, AI training) with **downturns** (e.g. efficiency breakthroughs, uptake overestimation, grid connections access, AI monetisation, supply chain and tariffs constraints)

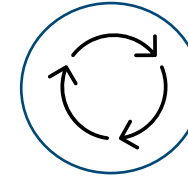
Sources: BNEF (2025), *New Energy Outlook*; IEA (2025), *Energy and AI*; Thunder Said Energy (2025), *AI energy: industrial demand and the Jevons effect?*

# There are some technical constraints on geothermal power flexibility; Next-generation geothermal is trialing flexibility innovations



## Conventional geothermal

- **Conventional geothermal** can **technically** vary output by adjusting fluid flow and reinjection
- However, frequent adjustment of fluid flow **can risk thermal shock and pressure imbalance**
- As a result, sustained turndown or ramp-rate testing is uncommon and no measured numbers are available



## Enhanced Geothermal Systems

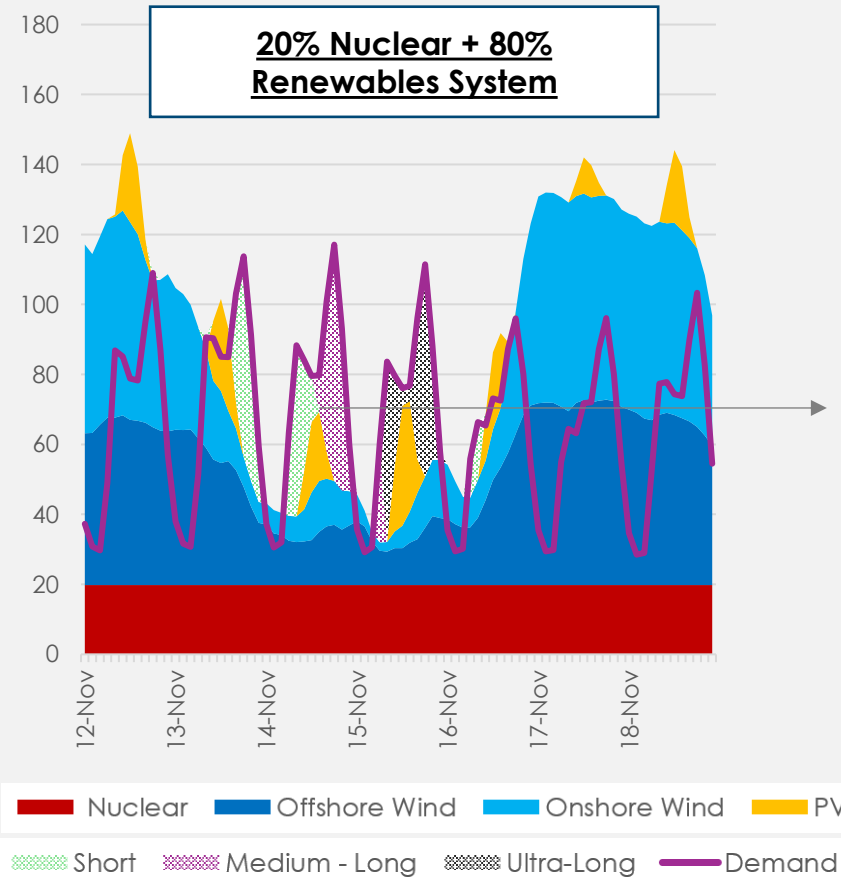
- Unlike conventional systems, it can vary injection and production to store pressure in the reservoir and release it later, allowing output to shift across the day or even across seasons
- Early modelling and pilots (Fervo, Princeton) show the reservoir can **shift output over many hours or weeks** with ~60-90% round trip efficiency.
- Flexible operation lowers yearly generation because more pumping is needed and flow must be reduced at times to protect reservoir temperature.



# Role of geothermal therefore likely to be as ‘baseload’; scaling geothermal could offer some limited offset to balancing costs

- Where deployed, geothermal likely to run as “baseload” given limited opportunity to run flexibly
- Geothermal could reduce but not eliminate balancing needs
- Adding some geothermal could also reduce some system curtailment costs, due to lower generation overbuild

UK Weekly balancing for November period, including nuclear as baseload example  
GW supply, demand, and balancing for each hour of the period



**Smaller supply deficit:** Less ultra-long duration balancing needed to match supply with demand – **but short and medium – long still required**



# Geothermal could provide some limited grid stability services, although overall scale of deployment within power grids likely to contribution

Grid Stability Service	Description	Can wind/solar provide?	Can geothermal provide?
<b>Inertia Support</b>	Instantaneous stabilising energy from synchronous mass	<b>Partially.</b> Requires additional technology such as synthetic inertia controls or hybrid storage, some can be provided through grid forming inverters	<b>Yes.</b> Geothermal plants provide real inertia through their synchronous rotating turbines.
<b>Frequency Response</b>	Ability to rapidly adjust power (seconds to minutes) to arrest frequency deviations. Includes FFR (Firm Frequency Response), Dynamic Containment, Dynamic Regulation.	<b>No.</b> Cannot inherently adjust output upward on demand. Requires additional technology such as curtailment controls or storage	<b>Unlikely.</b> Geothermal plants can adjust output modestly in response to frequency deviations, but ramp rates are limited. In practice, most geothermal units operate at steady output and rarely participate in frequency response markets.
<b>Voltage Control</b>	Managing voltage through reactive power injection or absorption. Services include reactive power tenders, voltage support	<b>Yes.</b> Solar and wind can inherently provide reactive power for voltage support. However, other technologies needed to provide location-specific voltage support and harmonic regulation.	<b>Yes.</b> Geothermal can provide reactive power to maintain voltage levels on the grid, preventing voltage sags and blackouts.
<b>Black Start Capability</b>	Ability to restart grid after a complete blackout without external supply.	<b>No.</b> Cannot restart the grid.	<b>Unlikely.</b> Some geothermal plants can be configured for black start, as it requires dedicated auxiliary systems and is uncommon outside a few specially equipped facilities, but it is not a standard feature and is used in limited cases.



Source: Systemiq analysis (2025); Thunder Said Energy (2025), Renewable-heavy grids: total system costs?

# Geothermal is likely to play a limited role in global scaling of clean power generation, but there are near-term region-specific scaling opportunities

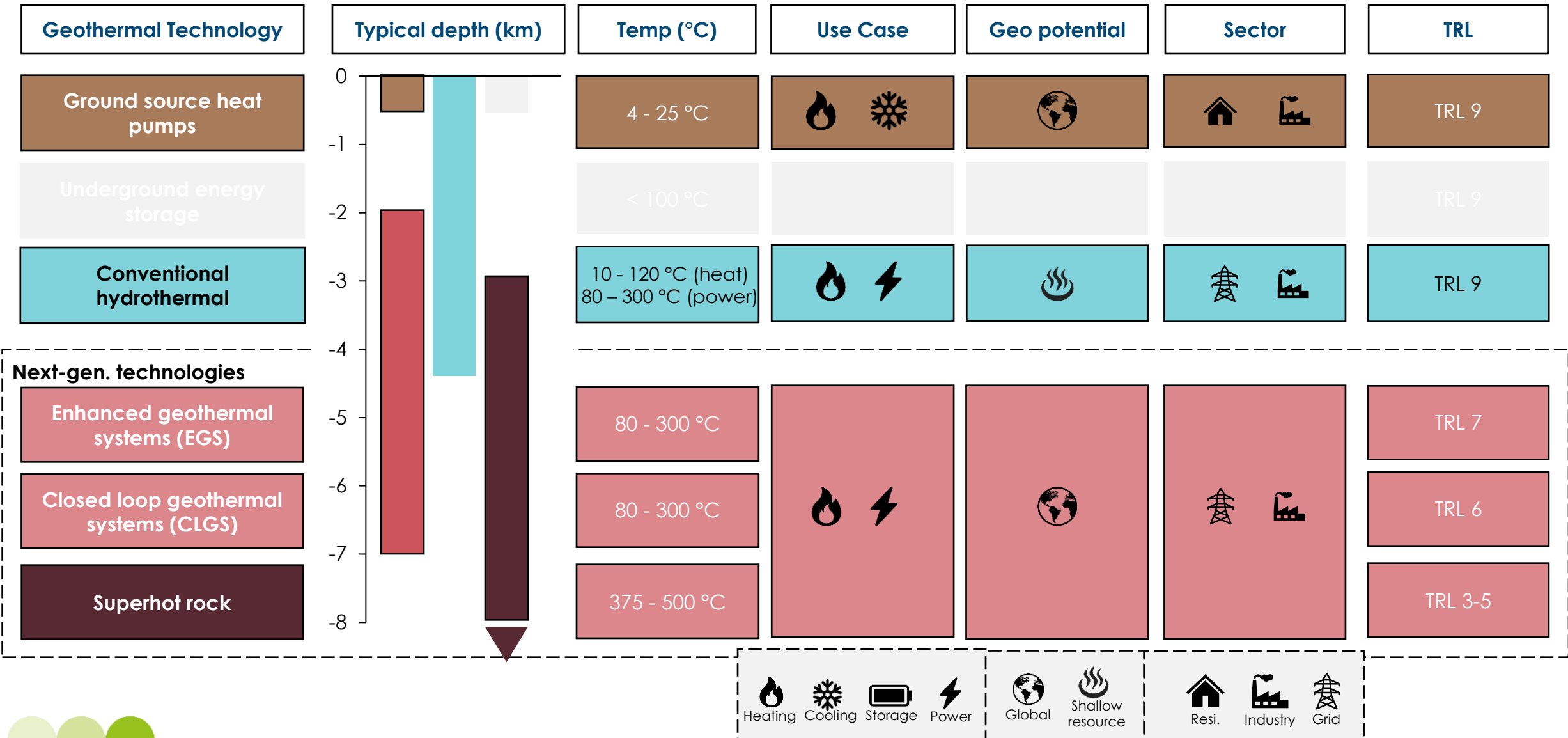
- 1) **Conventional hydrothermal will scale where shallow resources make it cost-effective, but its global share will remain small.**
  - 1) Growth potential in the Pacific Ring of Fire (e.g., Indonesia, Philippines) and the East African Rift (e.g., Kenya); costs may fall with advanced exploration and spillovers from next-gen markets.
  - 2) However, high upfront costs, long lead times, and persistent exploration risk could limit competitiveness versus wind and solar, and inflexibility limits role as a complementary balancing technology.
- 2) **Next-generation geothermal scalability depends on cost reduction and risk mitigation, likely focused on high load-factor locations (data centres, industrial sites) or regions with weak wind/solar resources.**
  - 1) Costs could fall substantially, but uncertainty is high; key risks include: slowing drilling cost declines; high project-level risks (e.g., well failure, thermal degradation); pipeline constraints (long lead times, bespoke projects limiting learning curves); dependence on access to low-cost financing
  - 2) **The near-term opportunity to scale next-gen geothermal for power applications is likely to be focused in the US, given growing demand for firm clean power;** geothermal has stronger project pipelines and workforce depth. Industrial loads and data centres may drive early deployment, though rollout speed could remain a bottleneck.
- 3) Considering these constraints on geothermal power deployment, **geothermal is unlikely to scale significantly beyond its current <1% share** of global generation, as other generation technologies (primarily) wind and solar will continue to scale significantly in the near-term.



# Heating and cooling

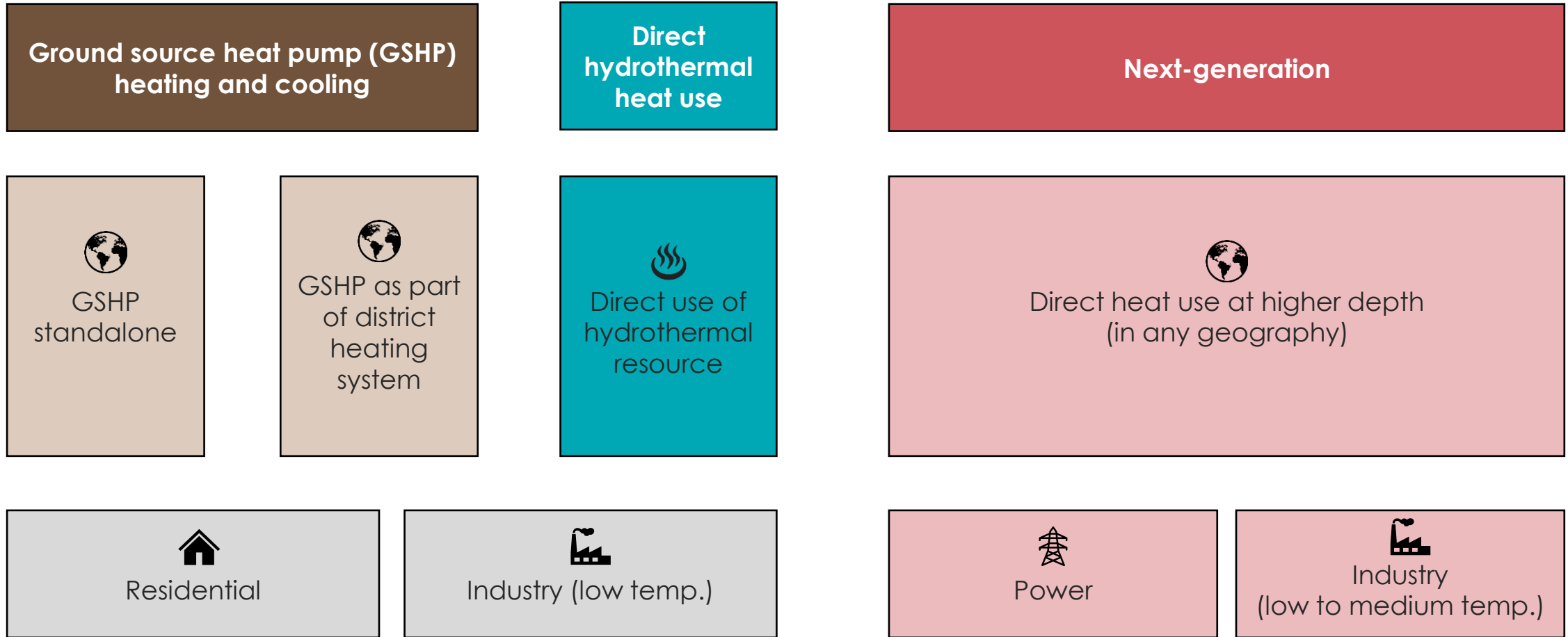


# Geothermal heat production is based on ground source heat pumps and direct heat use; next-gen. technologies could unlock higher temperatures

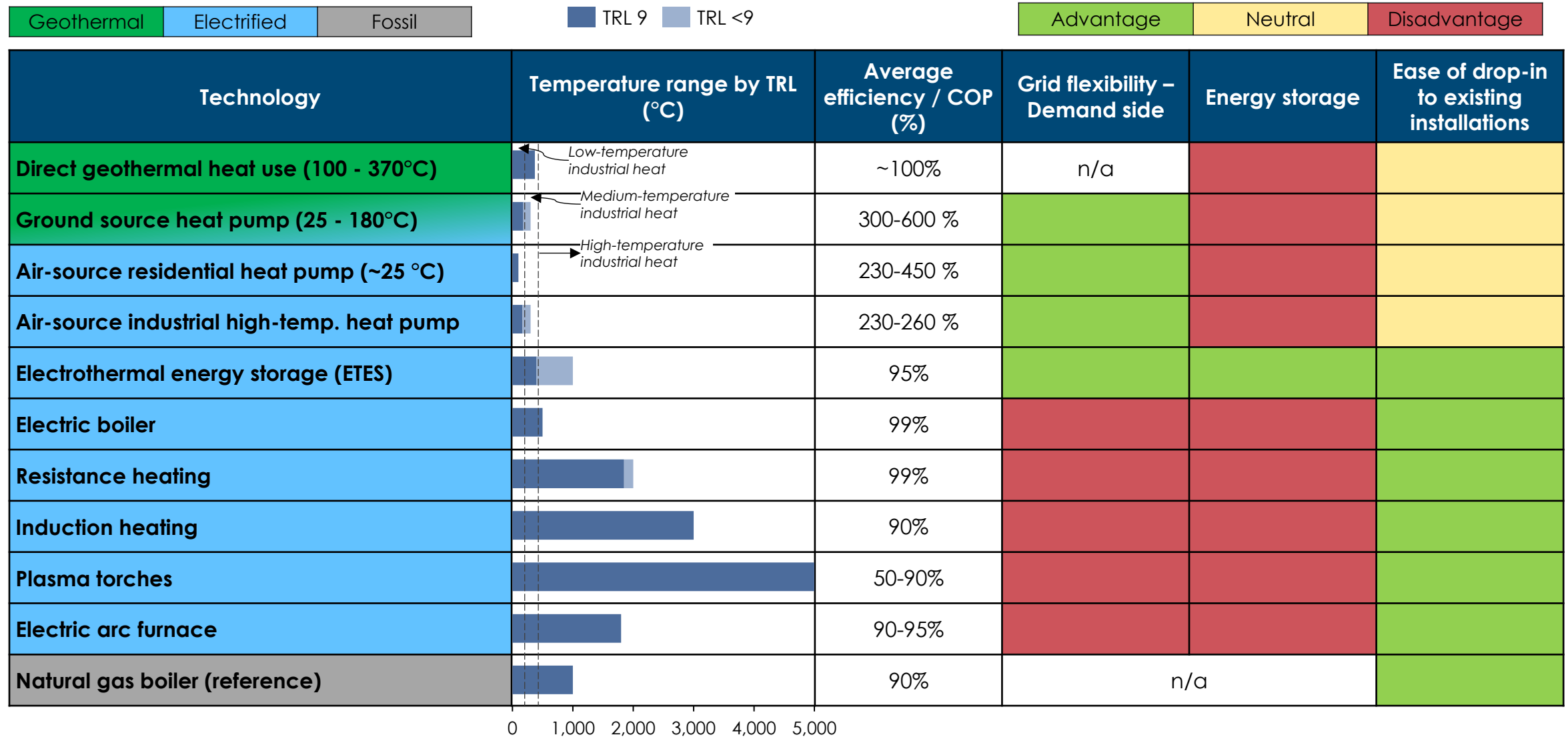


Notes: Underground energy storage parameters refer to underground thermal energy storage (excluding more nascent options such as geothermal mechanical storage). Assumed TRL scale: TRL 1-3 = Research to Proof of Concept; TRL 4-6 = Lab to Pilot Demonstration; TRL 7-9 = Prototype Demonstration to FOAK / Full Commercial Deployment

# Geothermal heat production can occur through shallow conventional technologies and deeper next-generation technologies



# Geothermal heat (via direct use and ground source heat pumps) can play a role in clean heat provision



Note: Efficiencies are Coefficients of Performance (COP) for heat pump technology and thermal-to-electricity efficiencies for the electrified technologies and thermal conversion efficiency for the natural gas boiler and direct geothermal heat use. Source: Systemiq (2024), *Global opportunities for Electrothermal Energy Storage*; Fraunhofer ISI (2024) *Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU. Study on behalf of Agora Industry.*

# Geothermal could provide residential and industrial heat; next-generation geothermal required to provide higher temperatures beyond key countries

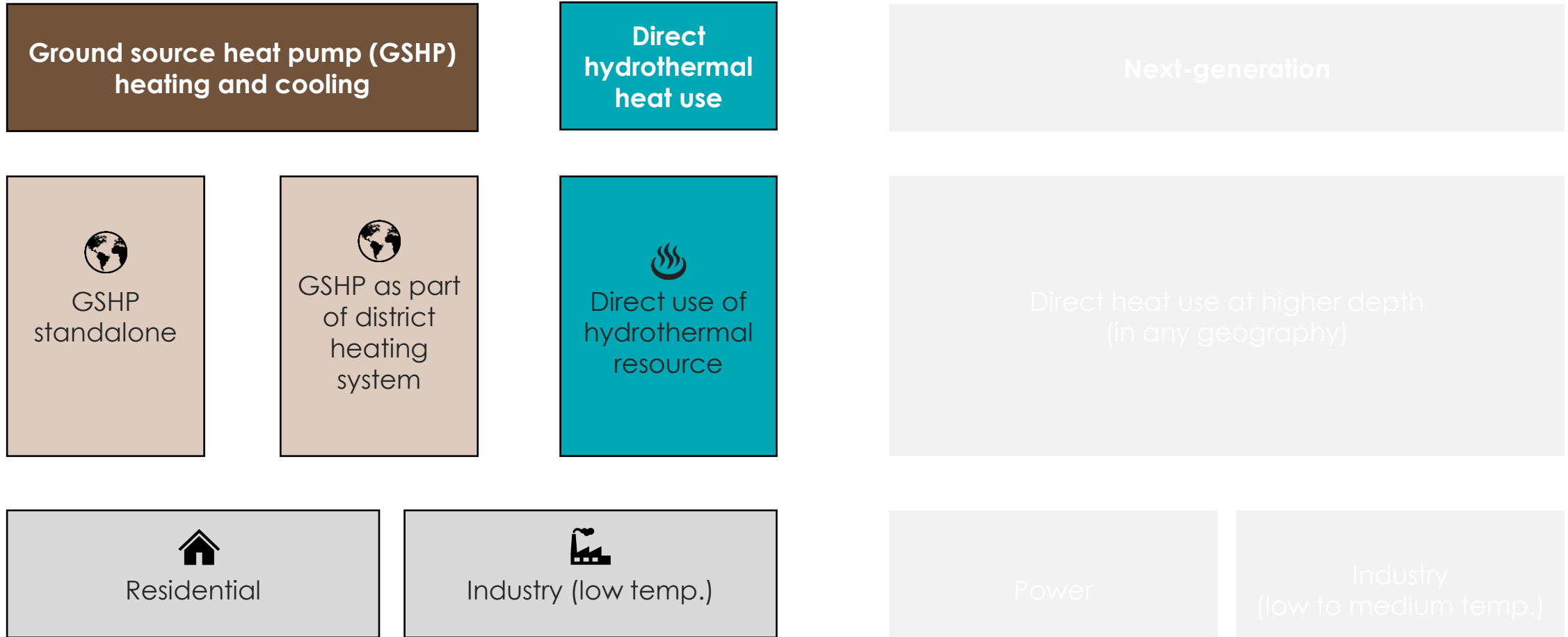
Industrial application	Estimated 2030 energy demand (TWh/y)	Temperature breakdown				Geothermal market potential (upper bound)		
		0–100 °C (Very Low)	100–200 °C (Low)	200–400 °C (Medium)	>400 °C (High)	Ground source heat pumps or direct use	Direct geothermal heat use only	Other
Total Residential (heating & cooling)	19,000	100%				100%		
Total Industrial (selected industries)	25,400	11%	16%	6%	67%	27%	6%	67%
Food, beverage & tobacco	2,000	41%	39%	11%	8%	80%	11%	8%
Pulp, paper & print	2,000	11%	83%	4%	2%	94%	4%	2%
Textiles	500	11%	65%	25%	0%	76%	25%	0%
Chemicals	5,000	21%	10%	3%	66%	31%	3%	66%
Alumina	400		60%	10%	30%	60%	10%	30%
Cement	4,500	2%	10%	14%	73%	12%	14%	73%
Iron & steel	11,000	3%			94%	3%		94%



Source: ETC (2025), *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible*  
Systemiq (2024), *Global opportunities for Electrothermal Energy Storage*

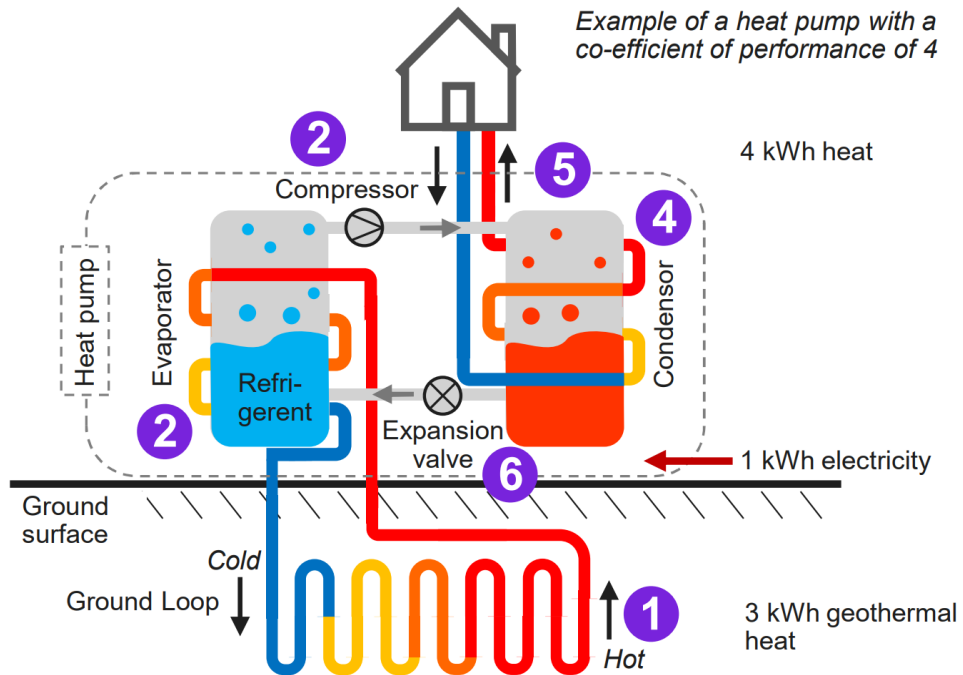
- Next-generation geothermal could be **competitive in industries requiring process heat of 100-200°C**, such as **paper and chemicals production, auxiliary processes in cement production and food processing**.
- Next-generation technologies can provide these temperatures in a **wider range of locations** than conventional, expanding the potential market.

# Geothermal heat production can occur through shallow conventional technologies



# Geothermal heating and cooling cycles rely on balanced heat-pump cycles using a working fluid

The working principle of geothermal heat extraction (via ground source heat pumps)



- 1 A ground loop absorbs thermal energy from the Earth and transfers it to a working fluid
- 2 The working fluid enters the evaporator (heat pump) where it transfers heat to a refrigerant that evaporates.
- 3 The vapor is compressed, raising its temperature and pressure.
- 4 The high-temperature, high-pressure vapor flows releases heat in the condenser and condenses back into a liquid.
- 5 Heat is transferred to the building via radiators, underfloor heating, or air ducts. For cooling, the refrigerant cycle is reversed, heat is instead transferred from the building to the ground.
- 6 The refrigerant passes through the expansion valve, drops in pressure and temperature, and returns to the evaporator.

## 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.

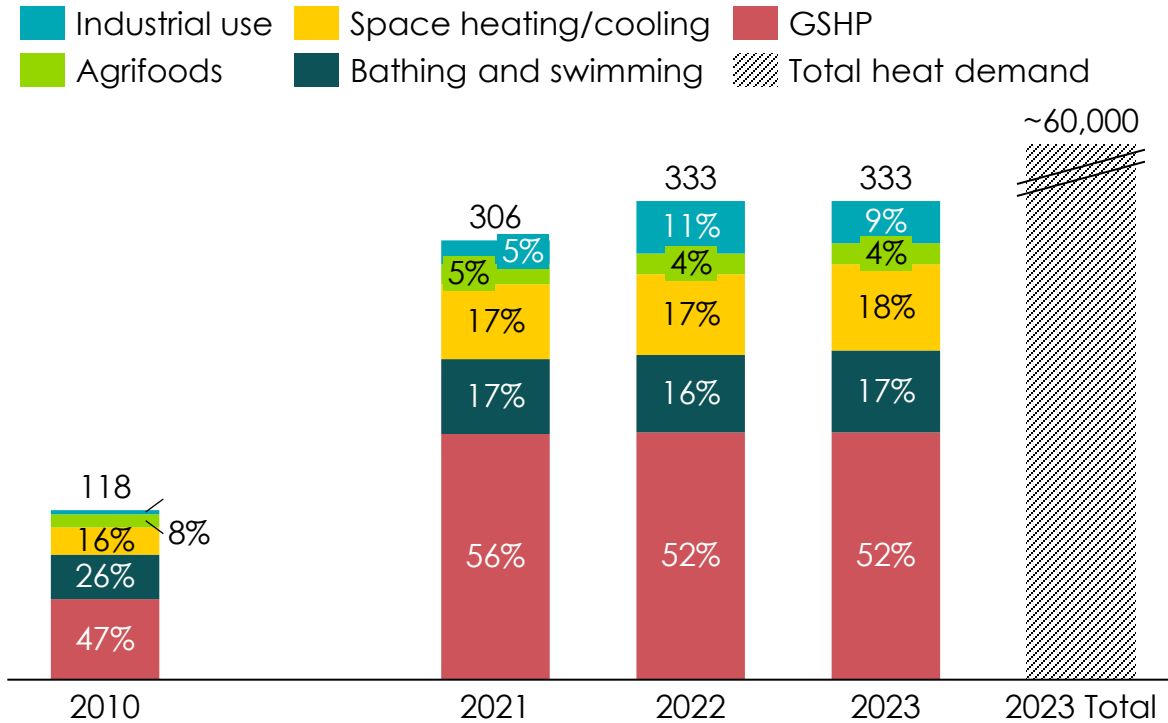
**System wear and tear:** Mechanical components, such as compressors and pumps, lose efficiency due to aging.

**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.

# Residential: Geothermal makes up less than 1% of heat demand today; China and US lead residential geothermal heating capacity

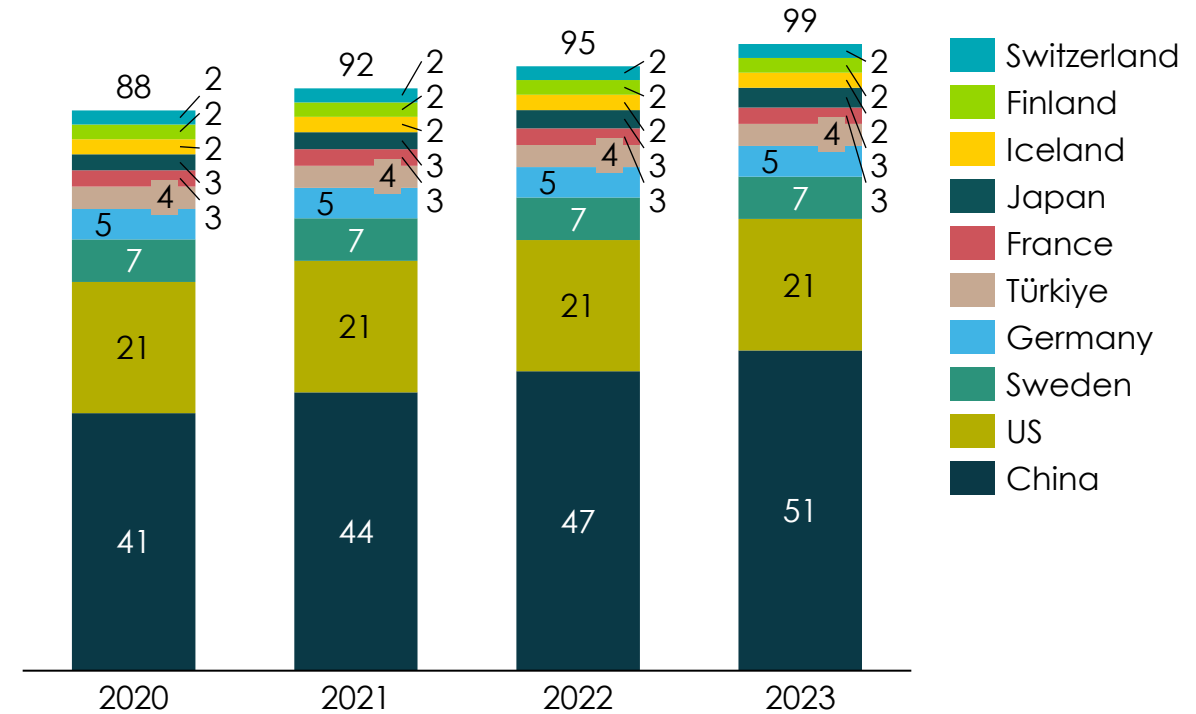
## Geothermal heating generation by application

TWh<sub>th</sub>, 2010-2023



## Top ten countries by residential geothermal heating capacity

GW<sub>th</sub>, 2020-2023



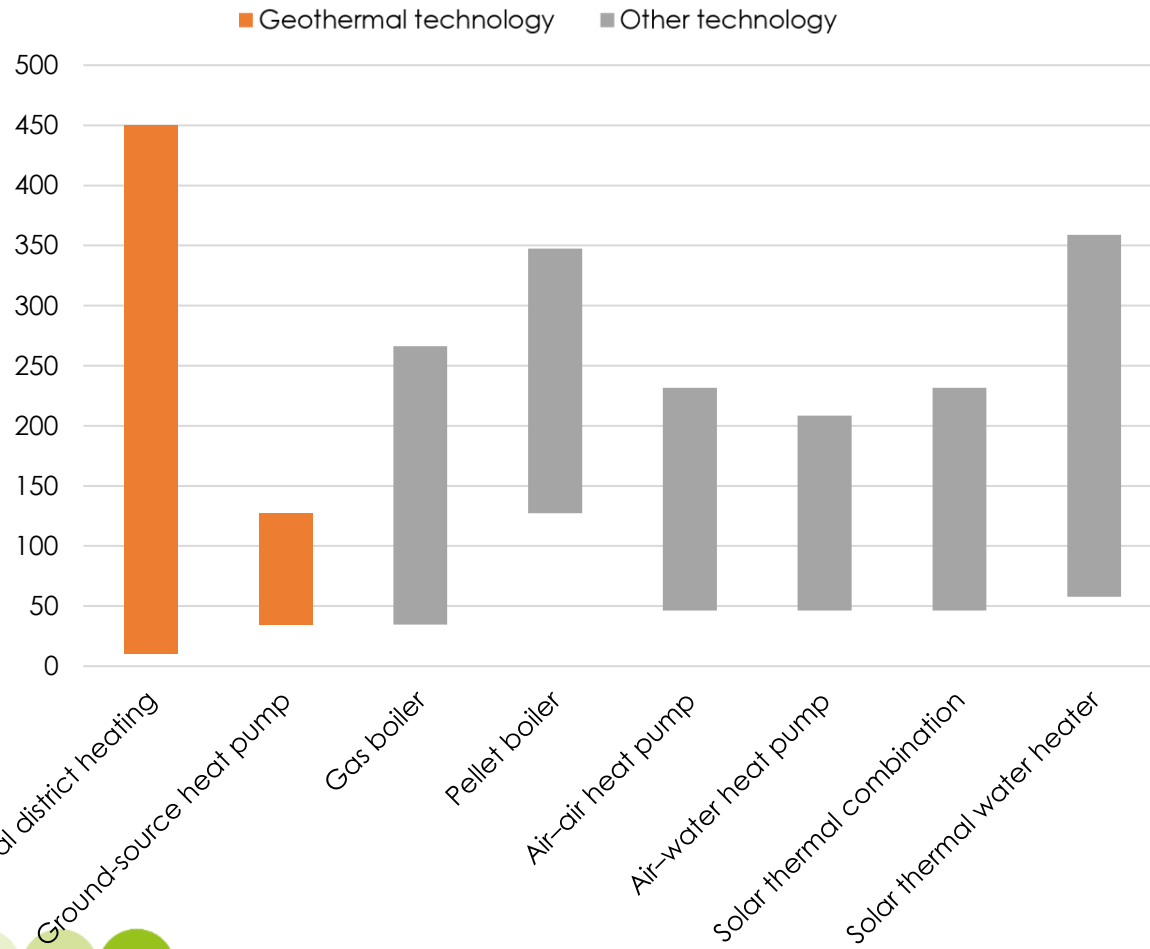
Around half of total global heat demand is for heat of less than 200°C. Two-thirds of the heat demand in this temperature range is for space and water heating in buildings, and the remaining one-third is for industrial processes

China is the largest user of geothermal district heating worldwide, accounting for two-thirds of the total, with extensive district network infrastructure in its Eastern and Northern provinces stemming from policies supporting the decarbonisation of heating

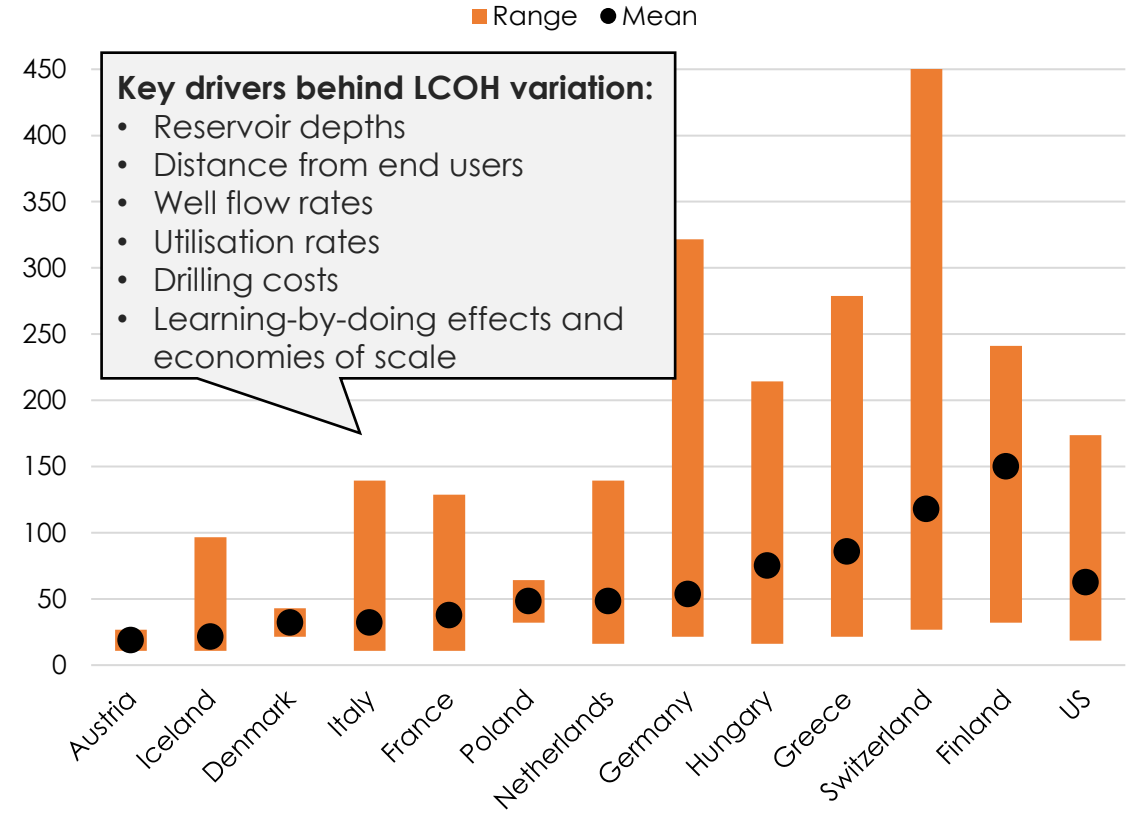
Note: GSHP = Ground source heat pump. Note: The 2022-2023 values for the top 10 geothermal countries from the 2020-2021 data. The top 10 countries represented 82% of global thermal capacity in 2020. Source: IEA (2024) *The Future of Geothermal Energy*; IEA (2023), *Renewables 2023*; ETC (2025), *Achieving Zero-Carbon Buildings: Electric, Efficient and Flexible*; KEARNEY ETI (2025), *Geothermal energy, turning up the heat*

# Residential: Geothermal levelised costs of heat (LCOH) competitive with alternatives although upfront costs are higher; costs range geographically

European LCOH range by technology, representative of early-2020s costs  
\$/MWh<sub>th</sub> (real 2024)



Geothermal district heating LCOH range by selected country  
\$/MWh<sub>th</sub> (real 2024)

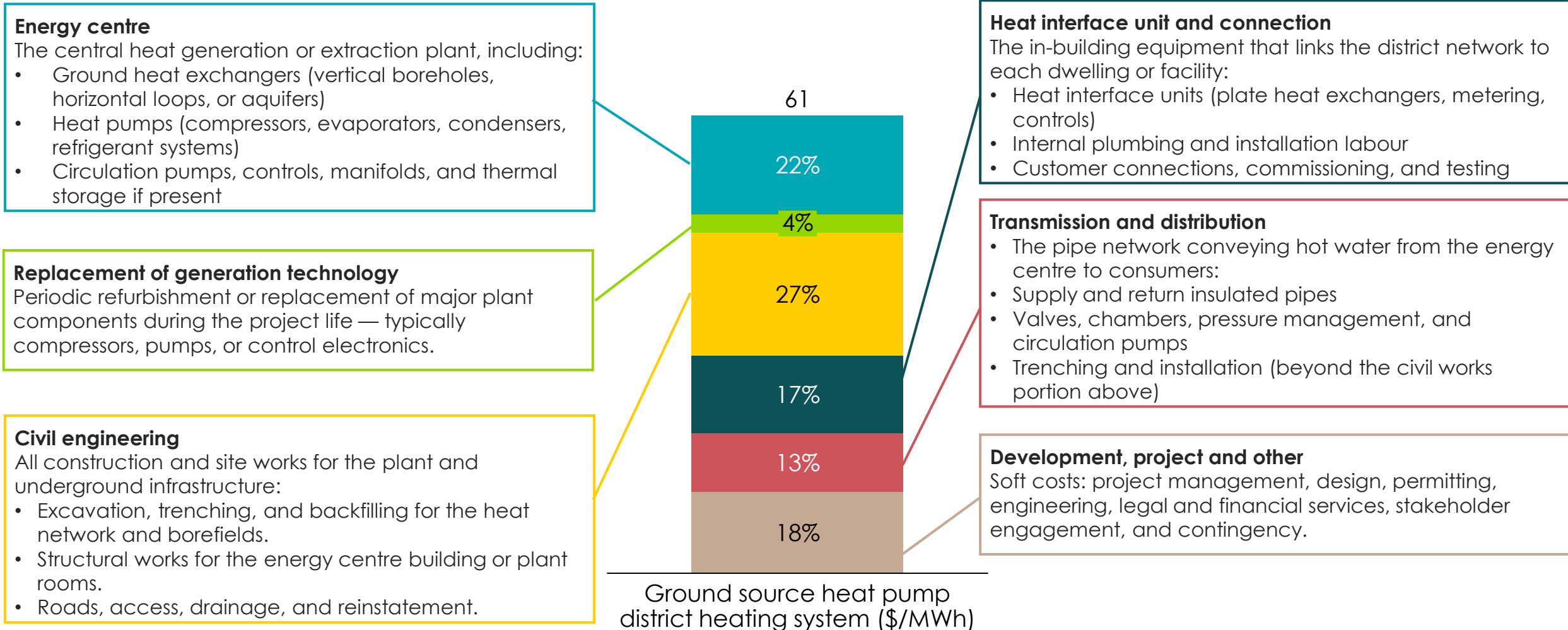


Note: LCOH ranges for geothermal district heating do not include network expenditure, therefore are mainly reflect drilling costs. Geothermal district heating systems typically use ground source heat pump technology. Source: KEARNEY ETI (2025), Geothermal energy, turning up the heat

# Residential: Geothermal district heating costs are driven by civils and the heat pump, followed by internal interfaces, transmission, and development

Levelised cost of heat breakdown for a ground source heat pump district heating network

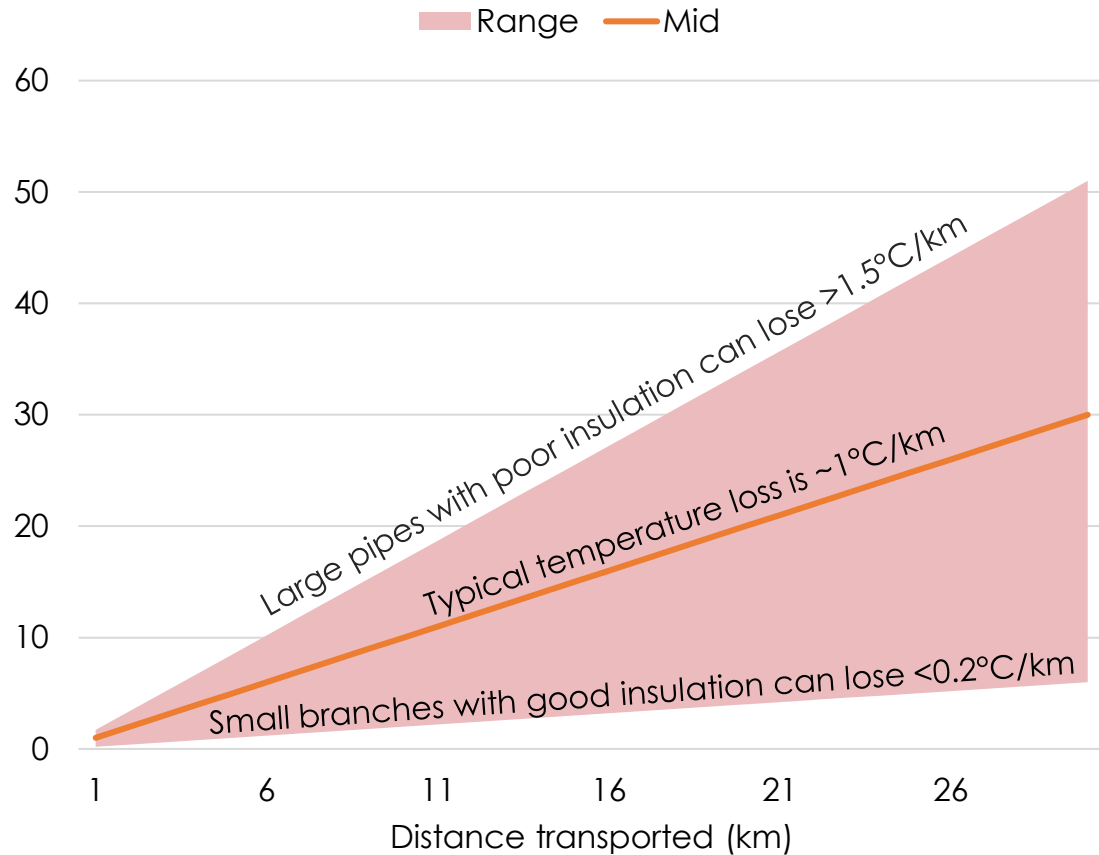
\$/MWh<sub>th</sub> (real 2024)



Notes: Represents an average flat in the U.K. using 7,961 annual kilowatt hours of heat and hot water, without subsidies. This geothermal district heating system uses ground source heat pump technology. Source: BNEF (2021), *District Heat Networks: To Build or Not to Build*

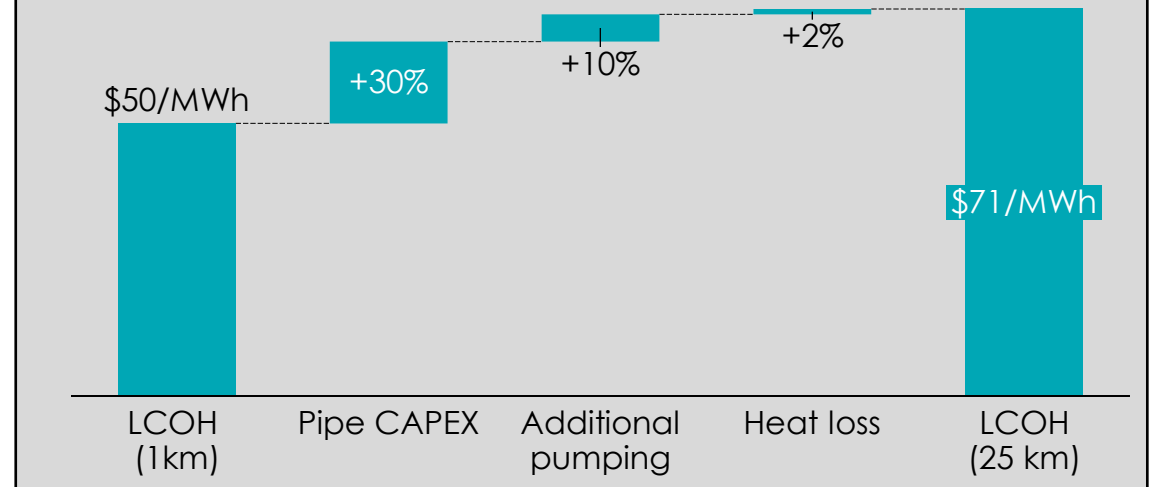
# Geothermal heat transport is limited by pipeline construction costs and logistics, rather than temperature loss

Typical temperature loss for pressurised water-based heat pipelines  
°C drop per pipeline



- **Temperature losses** can be designed accounted for in system design when the temperature differential between supply and demand levels are minimal
- **Pipeline construction cost/logistics** are often prohibitive – heat transport viability is likely to be confined to short distances or locations with existing networks

• **Illustrative case study:** increasing pipeline distance from 1 to 25 km for a district heating network could increase the delivered LCOH by ~50%, driven by pipe CAPEX and additional pumping requirements:



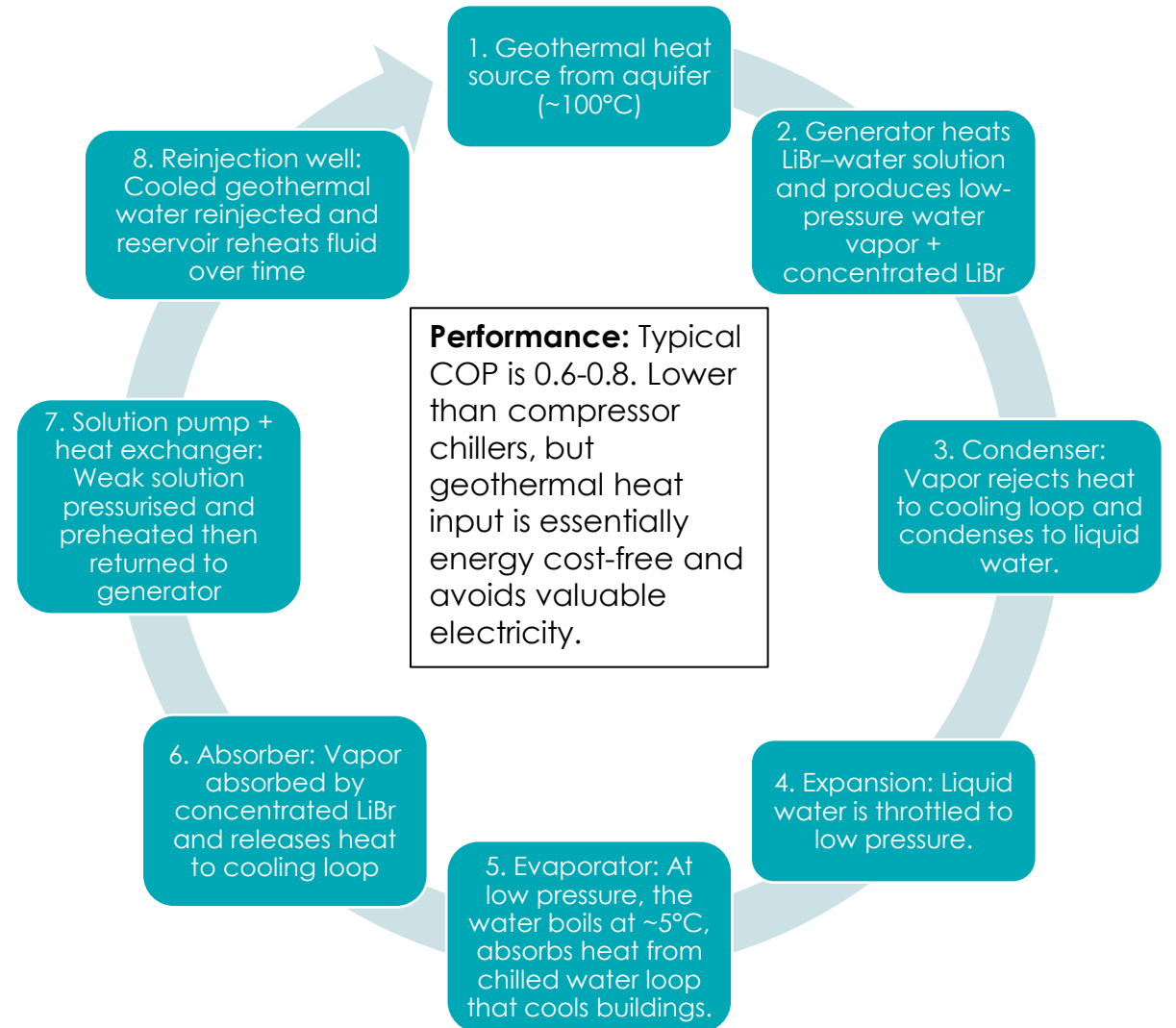
Notes: LHS – Pipeline temperature loss depends on pipe size, material, insulation class and condition, burial depth, fluid mass flow rate and velocity, and fluid temperature. RHS – LCOH calculations assume: a 90°C supply temperature and 50°C return temperature; 30 MW<sub>th</sub> average delivered heat with 65% load factor; 0.3m diameter pipeline with \$1500/m CAPEX and 20 W/m heat loss, pumping requirements calculated using the Darcy–Weisbach pressure loss equation.  
Source: Vovkey (2025), *Temperature Loss in Pipe Calculator*; Aquatherm (2025), *Heat loss in district heating: causes, calculation & solutions*

# Residential: Geothermal systems can provide efficient residential district cooling systems; this is an emerging use case thanks to high efficiency in district use

## District cooling:

- Air conditioning in hot countries (e.g. UAE) can make up to 70% of electricity demand
- **District cooling is established with TRL 9 and is around 50% more efficient than stand-alone systems; absorption chillers cut electricity use further.**
- **Geothermal district cooling works through the absorption cooling cycle:**
  1. System draws heat from a sedimentary aquifer, so sustainable operation requires reinjection.
  2. Refrigerant is water and the absorbent is lithium bromide (LiBr) – the absorption process enables low-pressure water vapour to absorb heat from a circulating loop of water, which then chills the building
  3. Reinjection into the aquifer should occur at the lowest feasible temperature to preserve the natural thermal gradient.
  4. Proper well spacing allows reheating and long-term stability over decades.

## Absorption cycle used in novel district geothermal cooling systems

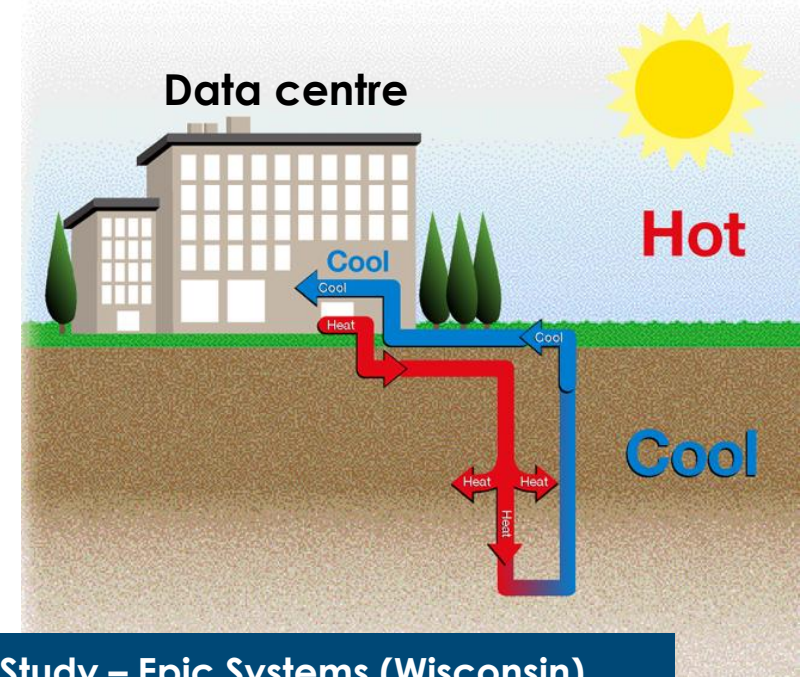


# Industry: Emerging use case of geothermal systems to provide industrial / data centre cooling systems

## Data centre cooling overview:

- ~40% of data centre electricity used for cooling
- Geothermal cooling systems could use the **constant underground temperature at 15-250m depths** (typically 10-15°C) to reject the heat from data centre servers
- Considerations:
  - **High upfront costs** compared to alternatives (e.g. standard chillers)
  - **Ideal for mid-sized** campus/colocation centres.
  - **Small edge centres uneconomic and infrastructure needed for large loads is challenging.**
  - Typical timeline: **2-3 years to integrate.**
  - Horizontal drilling and subsurface imaging lower risk and boost bankability.

## Data centre geothermal cooling concept

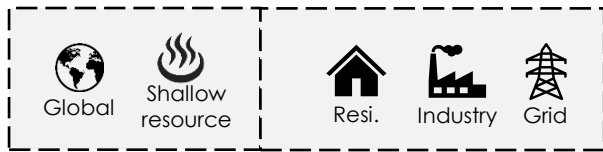
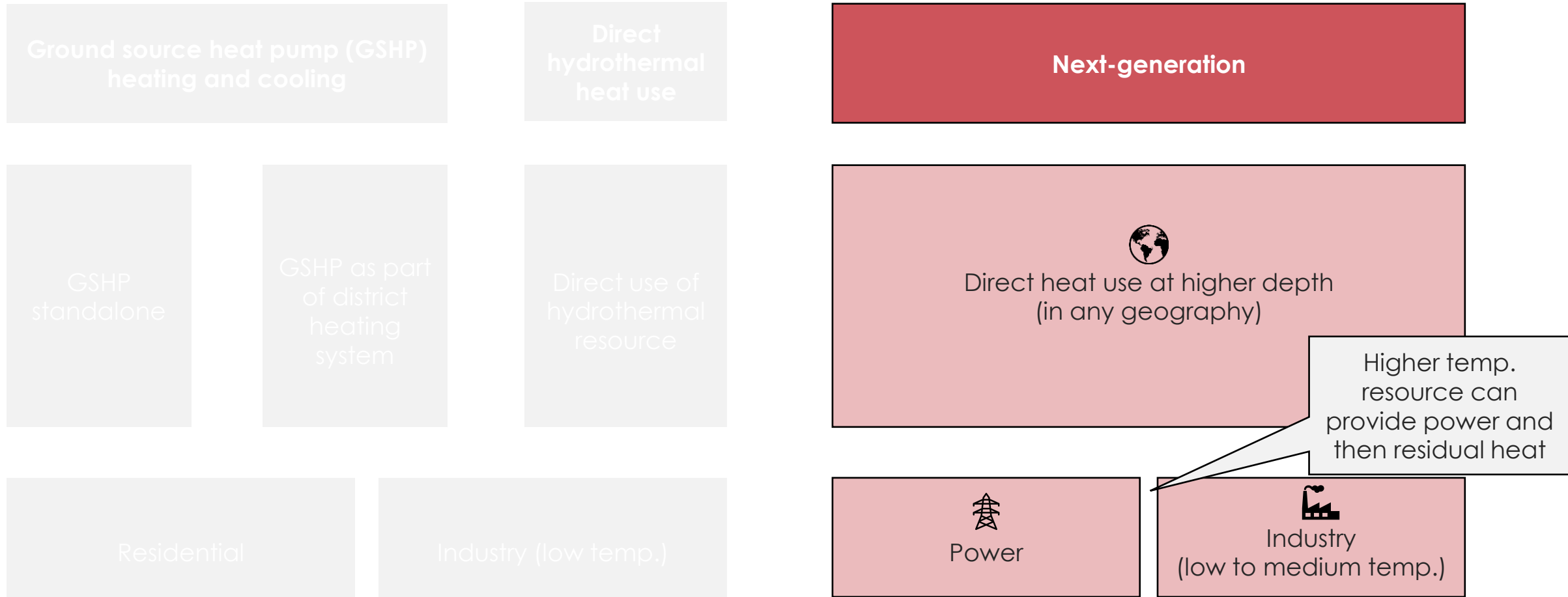


## Case Study – Epic Systems (Wisconsin)

Epic Systems drilled over 6,000 boreholes to create one of North America's largest geothermal cooling networks, cooling a 3.5 MW data center while simultaneously heating their expansive campus in winter.



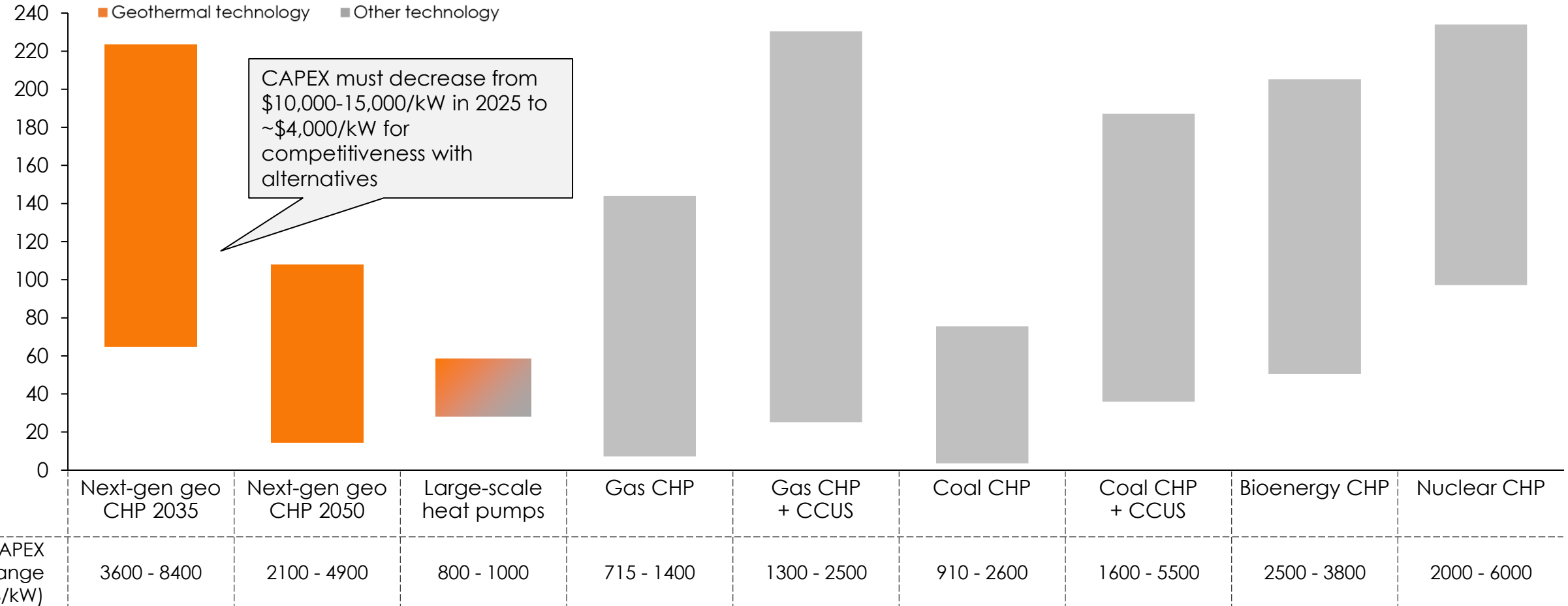
# Geothermal heat production can occur through deep next-generation technologies



# Next-gen. geothermal combined heat and power could be cost competitive for residential heat, if CAPEX drops to below \$4,000/kW

Levelised cost of heat supplied to district heating networks by source, assuming \$60/MWh<sub>e</sub> average electricity revenue

\$/MWh<sub>th</sub> (real 2024)

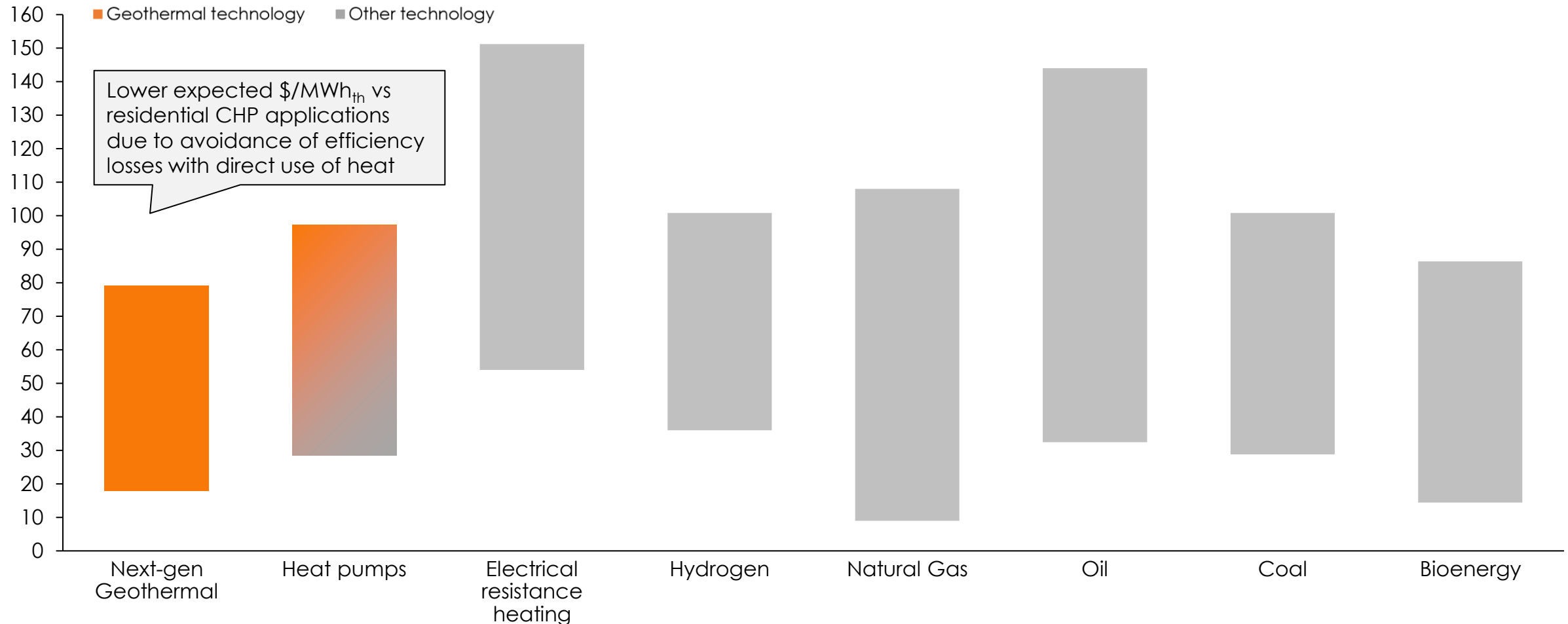


Notes: Costs based on the IEA's Announced Pledges Scenario. CHP = combined heat and power; all plants 80% utilisation; WACC 7%; Geothermal co-generation heat-to-power ratio = 1, with electricity revenue credited at USD 60/MWh; CCUS capture rate = 95%; CO2 prices of \$0-160/tCO2 (for gas and coal); heat pumps have COP of 3.8 - 4.1 and electricity input of \$50-150/MWh. Source: IEA (2024) *The Future of Geothermal Energy*

# Next-gen. geothermal could reach a similar cost range for industry to electrified and fossil heat sources by 2035

Levelised cost of heat for direct heat use in low temperature industrial heat (<200°C) in the IEA's Announced Pledges Scenario, 2035

\$/MWh<sub>th</sub> (real 2024)

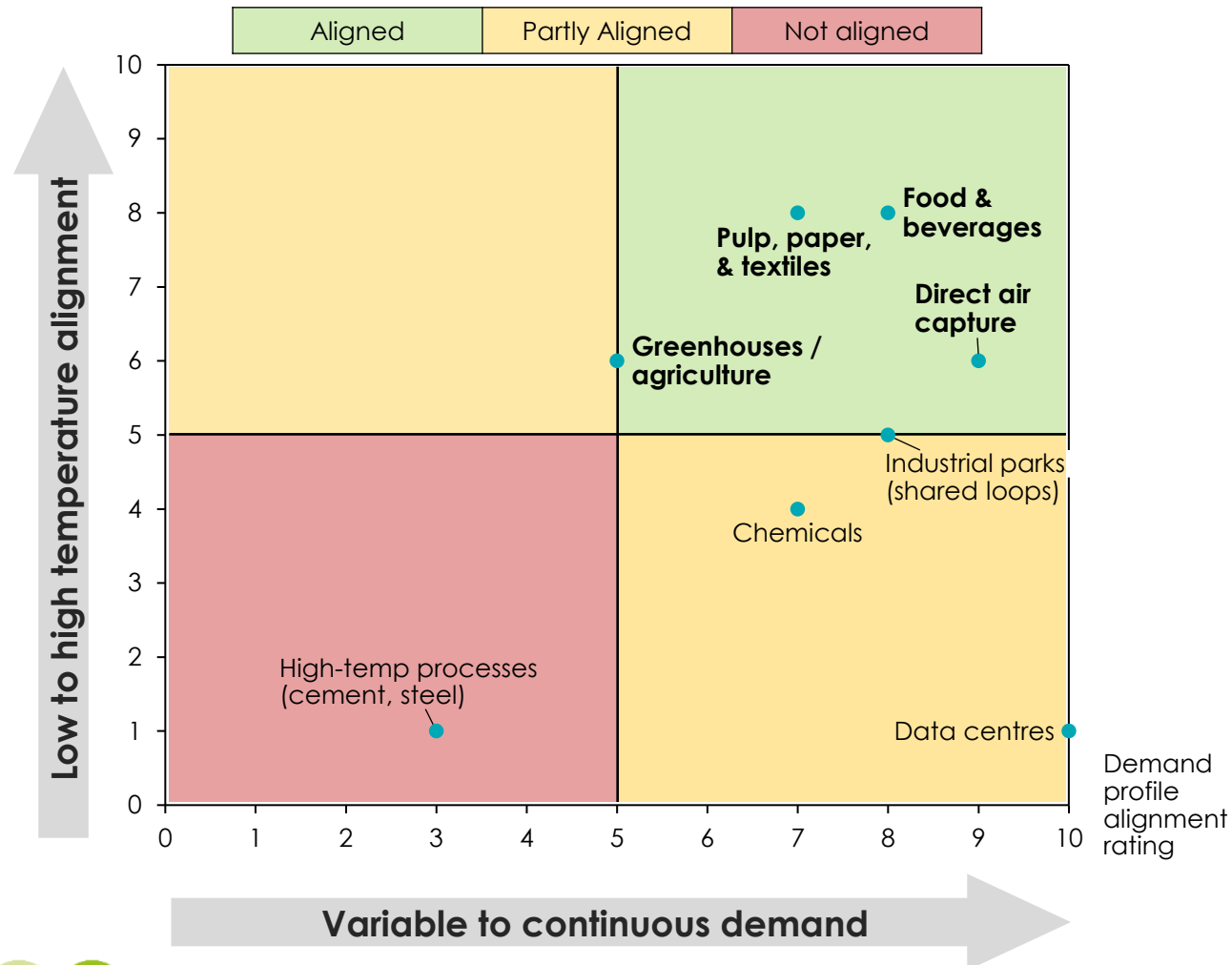


Notes: Subsurface costs: 1,000–3,000 USD/kW<sub>th</sub>; plant: 150 USD/kW<sub>th</sub>; COP range = 2–6; Electricity: 50–150 USD/MWh; conversion ratio = 2 kW<sub>th</sub>/kW<sub>e</sub>; Hydrogen: 1–4 USD/kgH<sub>2</sub>; Gas cost range: 2–20 USD/MBtu; CO<sub>2</sub> price: 0–160 USD/t; Oil cost: 350–1,100 USD/toe; Coal cost: 25–125 USD/Mtce; Biomass: 2–20 USD/MBtu.. Source: IEA (2024)  
The Future of Geothermal Energy

# Next-generation geothermal well suited for industrial new-build low-temperature applications with continuous heat and power demand

## Best-fit geothermal industrial co-location applications

Temperature alignment rating (/10)



- **Next generation geothermal aligns well with continuous-load industries and new greenfield zones where drilling can be integrated into site design.**
- **High utilisation drives strong economics across heat and power:** Co-location can enable revenue stacking, avoids heat network CAPEX, minimises losses, and supports flexible hybrid configurations such as CHP or low-grade heat for DAC.
- **Constraints limit deployment beyond well-matched, resource-rich sites:** Geographic resource availability, drilling feasibility, variable heat profiles, permitting, and the maturity of next-gen technologies constrain wider rollout.

Note: High temperature alignment is defined to be in the low-temperature industrial heat (0-200 °C) range.  
 Source: Systemiq analysis for the ETC (2025); Systemiq (2024), *Global opportunities for Electrothermal Energy Storage*

# Opportunities to scale shallow heating and cooling solutions for buildings, as well as next-generation geothermal co-location for greenfield industry

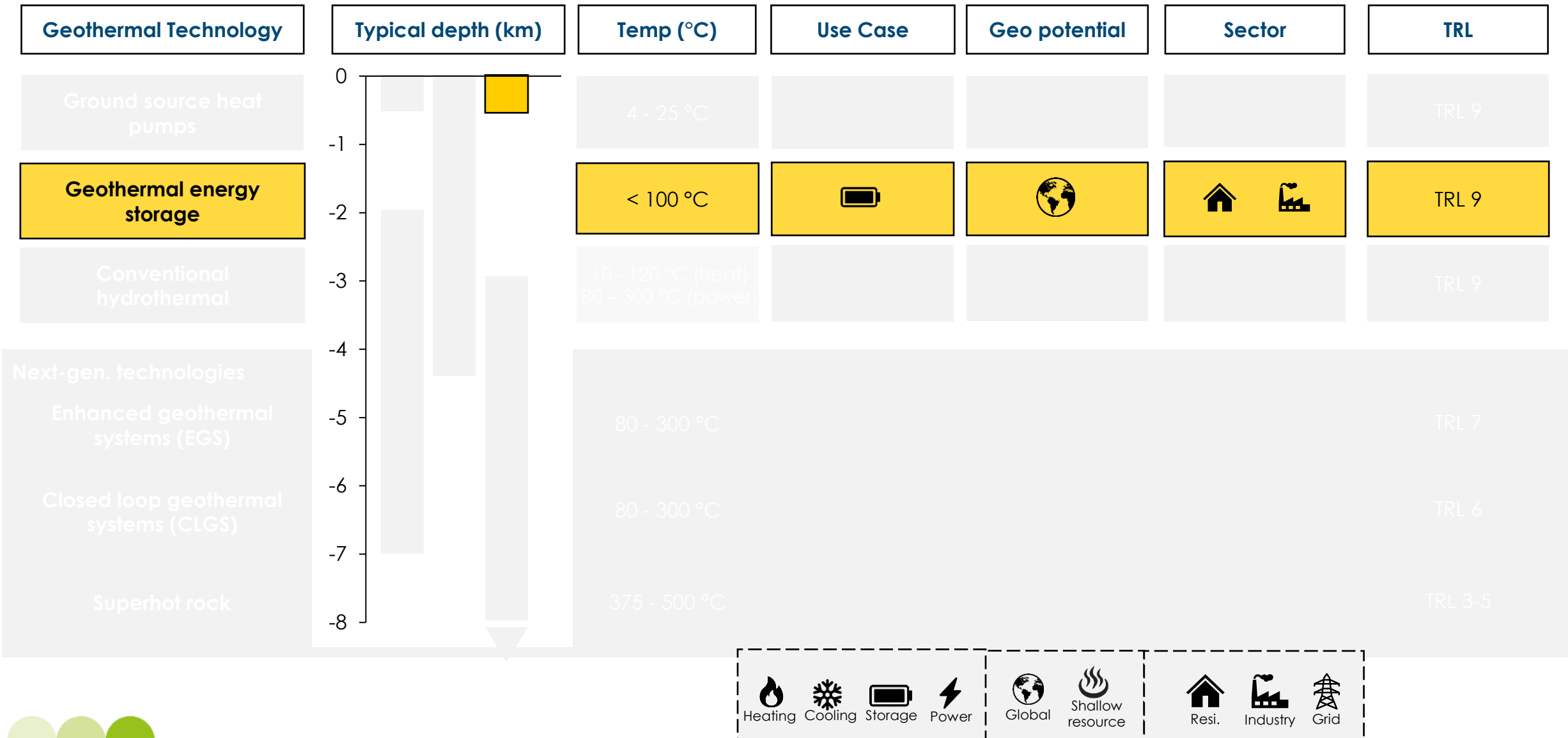
- 1) **Conventional ground source heat pumps (standalone and in district heating networks) could scale significantly for residential heating and cooling, although barriers need to be overcome:**
  - 1) Shallow (0 – 0.5 km) **low-temperature heating and cooling resources for building applications are ubiquitous across most regions.** Efficiencies and lifetime costs are competitive with alternative technologies.
  - 2) However, **high upfront costs are the most significant deployment barrier, alongside planning, permitting constraints in some locations** – limiting most deployment to new build homes or commercial buildings.
  
- 2) **Next-generation technologies could unlock a greater share of industrial heat applications around the world; co-located geothermal for greenfield industrial sites with constant load profiles for combined heat and power (CHP) is a key use case, but scalability will rely on cost declines and risk mitigation:**
  - 1) Regions with limited alternative low-cost heat options (e.g. natural gas) like Europe could be well-placed to leverage new geothermal heat applications in new industrial sites/clusters
  - 2) CHP could be the most cost-competitive setup to leverage heat and power output, where the geothermal plant and heat demand are co-located
  - 3) Key deployment risks include **uncertain cost declines for next-generation technologies, deep drilling (2 – 7 km) development risk, and site-specific considerations** around co-locating geothermal supply with industrial demand



# Geothermal energy storage



# Geothermal energy storage includes overbuilt capacity, high-maturity thermal energy storage and low-maturity mechanical storage technologies

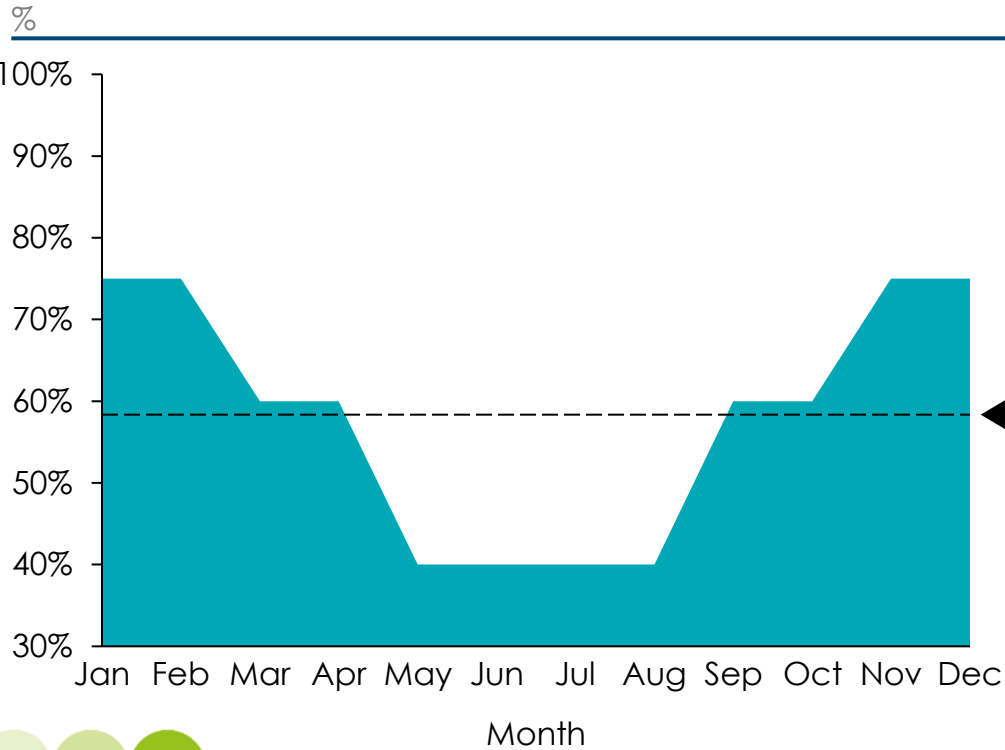


Notes: Underground energy storage parameters refer to underground thermal energy storage (excluding more nascent options such as geothermal mechanical storage). Assumed TRL scale: TRL 1-3 = Research to Proof of Concept; TRL 4-6 = Lab to Pilot Demonstration; TRL 7-9 = Prototype Demonstration to FOAK / Full Commercial Deployment

# Overbuilding geothermal plants could provide a system balancing option, if costs are low enough

- Geothermal power plants can be used for grid balancing by overbuilding the plant
- E.g., it can be run it at a **higher load factor in winter than in summer**, reducing the need for other seasonal storage in the power mix.

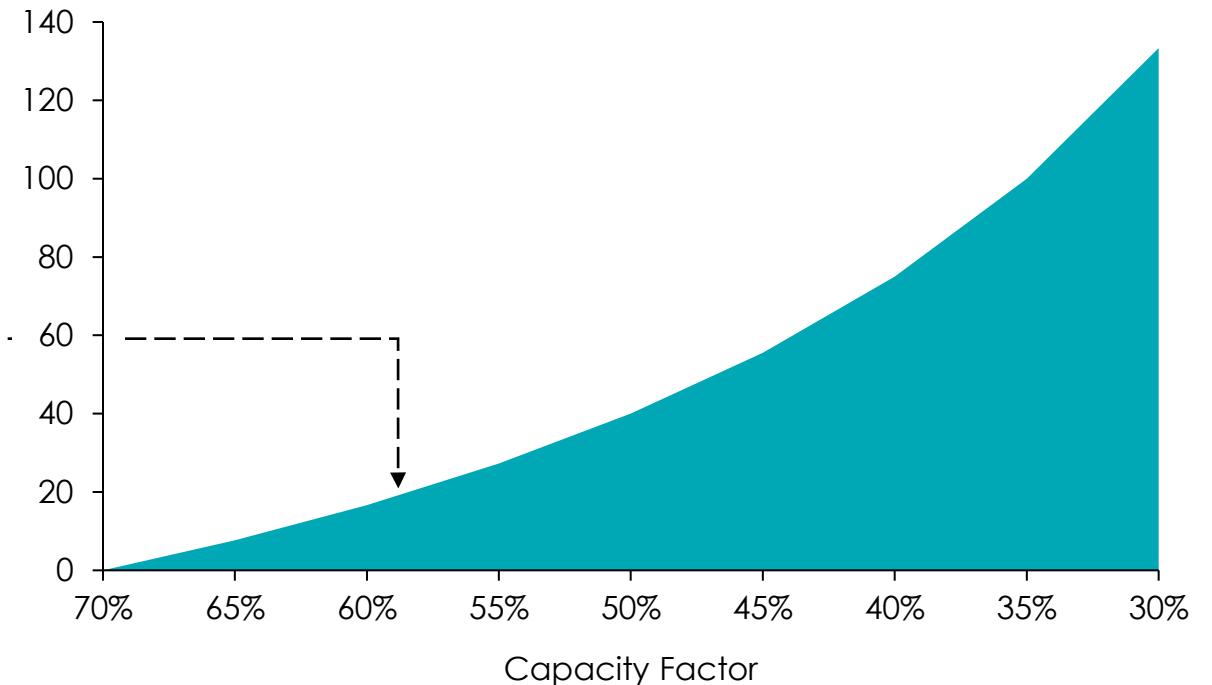
Illustrative example: capacity factor by month for overbuilt geothermal plant with higher winter utilisation



## Challenges:

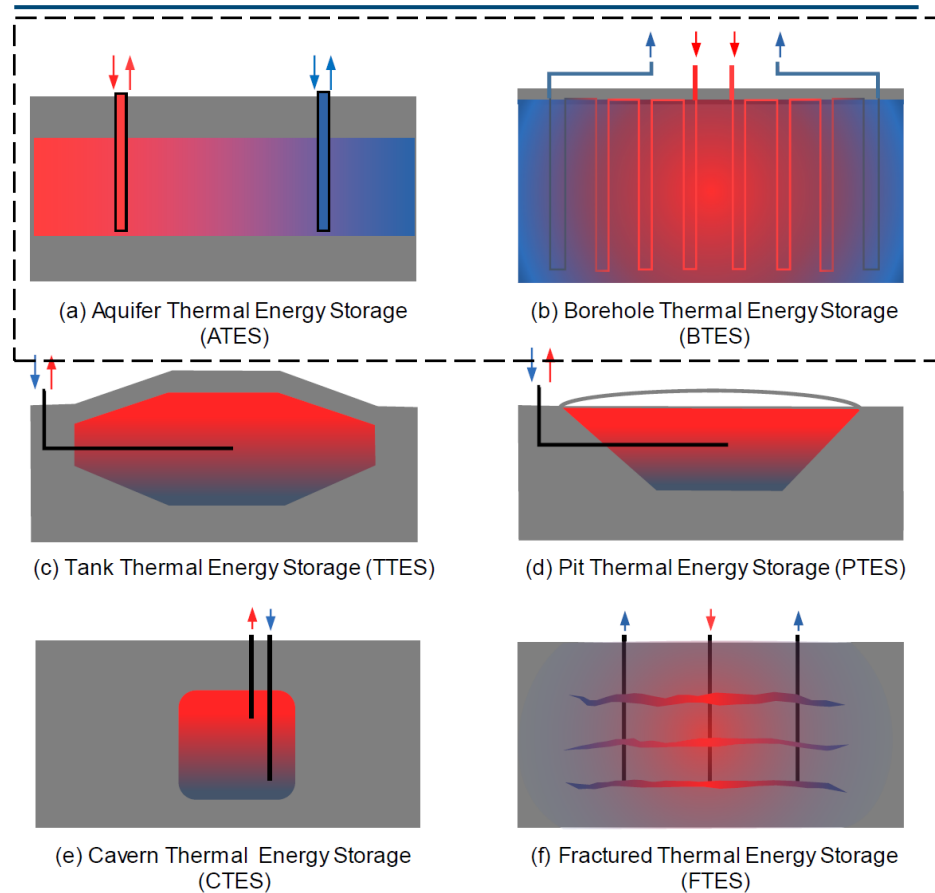
- **Lower utilisation means higher LCOE** so next-generation technologies will need significant cost declines low utilisation operation to become viable
- **High CAPEX and dominance of fixed operating costs** limit the economic viability of reducing output

LCOE premium by capacity factor (relative to \$100/MWh at 70% capacity factor)  
\$/MWh, real 2024



# Underground thermal energy storage: emerging opportunities to provide large-scale balancing for seasonality in heating supply and demand

## Underground thermal energy storage (UTES) methods



**Optimal option is geology-dependent: ATES and BTES are favourable in terms of simplicity, cost efficiency, adaptability, scalability, and reliability:**

### ATES overview:

- TRL 9
- Requires permeable unconsolidated aquifers and high, stable groundwater flow paths
- Moderate depths
- Highest round-trip efficiency (60-80%)
- Lowest cost and largest storage volume

Key applicable regions: Netherlands, Denmark, Germany, Northeast + Midwest US, North China

**ATES is the best option when suitable aquifers exist.**

### BTES overview:

- TRL 9
- Works in most ground types
- Drilling tech is standardised with some room for innovation
- Lower round-trip efficiency of 30-60% due to conduction losses
- Higher costs than ATES and generally lower storage volumes

Key applicable regions: Generably scalable everywhere, particularly cold countries lacking aquifers (Finland, Canada, some US states, South China, North UK)

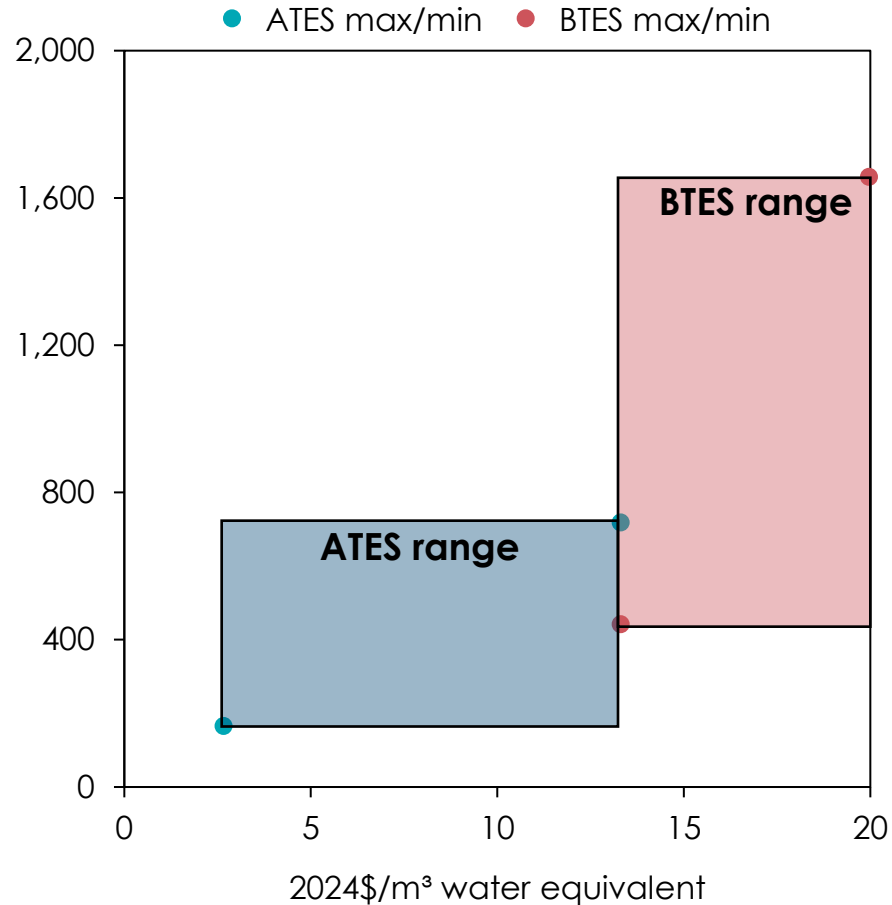
**BTES is generally the best option where suitable aquifers do not exist**



# Aquifer thermal energy storage (ATES) is typically lower cost and higher storage capacity than borehole thermal energy storage (BTES)

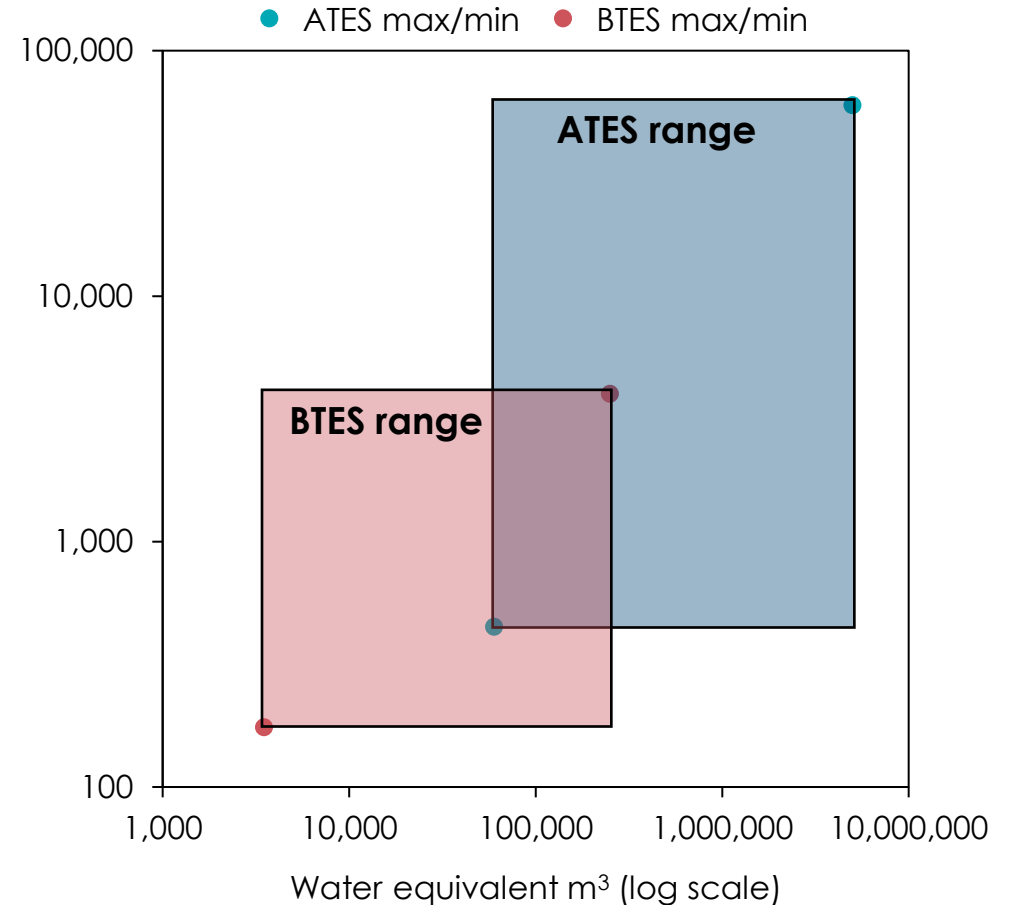
Thermal energy storage CAPEX range based on existing project data

2024\$/MWh<sub>storable, thermal</sub>



Thermal energy storage capacity range based on existing project data

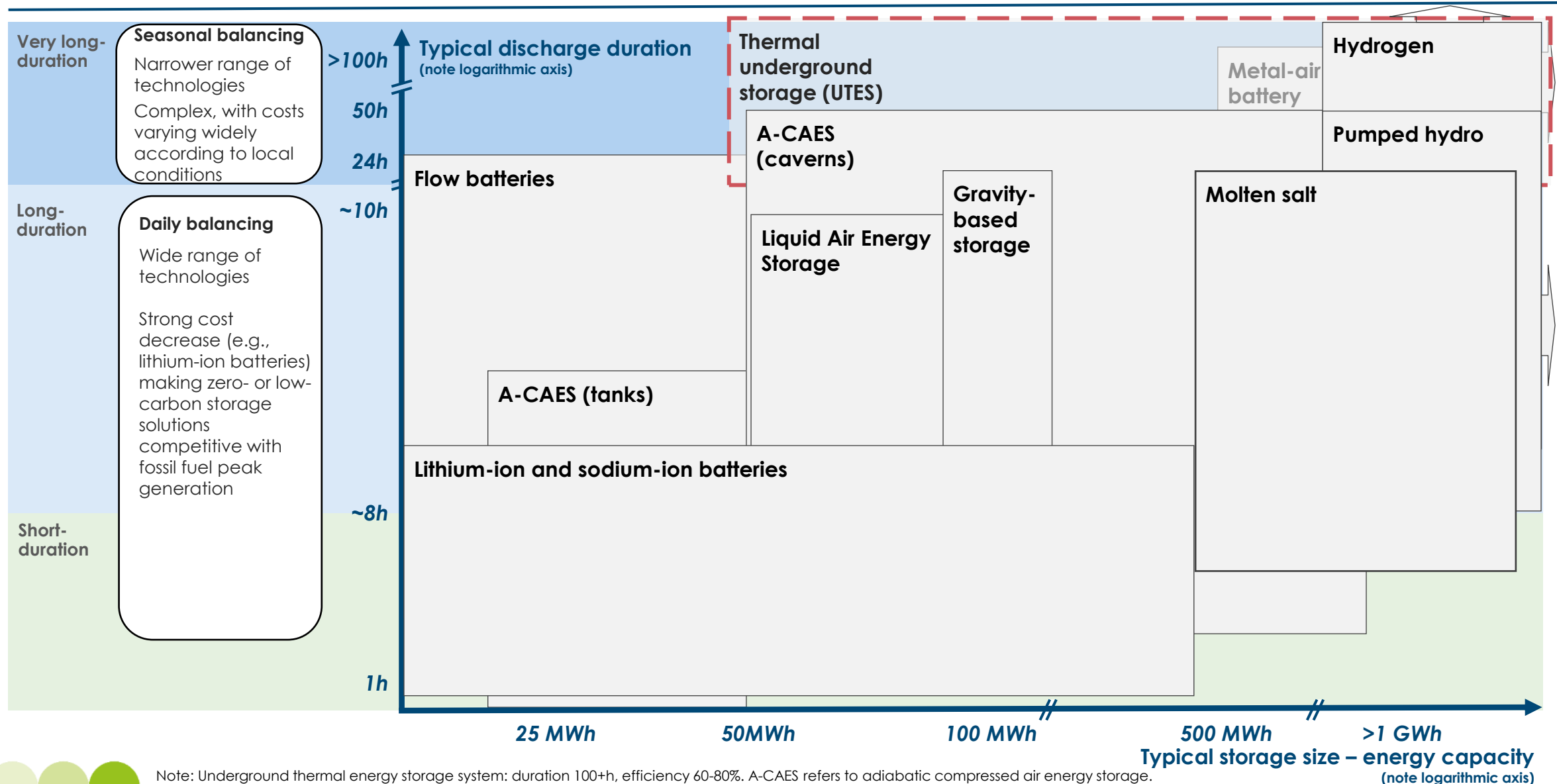
MWh<sub>storable, thermal</sub> (log scale)



Source: M. Herrmann (2025), *Capital costs of aquifer thermal energy storage (ATES): a review*

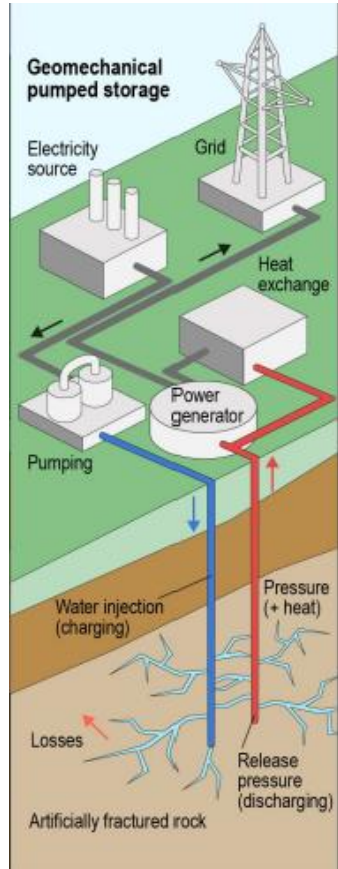
# Underground thermal energy storage is suited for ultra-long duration storage

Key long duration technologies currently operate at different typical storage sizes and durations



Note: Underground thermal energy storage system: duration 100+h, efficiency 60-80%. A-CAES refers to adiabatic compressed air energy storage. CCGT refers to combined cycle gas turbine. Source: Ricks et al (2025) The role of flexible geothermal power in decarbonized electricity systems; BNEF (2024), 2024 long-duration energy storage cost survey; Pacific Northwest National Laboratory (2023), Energy Storage Cost and Performance Database; IEA (2024), ETP Clean Energy Technology Guide.

# Mechanical underground storage: comparable to long duration storage offering 8-10 hours of duration



## Mechanical underground geothermal storage overview:

- TRL 7
- Requires deep competent rock at 2.5-6 km depth, artificially fractured reservoir and large injection/production wells
- Operates in geology with sufficient overburden and rock strength for the reservoir to elastically store pressure and fluid.
- High round-trip efficiency (70-75%)
- Costs remain uncertain (but could reach \$20-100/MWh<sub>e</sub>), depend on drilling depth, fracturing and pumping/injection expenses – crossover with oil and gas know-how useful in reducing costs

Key applicable regions: Deep continental stable rock basins with accessible rig infrastructure e.g. parts of the US, Australia, Western Canada, central Europe, parts of Asia

**Mechanical storage could emerge as a storage option in locations where surface pumped hydro is not viable, geology allows deep fractured reservoirs, and the power grid needs long-duration storage**

## Case Study – Texas, US



- SAGE has built and operated **the first field-scale demonstration** of a 3 MW mechanical pressure-based storage system
- The pilot validated **8-to-10-hour dispatch** and demonstrated operation up to 18 hours of mechanically stored pressure
- Achieved using **oil and gas drilling, fracturing and reservoir-control know-how**, applied to energy storage

# Geothermal energy storage is likely to be dominated by mature underground thermal energy storage; mechanical storage options are more uncertain

- 1) **Underground thermal energy storage (TES) could fill the need for seasonal storage in future decarbonised power systems, particularly in temperate, high-latitude countries:**
  - 1) Engineered aquifer or borehole TES systems can store additional summer heat or other low-cost thermal inputs to help meet peak winter heat demand
  - 2) TES CAPEX is sufficiently low for very low cycle rates to be economical, enabling seasonal system balancing, which could reduce the role for gas-based seasonal storage in future clean energy systems with high seasonal variability
  
- 2) **Mechanical underground storage is still low-maturity and will compete with other, more mature storage technologies for medium-duration (8-10h) power system balancing**
  - 1) Other technologies which will be able to meet this balancing need are pumped hydro, demand-side flexibility, interconnectors, compressed air energy storage, and batteries (as costs decline further)
  - 2) As commercial-scale cost data is not yet available, the competitiveness of mechanical underground storage is highly uncertain, however it could scale in locations lacking other medium-duration storage options



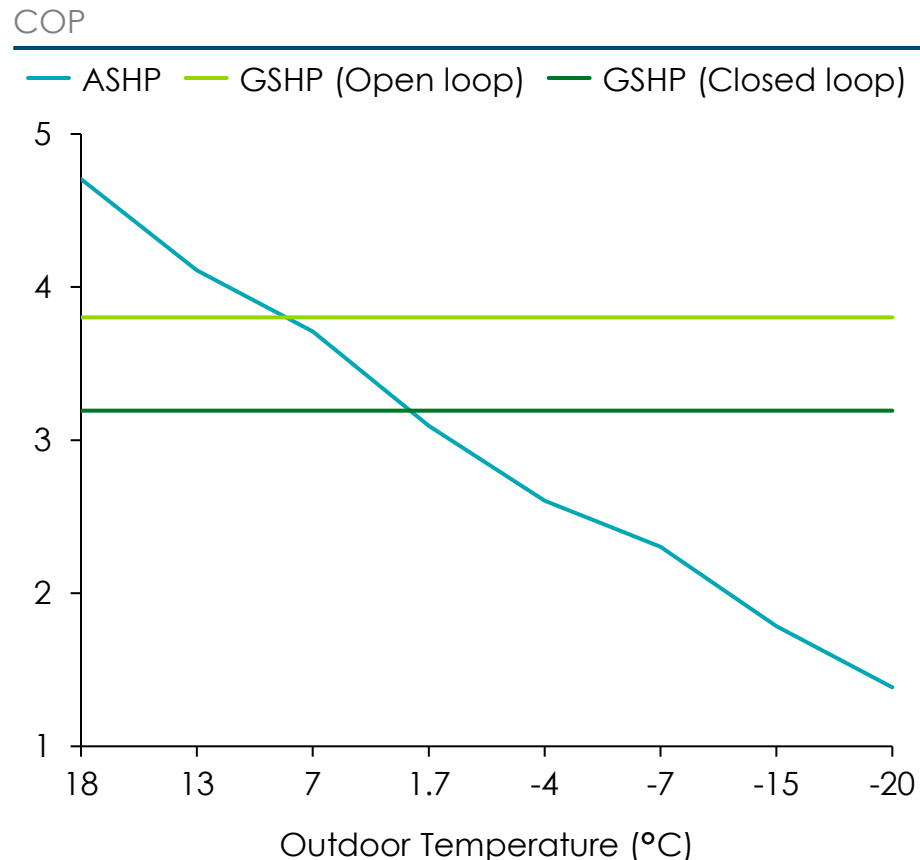
# Agenda

- Context: geothermal energy state of play
- Techno-economic deep dives: power, heat and storage
- **System value considerations**
- Wider considerations of geothermal development
- Emerging conclusions

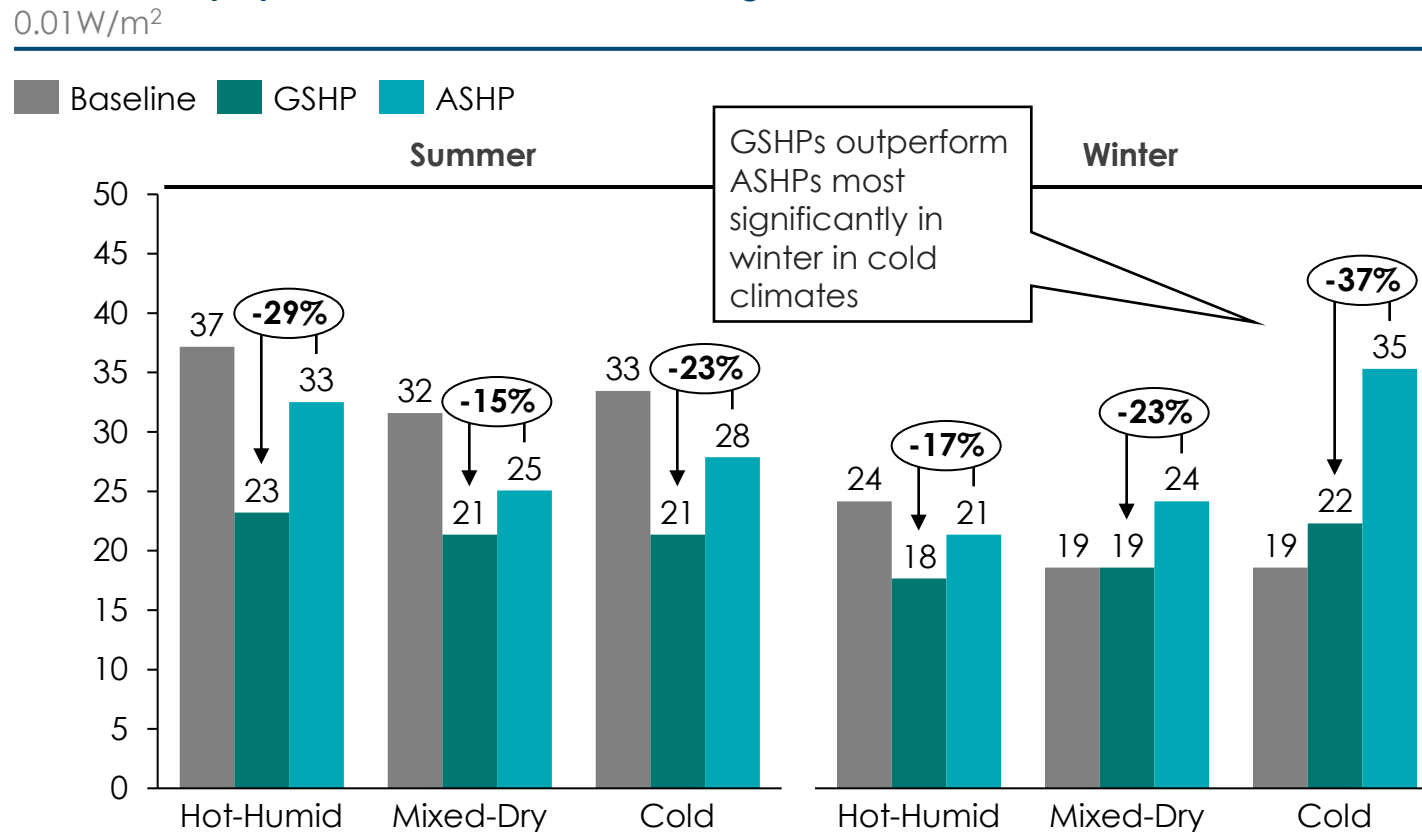


# Geothermal heating via ground source heat pumps (GSHP) requires less power input than air source heat pumps (ASHP)

COP vs outdoor temperature for ASHP and GSHPs



Peak intensity by season in commercial building stock and selected US climate zones

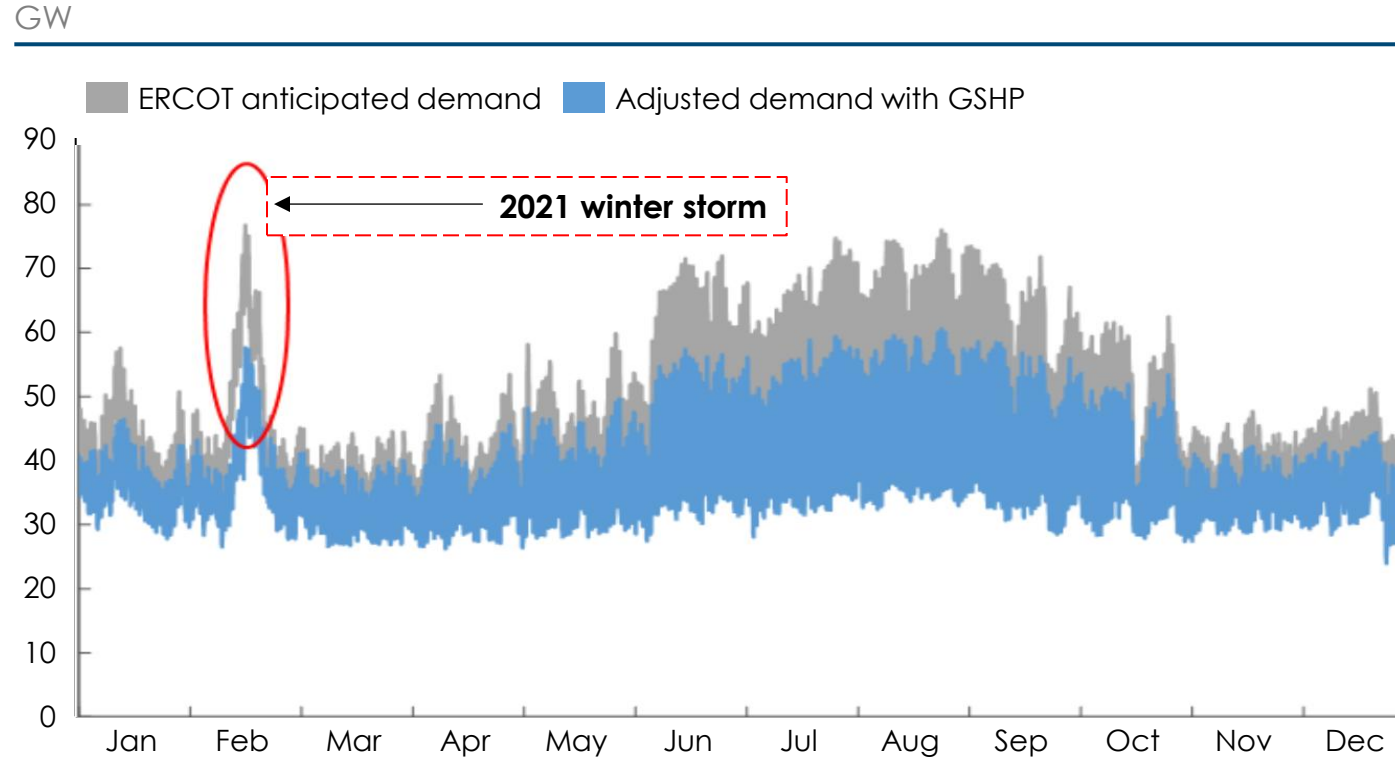


Notes: RHS - Peak intensity represents maximum electric demand for heating or cooling during the respective seasons. ComStock model scenarios were used to model "Baseline" represents the U.S. commercial building stock as it existed in 2018); "GHP" represents the "Packaged Water-to-Air Geothermal Heat Pump"; ASHP represents "HP RTU Std Performance Air Source Heat Pump". Regional humidity / temperature classifications based on the US DoE's Guide to Determining Climate Zones by County: Building America and IECC 2021 Updates. Source: Garcia-Cascales, M. (2020) *Spatial assessment of the Ground Source Heat Pumps suitability against conventional heat pumps based on Superficial Air Temperature*, The Engineering Toolbox (2025) *Heat Pumps - Performance and Efficiency Ratings*, US DoE (2025), *Pathways to Commercial Liftoff: Geothermal Heating and Cooling*



# Higher adoption of GSHPs could therefore significantly flatten summer and winter peak power demand

## Illustrative impact of mass GSHP on ERCOT electricity demand

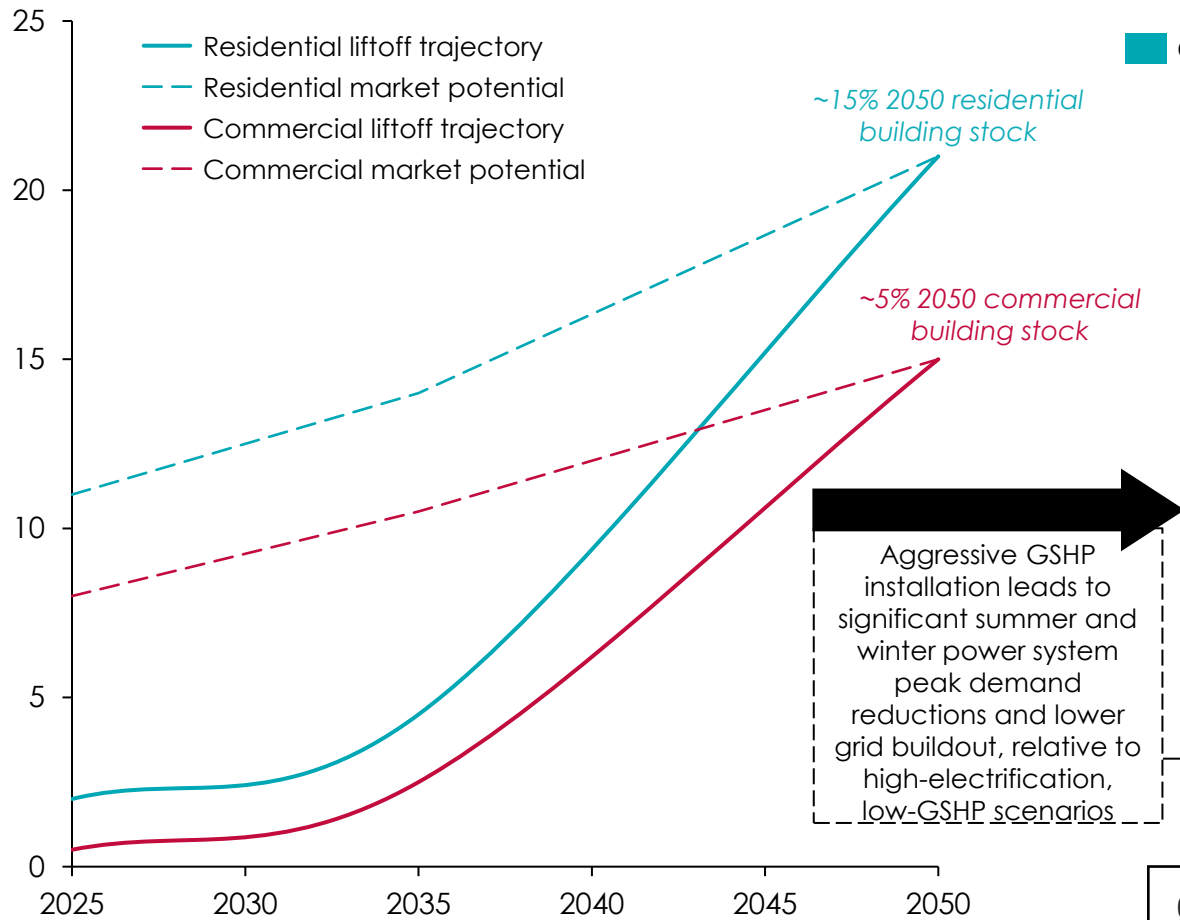


- **GSHPs significantly cut extreme winter peaks**, including the spike during the 2021 storm modelled in ERCOT.
- **Winter load becomes lower and smoother**, reducing strain on the grid during cold snaps.
- **Summer peaks are lower**, with reduced afternoon cooling demand.
- **Seasonal swings narrow**, creating a more stable year-round load profile.
- Overall effect: **less peak capacity needed** GSHP-heavy heating electrification pathways.

# This could reduce the strain on electricity grids – US case study shows high GSHP adoption scenario could reduce power capacity needs by 11%

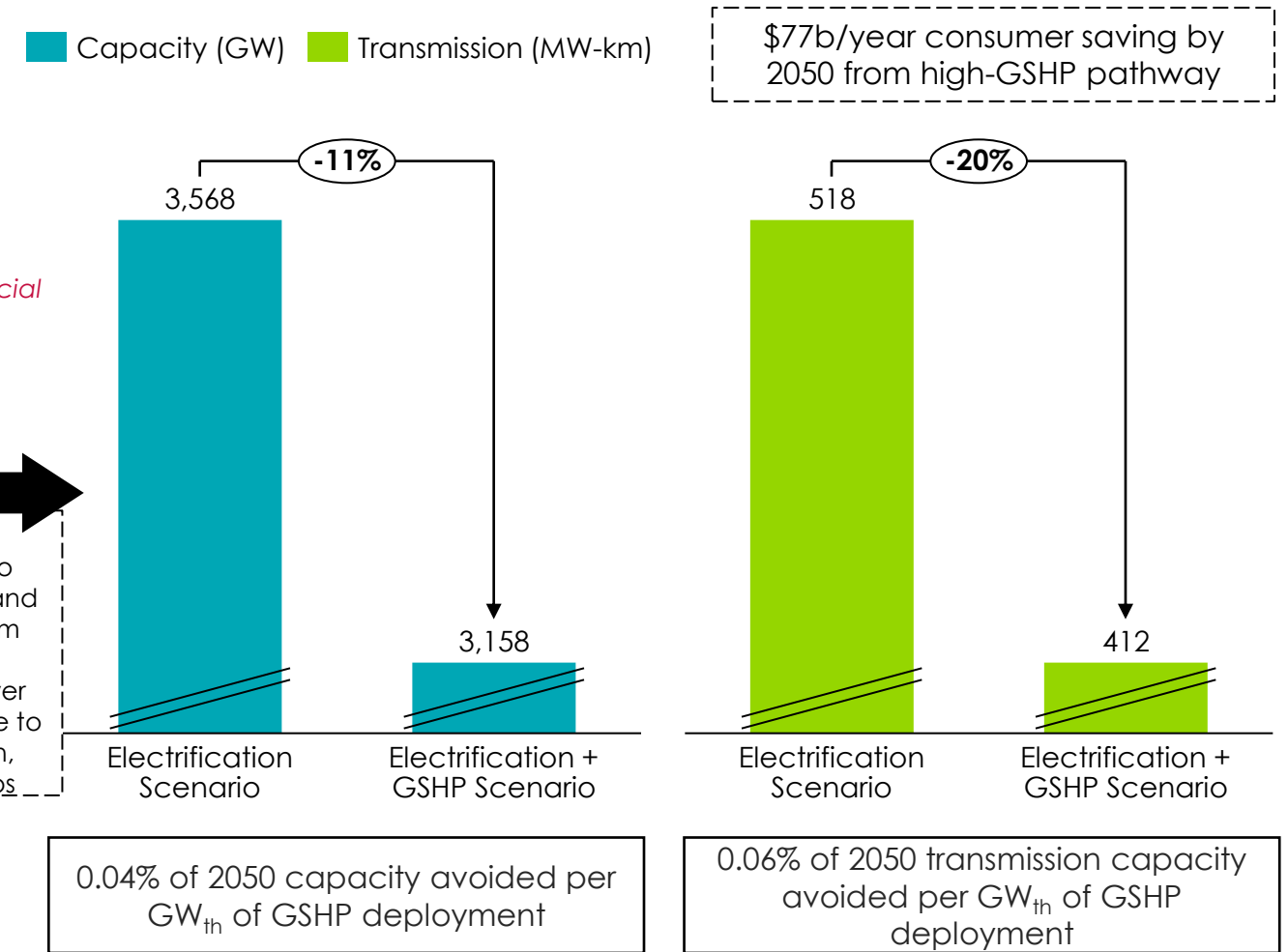
## US DoE Liftoff trajectory for GSHP installations

Million homes equivalent (by building type)



## Estimated 2050 US power system impacts by scenario

GW (LHS); MW-km (RHS)



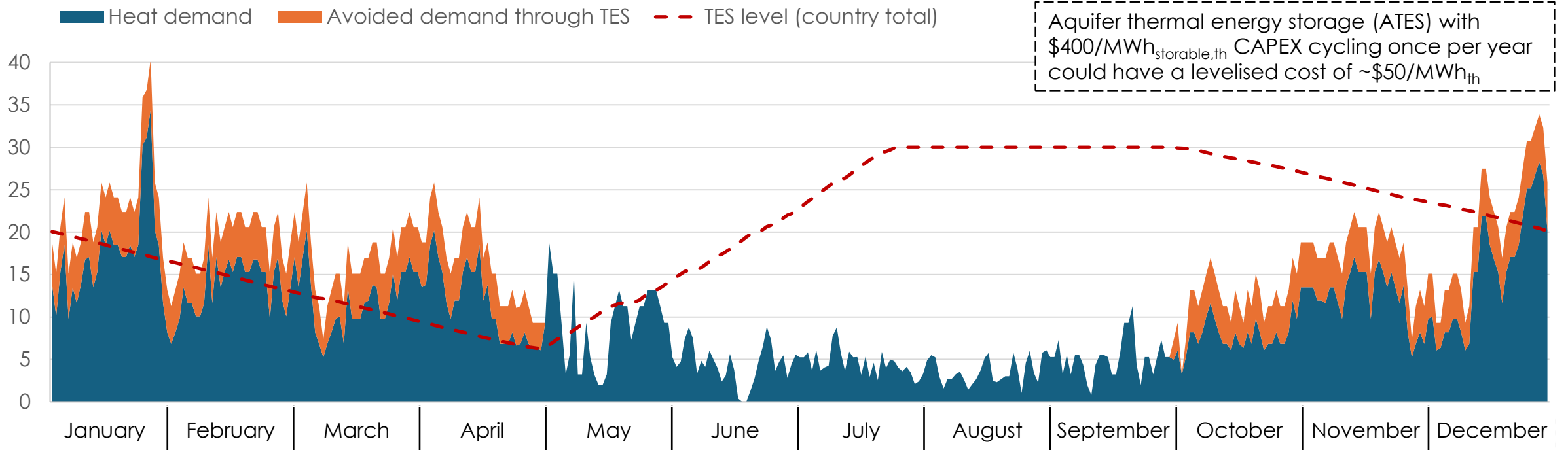
Notes: ERCOT = Electric Reliability Council of Texas

Source: US DoE (2025), Pathways to Commercial Liftoff: Geothermal Heating and Cooling; Oak Ridge National Laboratory (2023), Grid Cost and Total Emissions Reductions Through Mass Deployment of Geothermal Heat Pumps for Building Heating and Cooling Electrification in the United States

# Seasonal underground thermal energy storage (TES) could have material impacts on winter peak shaving, power system sizing, and system costs

## Hypothetical TES impact on UK 2050 clean electrified heating demand

Daily average heat demand –  $\text{GW}_e$ ; TES level –  $\text{TWh}_{\text{th}}$



In a highly electrified UK energy system, building out  $20 \text{ TWh}_{\text{th}}$  of seasonal thermal energy storage could:

- **Demand:** Reduce maximum winter heating demand by up to  $4 \text{ GW}_e$  (5% of peak heat demand)
- **System sizing:** Reduce peak power capacity needs by up to  $4 \text{ GW}_e$  and ultra-long storage needs by  $\sim 15 \text{ TWh}_e$
- **System costs:** Save  $\$5\text{b}/\text{year}$  in balancing costs and decrease average power system costs by  $\sim\$5/\text{MWh}_e$

Notes:  $20 \text{ TWh}_{\text{th}}$  of thermal storage is 13% of the UK's 2050 annual heat demand and 0.03% UK's technical TES potential. 80% round trip efficiency and 4% real WACC assumed, alongside average heat pump coefficients of performance of 3 in winter and 4 in summer. TES assumed to be charged between May and September during periods of excess renewables (though this would likely occur through heat rejection from cooling systems, solar thermal collectors, industrial waste heat, and excess renewables through heat pumps). TES assumed to discharge when national heating demand is above 10 GW. Source: Systemiq analysis for the ETC (2025); ETC(2025), *Power Systems Transformation: Delivering Competitive, Resilient Electricity in High-Renewable Systems*; NESO (2022), *Future Energy Scenarios 2022 (FES 2022)*; C.S. Brown (2024), *Assessing the technical potential for*



# Geothermal heat and energy storage could support optimal clean energy system pathways by reducing demands on electricity grids

- 1) **Scaling ground source heat pumps (standalone and in district heating) for heating and cooling could have significant impacts on power system sizing**, through reducing strain on electricity grids; a scenario with 36 million ground source heat pumps deployed in the US by 2050 could reduce power generation capacity needs by 11% and transmission capacity needs by 20%
- 2) **Underground thermal energy storage (TES) can significantly reduce seasonal heating and cooling balancing challenges in temperate countries** through long-duration thermal energy shifting:
  - 1) Ground source heat pumps can naturally store heat extracted during summer cooling in the subsurface, improving winter heating performance at the building scale
  - 2) Larger engineered aquifer or borehole TES systems can store additional summer heat or other low-cost thermal inputs to help meet peak winter heat demand
- 3) **Potential power system impacts of next-generation geothermal technologies are still uncertain and will depend on cost reduction and risk mitigation:**
  - 1) Cost declines could enable scale-up in the medium- to long-term, however the need to derisk the development and operation of next-generation technologies makes scaling significantly beyond the current shares of global power generation unlikely in the short-term



# Agenda

- Context: geothermal energy state of play
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- System value considerations
- **Wider considerations of geothermal development**
- Emerging conclusions



# Wider considerations of geothermal energy

## Key considerations



### 1. Emissions, environmental and resource footprint

- **In deep geothermal, CO<sub>2</sub> emissions can occur from reservoir gases**, vary widely by plant type and local geology; **average geothermal lifecycle intensities are well below fossil power**. Emissions do not occur with shallow heat geothermal.
- **Other environmental risks** (e.g. groundwater pollution, local gas release) are **manageable with correct regulatory and safety mechanisms**
- **Geothermal uses low levels of water and materials compared to other technologies:** water-use only of concern with conventional high-temperature power plants in arid regions



### 2. Public acceptance and permitting

- **Perceived risks occur infrequently and are manageable** - active community management essential, and siting of deep geothermal projects best in rural or new build zones
- **Permitting challenges could cause projects to face delays in deep and shallow geothermal projects, potentially limiting deployment**



### 3. Economic and skills co-benefits

- Geothermal can **leverage oil and gas expertise**, infrastructure, supply chains, and enable job creation – however, **component sharing** must be managed to prevent bottlenecks
- **Co-production of critical minerals** such as lithium from geothermal brines can strengthen project economics

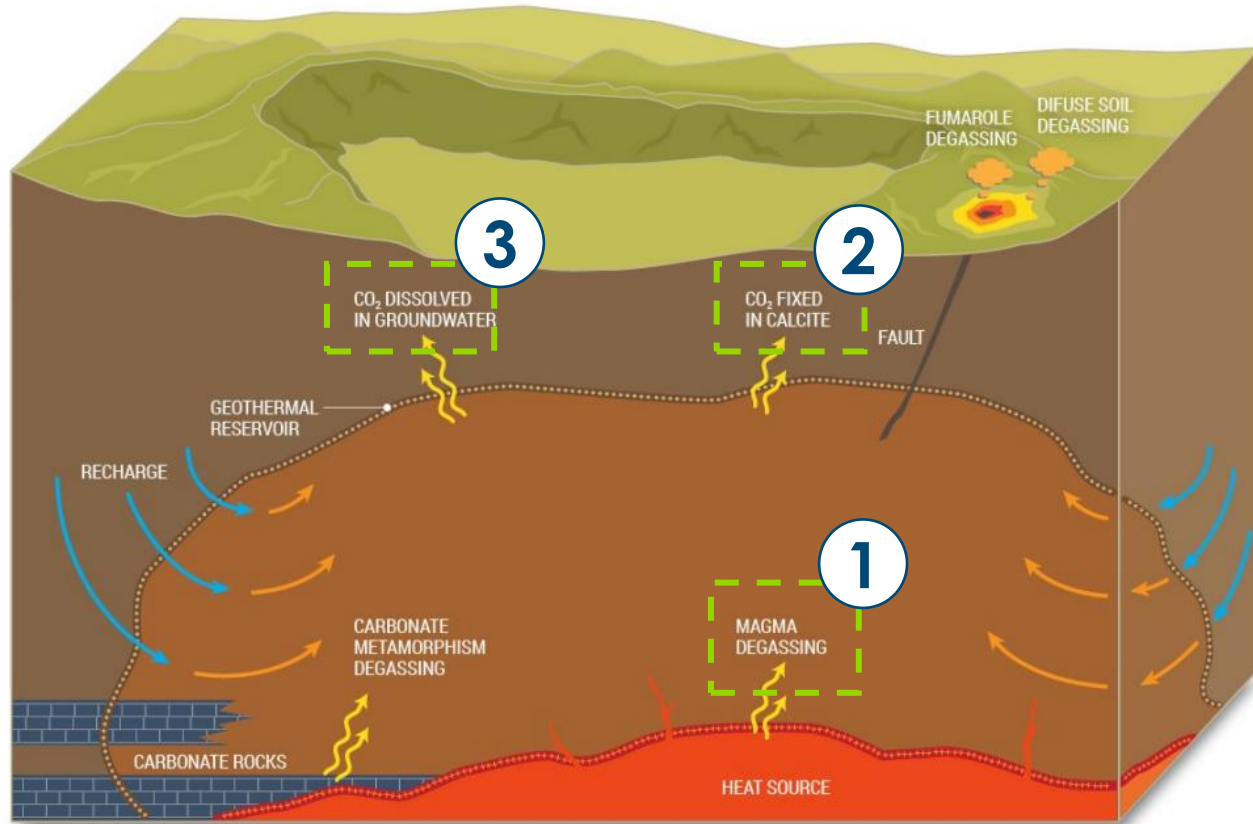


### 4. Political economy

- Geothermal (and “baseload” designation) used to **tap into political narratives** linking firmness with reliability and energy security distracts from its real value and overshadows the opportunity in shallow heat

# 1. Carbon emissions (CO<sub>2</sub>) are the main direct emission from deep geothermal, coming from three key origins

Diagram of volcanic geothermal system showing natural sources and sinks of CO<sub>2</sub>



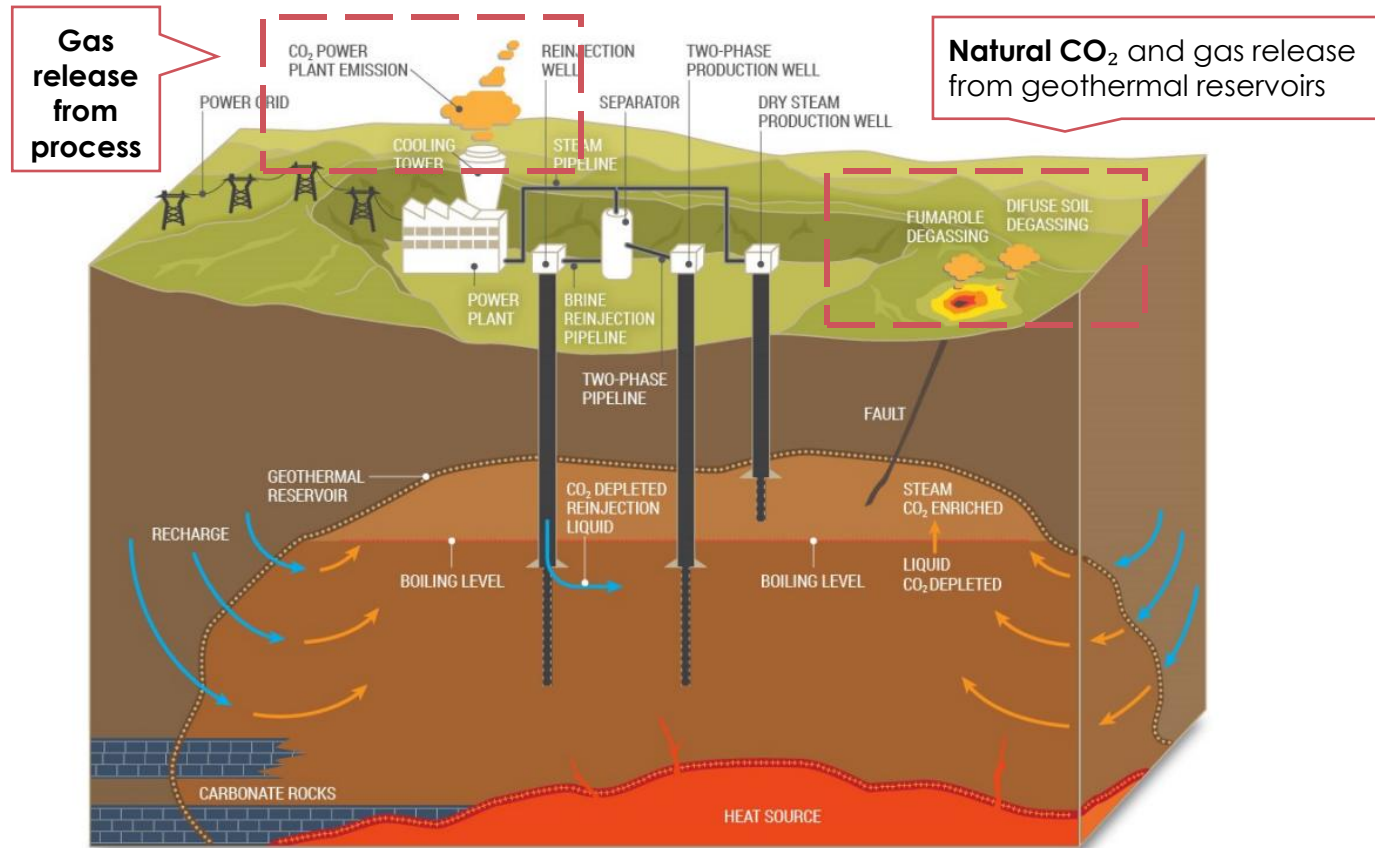
**1 Magma degassing**  
Hot magma naturally releases CO<sub>2</sub> that seeps into geothermal fluids

**2 Carbonate rocks**  
Limestone and carbonate rocks release CO<sub>2</sub> when heated or chemically altered

**3 Rock-water interactions**  
Hot water moving through rocks dissolve small amounts of CO<sub>2</sub> trapped in rock

# 1. Direct emissions released in conventional geothermal plants come from vents after CO<sub>2</sub> is separated from steam

## Diagram of conventional geothermal plant with CO<sub>2</sub> emissions release

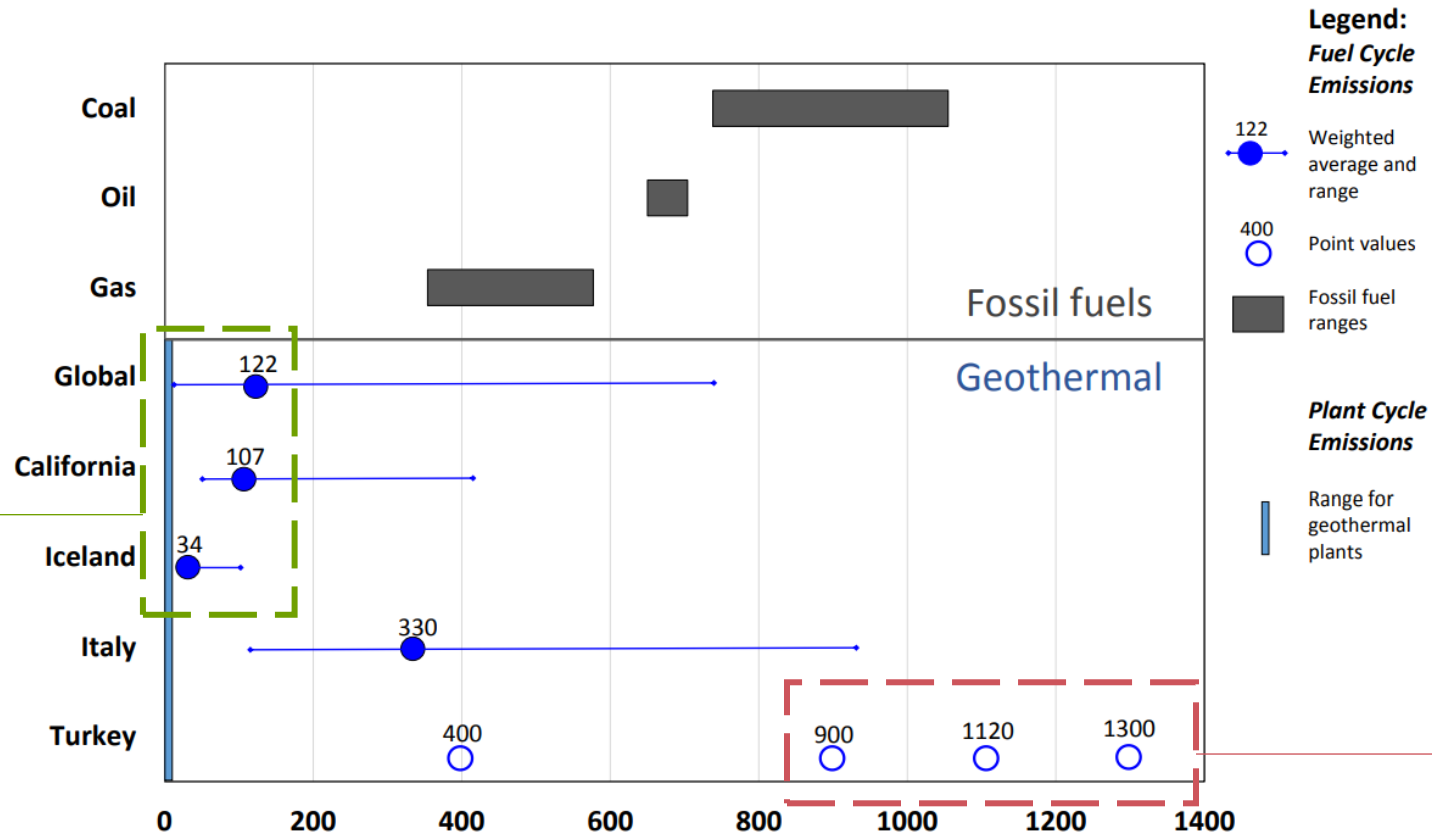


## How does geothermal release emissions?

- CO<sub>2</sub> emissions can be released from geothermal reservoirs, via:**
  - Magma degassing:** Hot magma naturally releases CO<sub>2</sub> that seeps into geothermal fluids
  - Carbonate rocks:** Limestone and carbonate rocks release CO<sub>2</sub> when heated or chemically altered
  - Rock-water interactions:** hot water moving through rocks dissolve small amounts of CO<sub>2</sub> trapped in rock
- Geothermal power generation processes can release emissions via:**
  - Fluid extraction:** wells bring hot water and steam to the surface)
  - Pressure drop** (lower pressure causes dissolved CO<sub>2</sub> to separate into the steam).
  - Power generation and gas release:** CO<sub>2</sub>-rich steam drives turbines to produce electricity; CO<sub>2</sub> is then vented unless captured or reinjected.
  - Reinjection.** Cooled, gas-poor water is pumped back underground

# 1. Direct geothermal emissions are generally low, and well below fossil power, but depend on reservoir geology and management

Weighted average and range of direct emission factors from geothermal plants  
CO<sub>2</sub> emission factor (g/kWh)



Historically, about two-thirds of global geothermal capacity has **released direct emissions of less than 100 gCO<sub>2</sub>/kWh**, while a third has been above this figure

**Very high-emitting examples are rare;** carbonate-hosted or magmatically influenced systems in Italy and Turkey show extreme emissions up to 500–1300 gCO<sub>2</sub>/kWh, rivaling or exceeding coal.

These cases are **geological anomalies** linked to CO<sub>2</sub> release from carbonate rocks or deep mantle degassing rather than the geothermal process itself.

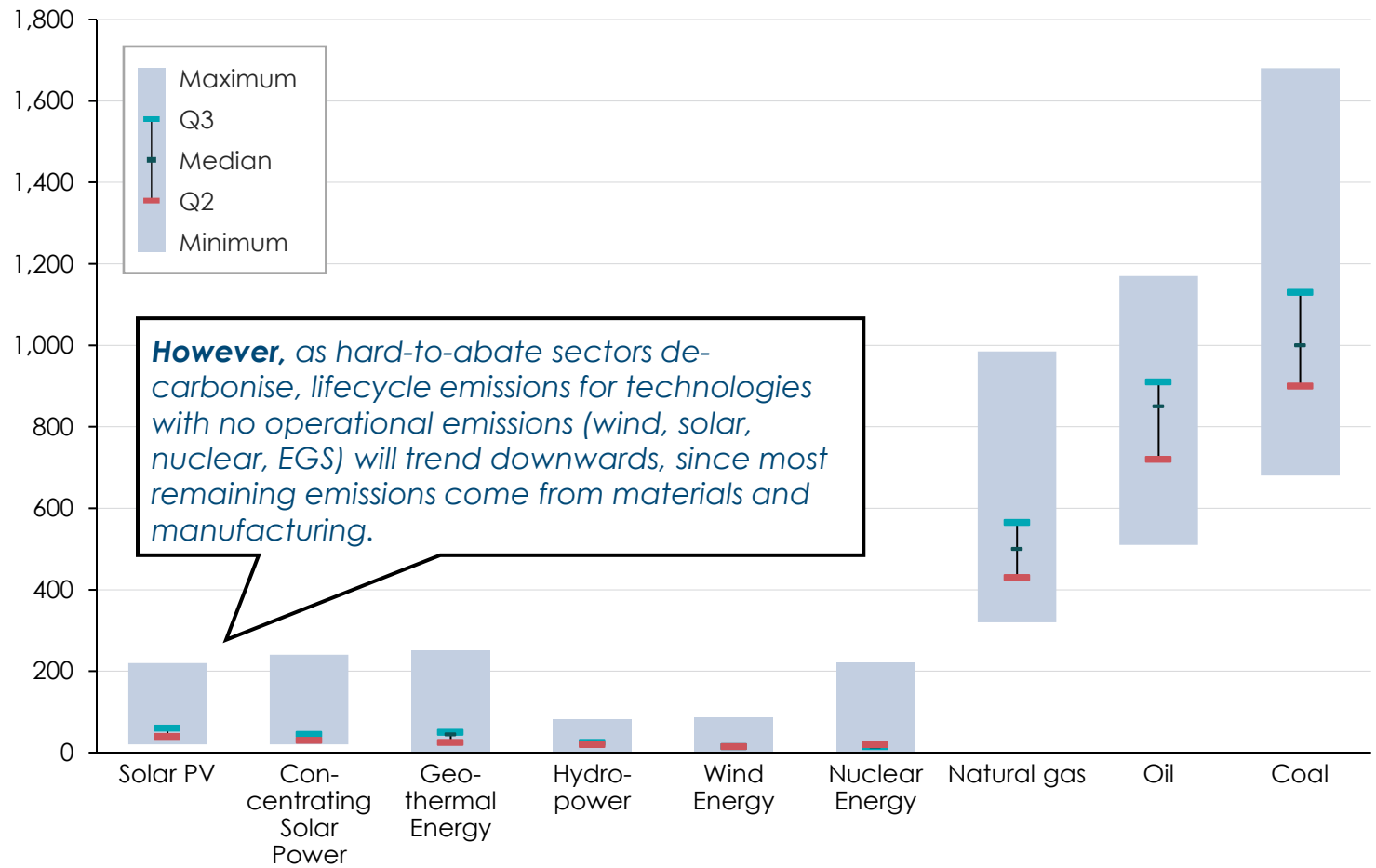


Note: The range of plant cycle emissions is shown with a light blue box. Emission ranges for power plants using fossil fuels shown in grey bars. Source: World Bank (2017), Greenhouse Gas Emissions from Geothermal Power Production

# 1. Lifecycle emissions of geothermal generally remain as low as other clean technologies; much lower than fossil

## Lifecycle GHG emissions of electricity generation technologies

g CO<sub>2</sub> eq/kWh



### Lifecycle emissions:

- Lifecycle emissions include all GHG emitted across the entire life of a power plant - from materials extraction to decommissioning.
- Average lifecycle emissions for geothermal power average 45g CO<sub>2</sub>e/kWh, **well below fossil generation (coal 1000g, gas 500g).**
- Variations in geothermal lifecycle emissions reflect well depth, number of wells, drilling energy source, and reinjection practices rather than operational venting alone.
- EGS systems may appear higher due to greater drilling and stimulation energy use, even though they have near-zero direct emissions during operation.

Notes: Source: NREL (2025) Life Cycle Assessment Harmonization. Image link - <https://www.nrel.gov/analysis/life-cycle-assessment>

# 1. Geothermal emissions vary by reservoir geology and plant type; they don't necessarily decline over time

Emissions from geothermal systems can be classified as **direct** (from on-site operation) and **life-cycle** (from the full construction-to-decommissioning process). **Deep geothermal power plants have direct CO<sub>2</sub> and CH<sub>4</sub> emissions from naturally occurring sources - shallow geothermal heat systems have no direct emissions.**



## Geology

- **Direct emissions depend strongly on reservoir geology and management** (e.g. typology, rock-water interaction)
- Deeper or harder-to-access reservoirs increase drilling and material needs, raising embodied carbon and overall lifecycle emissions



## Plant type

- **Direct emissions vary by plant type:**
  - Closed-loop emits minimal CO<sub>2</sub> as the fluid remains sealed
  - Conventional emits more due to steam separation releasing reservoir gases.
- EGS systems have higher embodied emissions from drilling and stimulation, though operational emissions are near-zero



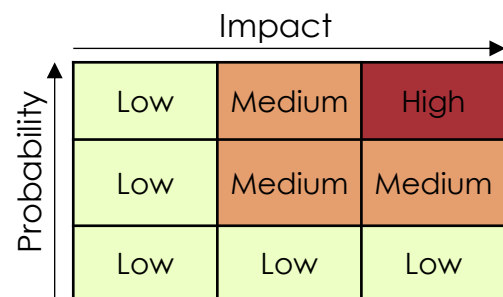
## Operation

- **Direct emissions don't necessarily decline over time;** Emissions trajectories vary by reservoir pressure, reinjection efficiency, and operational practices – there is no consistent CO<sub>2</sub> decline globally.

# 1. Additional geothermal environmental risks are technology and site-specific, but all manageable with modern practices

Comparison with fracking is helpful to illustrate relative risk drivers across technologies, but indicative only because impacts vary by geology, design and regulation

Risk	Description	Risk Level – Shallow Heat	Risk Level – Deep geothermal incl. conventional and EGS	Risk Level – Oil and gas fracking
Groundwater pollution	Leakage of artificial fluids, drilling chemicals or refrigerant leakage	Low-Medium, none for closed loop systems	Low-Medium	Medium
Toxic gases or contaminants entering water sources	Migration of arsenic, boron, or hydrogen sulfide into nearby waters	None	Medium	Medium
Disruption of local water supply	Alteration or depletion of aquifers from extraction	Low, none for closed-loop systems	Low-Medium	Medium
Release of gases locally	Emission of CO <sub>2</sub> , H <sub>2</sub> S, and trace gases during venting or maintenance	None	Medium	Medium
Induced seismicity	Small earthquakes triggered by injection or extraction	None	Medium	Medium
Land subsidence	Ground compaction due to pressure or fluid withdrawal	None	Low	Medium
Other local impacts over time	Noise, visual impact, or surface disturbance	Low	Low	Low-medium



**Geothermal risks are low and can be well managed** with modern monitoring and reinjection practices. Risks generally lower for shallow heat.



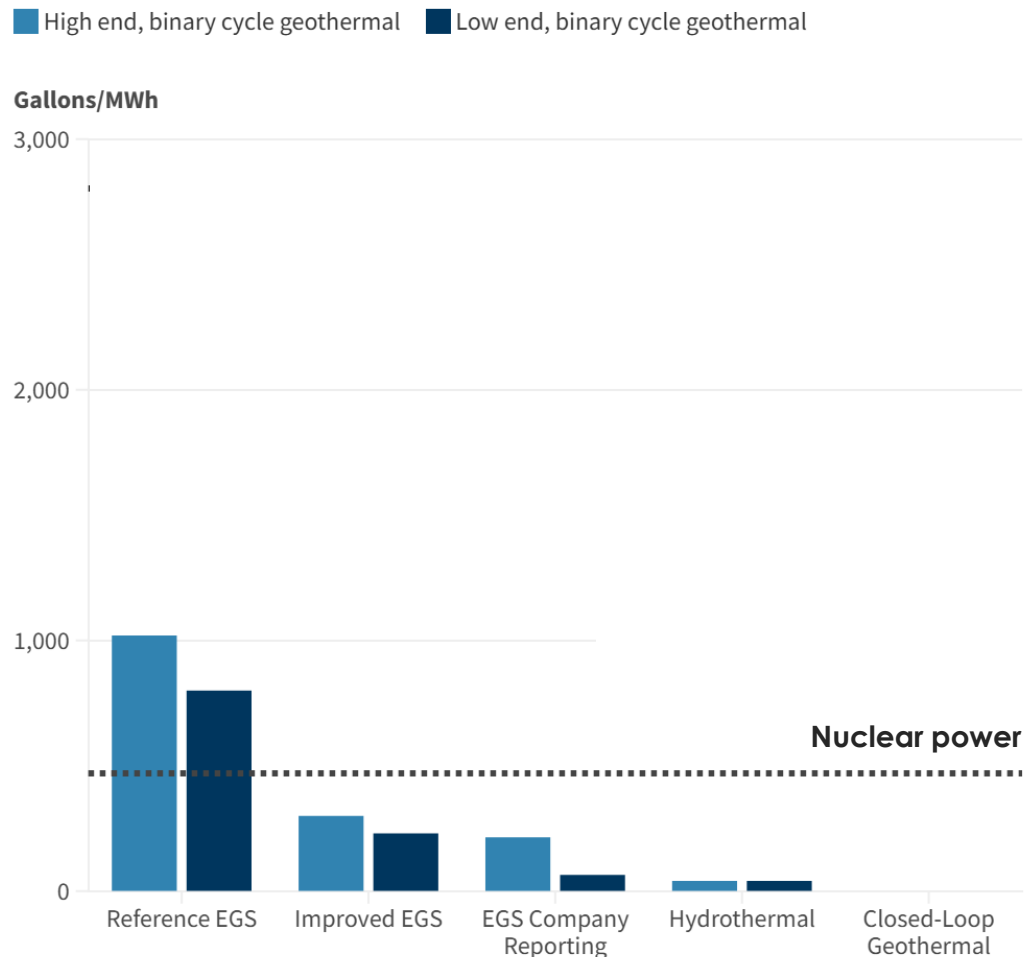
Fracking scores higher **due to greater surface activity and fluid handling**, but all risks are **manageable with modern practices**

Note: Risk levels reflect published reviews and regulatory assessments. Actual impacts depend on geology, design, regulation and operator practice. Source: U.S. Department of Energy (2024) *Environmental Analysis of Geothermal Energy Clean Air Task Force (2025) Introduction to the Next Clean Energy Frontier: Superhot Rock Opportunities and Responsible Development*; Union of Concerned Scientists (2024) *Environmental Impacts of Geothermal Energy*; BKV Energy (2024) *Environmental Impact of Geothermal Energy*; Fiveable (2024) *Environmental Impacts of Geothermal Energy*; University of Texas (2023) *Geothermal Energy Systems: Environmental Considerations*; U.S. Geological Survey (USGS) – Induced Seismicity Studies (2015–2023); International Energy Agency (IEA 2012, 2020): "Golden Rules for a Golden Age of Gas"; Groundwater watch studies – Jackson et al. (PNAS 2014, 2015; Science 2013)

# 1. Water use in geothermal only notable for conventional geothermal systems; not a major constraint except in highly water-stressed regions

## Water demand for next-generation deep geothermal systems during operation

Gallons/MWh

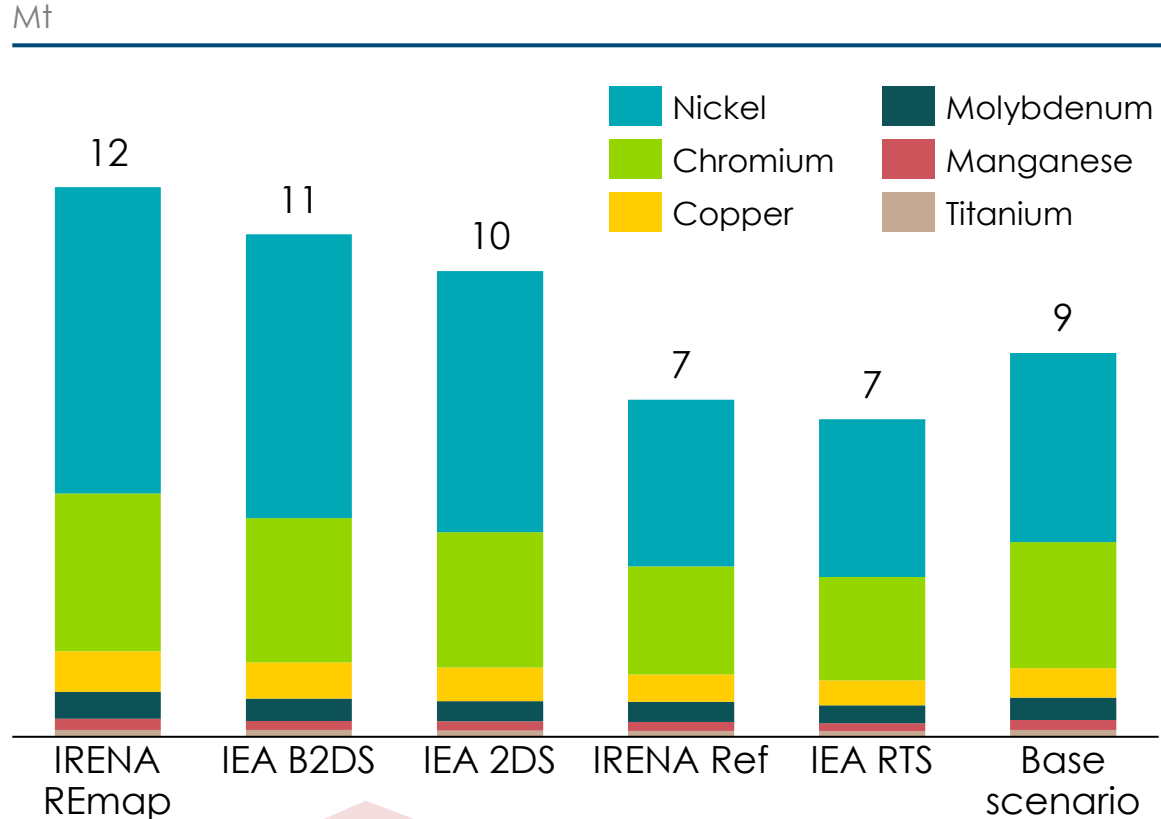


- **Water-use only notable for conventional geothermal systems using wet-cooled systems** that need higher amounts of water. Still not a notable risk unless in arid regions.
- **Power systems:** Water demand comes almost entirely from cooling during operation, and during the construction period. It is **high in older wet-cooled conventional systems**, very low in binary and closed-loop systems.
- **Shallow heat:** Negligible water use. Closed-loop heat pumps consume no water; open-loop systems reinject what they extract.
- Co-located lithium extraction can raise water needs depending on method.

Note: "Reference EGS" is the *baseline Enhanced Geothermal System configuration* used in modelling studies such as DOE GeoVision. It represents a conservative, first generation EGS design with today's drilling performance, stimulation effectiveness and reservoir productivity. All the other categories Improved EGS, EGS company reporting, and closed loop represent progressively more advanced or next-generation system assumptions. Source: Carnegie Endowment for International Peace (2025), *Unlocking Global Geothermal Energy: Pathways to Scaling International Deployment of Next-Generation Geothermal*

# 1. Geothermal contributes a small amount to the global demand for materials and needs far fewer materials than other technologies

## Cumulative demand for materials for geothermal through 2050



- **Material needs for geothermal are concentrated in nickel** for high-temperature alloys and chromium for corrosion-resistant casing steels.
- It has a small amount of **copper** need for surface plant components and power connection tools, which is one of the high-stress materials in the transition
- Other issues remain minor: geothermal uses no critical rare earths and requires far **less steel, aluminium, and copper per MWh than wind or solar.**

**ETC finds 7,000 Mt of end-use materials required by 2050; by comparison, geothermal would make up only 0.14% of this**

Note: These scenarios are no longer used by these bodies, however, they reflect different global transition pathways used by IEA and IRENA: REmap and B2DS show high-ambition decarbonisation with faster geothermal uptake, IEA 2DS and IRENA Reference represent moderate deployment aligned with current policies, and the IEA RTS and Base Scenario illustrate lower-ambition or business-as-usual pathways; across all of them, geothermal's cumulative material demand remains very small relative to the overall energy transition. Source: ETC (2023), Material and Resource Requirements for the Energy Transition; World Bank (2020), Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition

## 2. Public concern centres around perceived seismic activity risks, environmental and land-use conflict, and community acceptance

- Public pushback on geothermal projects **remains limited** but is growing where development intersects with **social or environmental concerns, mainly relating to deep geothermal projects.**
- Opposition often stems from perceived seismic risks, land-use conflicts, and lack of local consultation.

A fight is brewing to build Colorado's first geothermal plant as neighbors oppose development

Contested deep geothermal energy in Germany—The emergence of an environmental protest movement

**A coalition of civil society groups on Indonesia's Flores Island has rejected a recent report by a provincial task force on controversial geothermal energy projects, claiming it misrepresents community sentiment and excludes those most affected.**

## 2. Effective risk management and community engagement are essential to maintain public acceptance of deep geothermal

As noted, accidents relating to geothermal sites can technically occur, but these are **now rare due to effective regulation and policy**. This makes **community engagement key** to prevent these topics creating social pushback to geothermal, as occurred in examples below.

Type of event often discussed	Incident impacting local community	Impact on acceptance and development
1 Seismic shocks	<b>Pohang, South Korea (2017):</b> M5.5 induced earthquake halted national EGS programme	<b>National EGS programme suspended;</b> long-term public opposition
2 Ground uplift / subsidence	<b>Basel, Switzerland (2006):</b> Minor uplift and tremors led to project cancellation	Project cancelled; local moratorium on deep geothermal activity and <b>heightened scrutiny in Switzerland.</b>
3 Toxic gas emissions (H <sub>2</sub> S, CO <sub>2</sub> )	<b>The Geysers, USA (1990s):</b> Odour complaints from H <sub>2</sub> S emissions heightened local opposition	Increased local complaints and tighter environmental monitoring requirements; projects continued but under stricter conditions.
4 Explosions / well blowouts	<b>Larderello, Italy (1950s):</b> Early uncontrolled steam release damaged wellhead and public trust	Strengthened national drilling standards; early public trust setback but industry able to continue with modernised well-integrity rules.

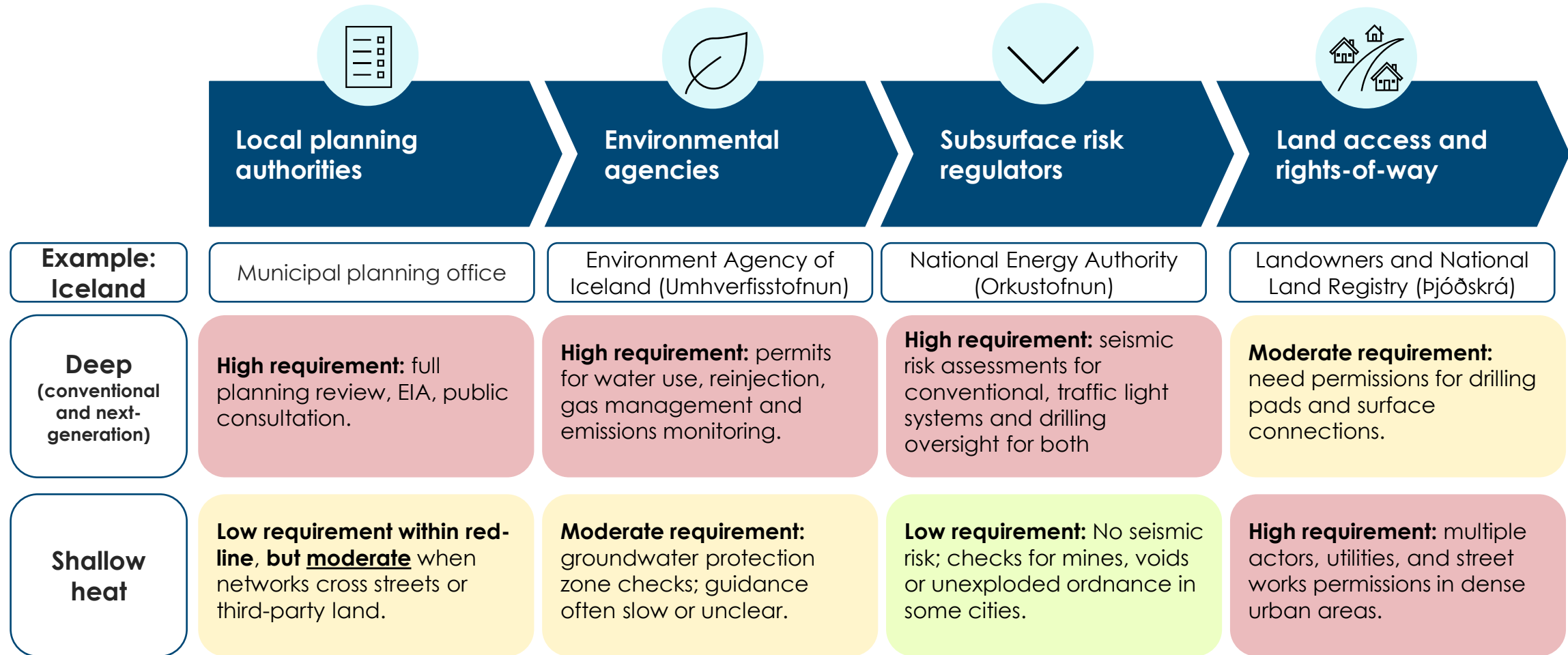
### Implications for scalability:

- For **deep geothermal power systems** that carry higher seismic risk, **development is suited to new build or rural locations to reduce likelihood of induced events**
- Meanwhile, **shallow geothermal heating** remains suitable for urban deployment because it uses very shallow, low-pressure boreholes and creates **no induced seismicity or gas release risks.**

Source: Gombert et al (2022) Main risks relating to deep geothermal energy in the world; Kim K.-H. et al. (2018) "Assessing whether the 2017 Mw 5.4 Pohang earthquake was induced by enhanced geothermal system stimulation; Deichmann N. & Giardini D. (2009) "Earthquakes induced by the stimulation of an enhanced geothermal system below Basel

## 2. Permitting process for geothermal involves four key steps...

Geothermal development faces low geological risk but high permitting and coordination complexity and can become a key barrier preventing deployment for both power generation and district heating applications. **Permitting timelines can range from 1-7 years dependent on location, impacting the financing profile of a project.**

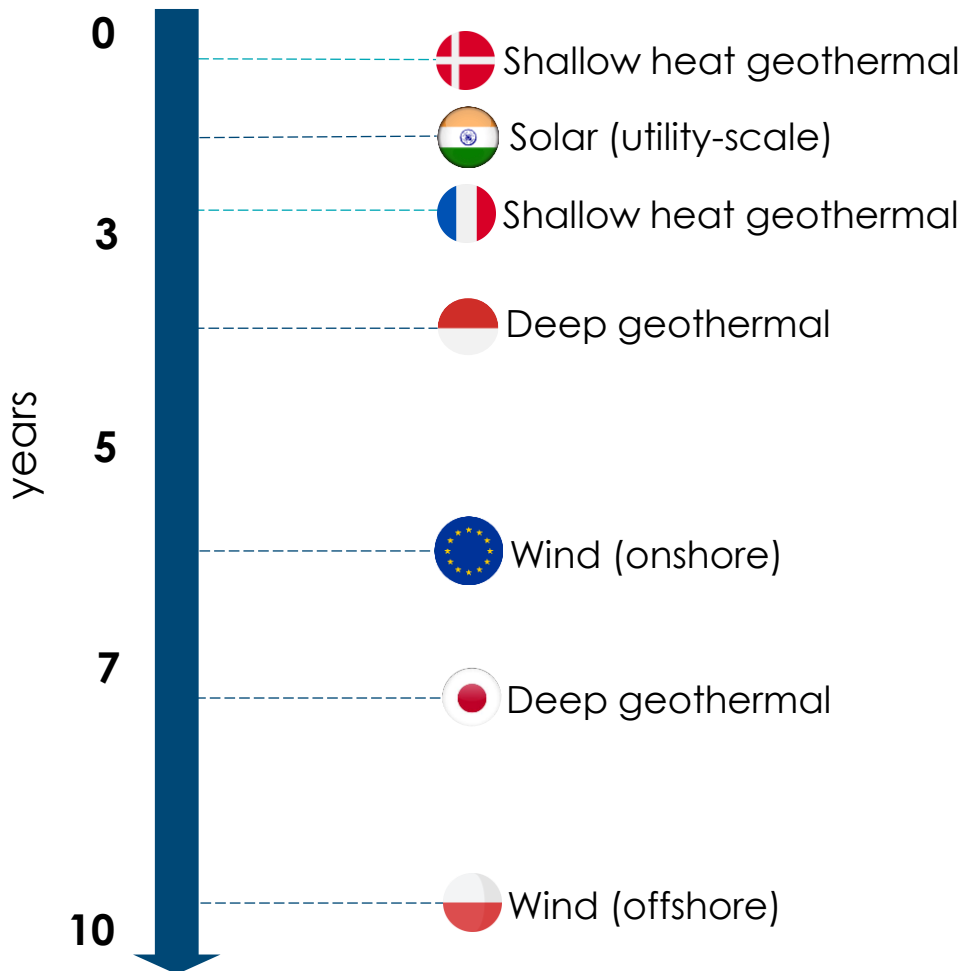


Source: ETC Expert Interviews; IEA (2024) "The Future of Geothermal Energy; Andrésdóttir & Jakobsson (2003) "Regulatory framework and preparation of developers planning research and utilisation of high temperature geothermal resources in Iceland; Orkustofnun (2023) "Geothermal Energy in Iceland; US GAO (2023) "Geothermal Permitting: Delays and Opportunities for Federal Process Reform

## 2. ...timelines can be lengthy, with the US advancing new permitting policies to speed deployment

### Permitting timelines, averaged, by technology

years



### Challenges to permitting across the 4 key stages



Multiple agencies require sequential approvals and extensive public consultation, slowing planning consent.



Slow groundwater and environmental permitting, with **unclear rules for closed loop and new geothermal technologies.**



Seismic and subsurface risk assessments, plus checks for mines or underground hazards in some cities.



Negotiations for access to drilling pads, pipelines and street works, especially challenging in dense urban areas.

### Advancing timelines



The US has been improving deep geothermal permitting through:

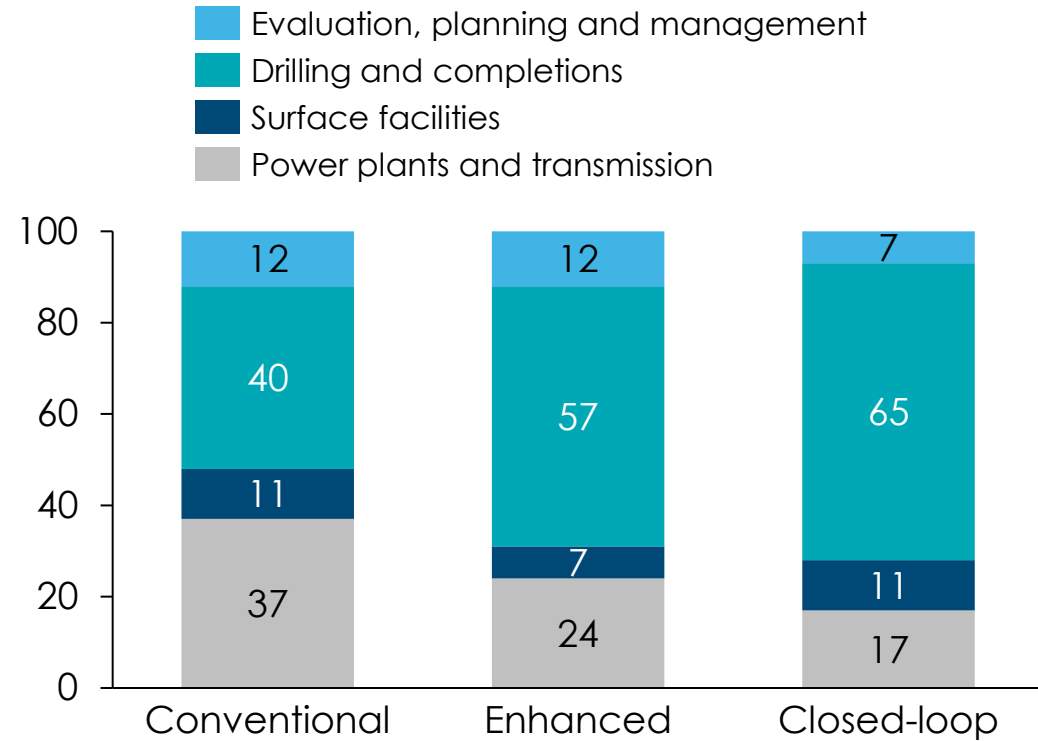
- Today, deep projects on federal land can take 5-10 years to secure full approvals
- New reforms aim to bring this down to 1-2 years by simplifying environmental reviews and creating faster approval routes for low-impact drilling

Source: ETC (2023) Streamlining planning and permitting to accelerate wind and solar deployment; ADEME France (2021). *Regulatory Pathways for Shallow Geothermal Systems.*; IEA (2023). *Permitting Renewable Energy Projects*; International Renewable Energy Agency (IRENA) (2023). *Offshore Wind Outlook*, US GAO (2023). *Geothermal Permitting Challenges on Federal Land.*

# 3. Geothermal can leverage oil and gas expertise, but new job opportunities are minimal compared to the losses in oil and gas

Shares of conventional and next-generation geothermal technology investments that overlap with oil and gas industry skills and expertise

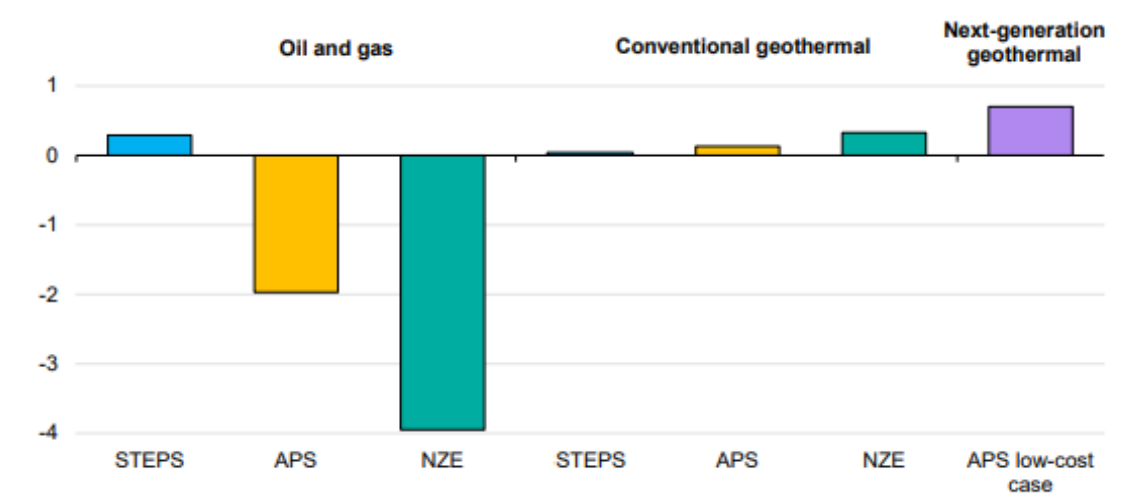
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- **Around two-thirds of investment in conventional geothermal overlaps with oil and gas industry capabilities - primarily in drilling and completions.**

Total oil and gas and geothermal employment changes by scenario, 2023-2030

Million workers



## However, overall job creation remains limited

- IEA estimates geothermal employment could rise from around 145,000 jobs today to **around 1 million by 2030**
- This is far smaller than the 4 million job losses projected in oil and gas under a net zero pathway.

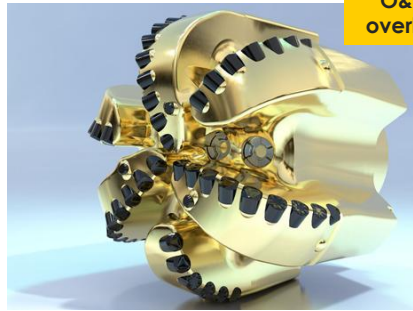


# 3. However, this crossover can also cause supply chain risks, with particular issues around certain components requiring management

Geothermal components with potential for supply chain disruptions



Heavy hook-load rigs



Downhole tools



Organic Rankine Cycle Turbines

## Key insights about overlap with O&G industry



Geothermal relies heavily on O&G supply chains

- Certain components compete directly with oil and gas demand
- This creates exposure to price spikes and capacity shortages.



Specialised components have thin global supply

- Certain products are produced by a very small number of manufacturers
- This raises lead times and project risk.



Skilled labour shortages can delay deployment

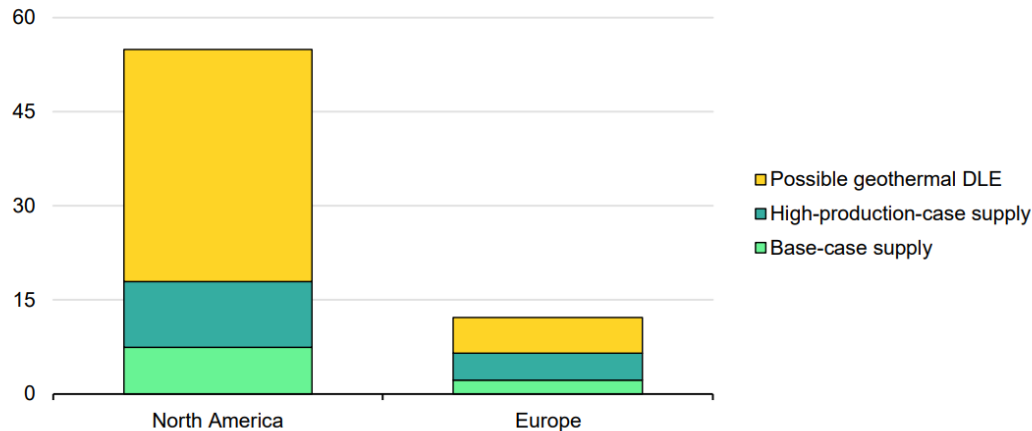
- Geothermal drilling requires specialist crews
- Timelines for obtaining qualifications for shallow and deep drilling are 2-3 years

### 3. Geothermal–lithium co-production can improve project bankability

- **Co-located direct lithium extraction (DLE)** allows use of **the same wells, pumps, heat exchangers, and permits**, creating shared capital and operating costs.
- These projects are an emerging frontier for improving the **financial attractiveness and scale-up potential** of geothermal.
- Bankability gains depend on DLE performance, brine chemistry and lithium market conditions

#### Lithium mining supplies in Europe and the US, 2035

kt Li



- Notable opportunities today include the Salton Sea in the **United States** and the Upper Rhine Valley in **Europe**
- Additional prospective resources in Latin America (Chile, Argentina), East Africa (Kenya) and parts of Asia

Notes: DLE = direct lithium extraction. Lithium mining covers extraction from hard rock ore, brines and clays. Supply is predicated on operating and announced mining and refining projects by country. These projections are categorised into base and high-production cases according to their probability of coming online given various factors such as financing and permitting status and feasibility studies. The European high-production case already includes some geothermal DLE production. Source: IEA (2024) The Future of Geothermal

## 4. Political narratives oversell deep geothermal as ‘baseload’, distracting from its real value and overshadowing the opportunity in shallow heat



Markets its systems as “**firm, dispatchable baseload renewables**”



Geothermal developers



Describes geothermal as “**the missing piece of firm, clean energy**”.



Stated that geothermal is “**more reliable than solar or wind and should replace them in policy priorities**”



**Chris Wright, CEO of Liberty Energy and US Energy Secretary**



- Geothermal's branding as “baseload” appeals to energy-security narratives but creates a **false rivalry with wind and solar**.
- This framing over-emphasises deep power geothermal, which is technically promising yet slow to scale, while ignoring the strong **opportunity presented by shallow heat**.
- Geothermal should be presented as a **complementary resource** across both power and heat, not a substitute for variable renewables.

# Key conclusions on wider impacts

- 1) **Geothermal is not always zero-carbon; direct emissions from deep geothermal depends on local resource, geology and technology.** Shallow geothermal heat systems have no direct emissions. Lifecycle emissions from geothermal are typically far lower than fossil generation.
- 2) **Regulation and safety measures ensure that geothermal environmental risks are manageable,** and the technology remains lower risk than fracking. **Geothermal uses low levels of water and materials compared to other technologies;** water only a material risk in dry regions using legacy EGS setup, particularly in arid regions.
- 3) Active community management is essential, and siting of deep geothermal projects best in rural or new build zones to mitigate real and perceived seismicity and other related environmental risks. **Permitting challenges could cause projects to face delays in deep and shallow geothermal projects, potentially limiting deployment.**
- 4) Political narratives oversell deep geothermal as 'baseload', **distracting from its real value and overshadowing the opportunity in shallow heat**



# Agenda

- Context: geothermal energy state of play
- Techno-economic deep dives: power, heat and storage
- System value considerations
- Wider considerations of geothermal development
- **Emerging conclusions**



# What's holding geothermal back? Key barriers span upfront costs, development risk, and supply chain availability

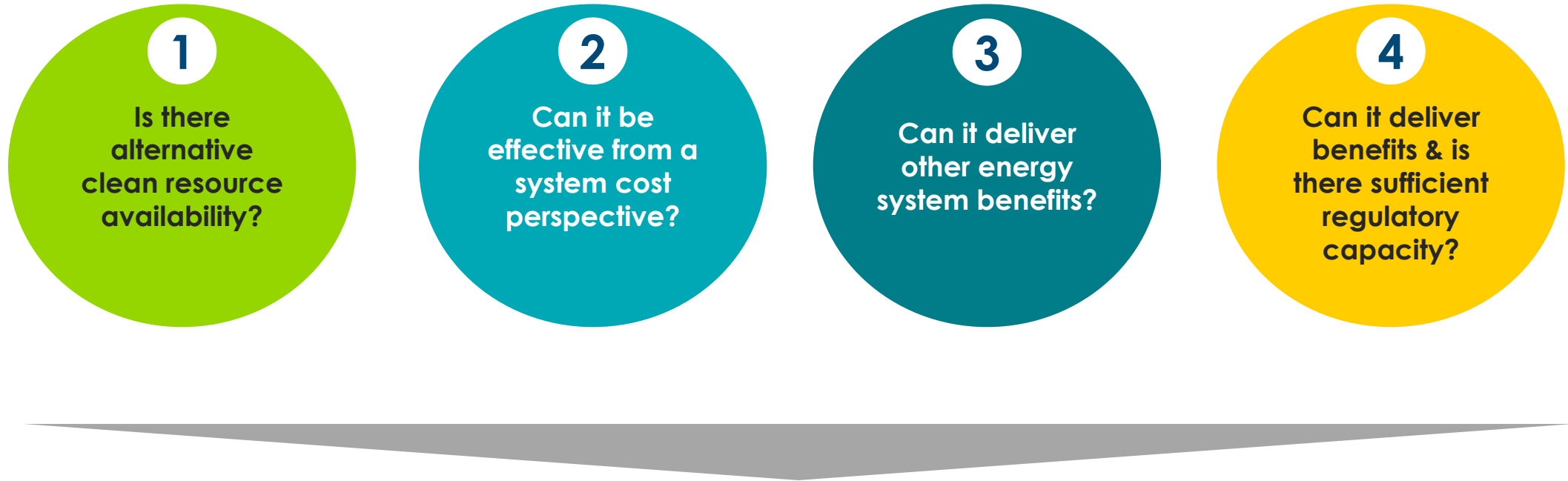
**Risk rating:**

- Low
- Medium
- High

Risk rating by category and geothermal technology type

	Heating / Cooling / Storage	Power or Heat		
Category	Ground source heat pumps / thermal energy storage	Conventional hydrothermal	Enhanced (EGS)	Closed-loop (CLGS)
Technology readiness level	9 – commercially deployed	9 – commercially deployed	7 – demonstration projects	6 – pilot projects
Cost	High upfront cost but competitive lifetime cost	High upfront cost but competitive lifetime cost	Currently high but could decline with learning & economies of scale	Potential for decline but project pipeline is limited
Resource / development risk	Relatively unconstrained	Constrained due to need for suitable temperature, presence of water and permeability	Exploration risk is low but development depends on fracture creation success	Theoretically decoupled from resource permeability
Supply chain availability (incl. O&G transferability)	Mature supply chain, though skilled labour is a bottleneck	Geographically-concentrated	High O&G transfer potential but uncertain skilled workforce availability	
Environmental impact (fugitive emissions, seismicity risks)	Closed systems limit emissions, low depths avoid seismicity concerns	Emissions intensity typically low but can reach fossil fuel levels	Low-medium emissions intensity Induced seismicity risk	Very low emissions intensity No water contamination Induced seismicity risk
Reliance on regulatory / government support	Required to overcome planning, permitting, and financing hurdles	Mature, commercially available technology	Government support could be required to commercialise, particularly in regions lacking big tech involvement	
Hybrid application suitability	Potential synergies with low-to medium-temp. industrial heat	Heat applications limited by geographical resource availability	High potential for co-location with industrial heat demand	

# Role of nuclear and geothermal will vary in different geographies



**Role of nuclear and geothermal across key geographies**



# Next steps for the nuclear and geothermal workstream

	Workshop	Date	Focus
1	<b>Workshop One: The role of Nuclear</b>	02 October 2025	The current state of play, the techno-economics of new projects, the system value nuclear can provide, and the wider risks and benefits of development.
2	<b>Workshop Two: The role of Geothermal</b>	03 December 2025	Geothermal techno-economics, system value, wider risks and benefits.
3	<b>Workshop Three: Key enablers to scale Nuclear and Geothermal</b>	Early 2026	Guidelines and enablers required to scale nuclear and geothermal.

