Technology Fact Sheet

Energy Transitions Commission

Beneath the surface

Geothermal's role in delivering clean heating, cooling and power

Underground thermal energy storage

JULY 2026

This technology fact sheet is part of the ***Beneath the surface*** series. Each highlights a key technological innovation that can drive geothermal's role in delivering clean heating, cooling and power.

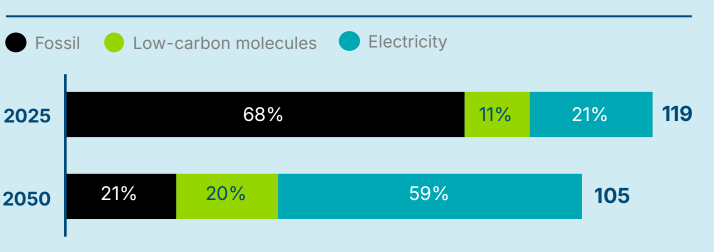
Learn more at www.energy-transitions.org/beneaththesurface

The ETC's energy transition vision

A net-zero global energy system is possible by 2050, driven by clean electrification:

- Electricity increases from 20% to 60%+ of final energy demand, which decreases overall due to energy productivity gains.
- Solar and wind can provide 75%+ of power system generation in most systems, supported by batteries, flexibility and other firm power sources.
- Some flexible dispatchable power capacity will be needed to complement variable renewables.

Global 2025 and 2050 final energy demand breakdown by source (ETC Accelerated but Clearly Feasible scenario) '000 TWh



Geothermal can provide firm low-carbon power, heat, cooling and seasonal energy storage. It spans three broad technology categories across a wide range of depths and temperatures.

1. Shallow geothermal
   - Ground-source heat pumps
   - Underground thermal energy storage
2. Conventional hydrothermal
3. Next-generation geothermal – EGS, CLGS and Superhot Rock

Technology overview and status:

Geothermal Technology	Typical depth (km)	Resource temperature (°C)	Application	Surface technology	Geographic technical potential	TRL Technology readiness level	Current global capacity
Underground thermal energy storage (UTES)	< 0.5 km	4 - 25 °C	Heating and cooling	Typically heat pump (output)	Anywhere (Seasonal climates)	9	3 GW-th

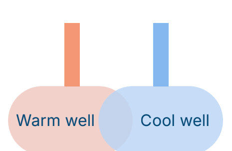
Techno-economics: UTES stores surplus summer heat for winter use at low cost and high round-trip efficiency – favourable economics.

How it works – Aquifer thermal energy storage (ATES) or borehole thermal energy storage (BTES) are the main types of UTES:

1. In summer, surplus summer heat (solar, waste heat or renewables via heat pumps) is injected underground and stored.
2. In winter, the heat is transferred above ground, upgraded by a paired heat pump and distributed to individual buildings, shared ground loops or a district heating network.

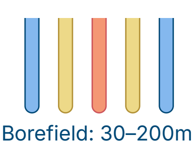
There are two main technology types to transfer and store the heat:

ATES
Open-loop system using two wells to extract and reinject groundwater, transporting and storing heat in a permeable aquifer at ~20–500 m depth.

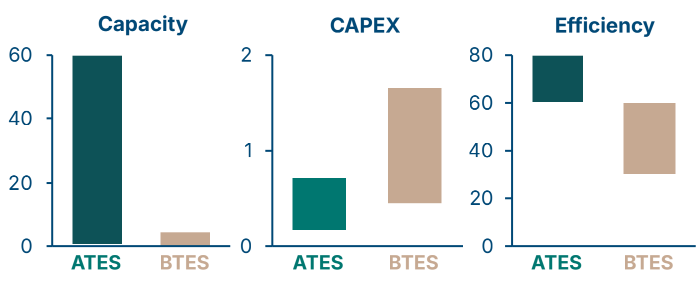


Aquifer: 20-500m

BTES
Closed-loop system using arrays of sealed boreholes (~30–200 m depth) that exchange heat with the surrounding soil or bedrock, which serves as the storage medium.


Borefield: 30–200m

ATES vs. BTES comparison across typical capacity, CAPEX and round-trip efficiency LHS GWh-th; Middle $/kWh-th, stored; RHS %

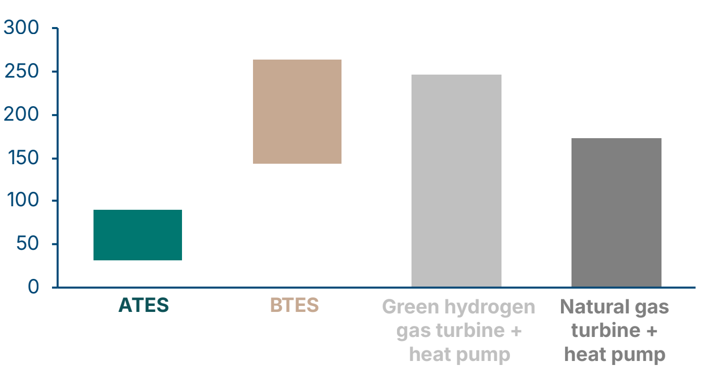


ATES is cheaper, BTES more scalable
ATES achieves low seasonal round-trip costs of ~$30–90 per MWh-th, driven by low CAPEX and high RTE from using natural aquifers as the storage medium.

BTES is viable in most ground types but costs ~$140–260 per MWh-th at 30–60% efficiency, with hundreds of boreholes needed for storage volume.

Cost competitiveness and system benefits: UTES is one of the cheapest low-carbon seasonal storage options deployable at scale today, shifting surplus summer heat into winter to cut peak power demand and firm-capacity needs in seasonal demand systems.

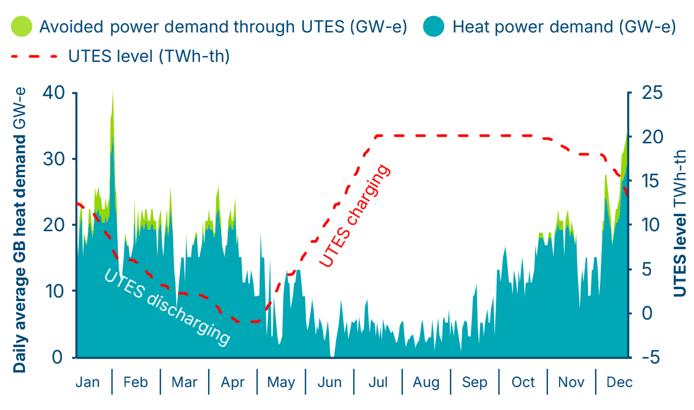
Seasonal storage cost comparison: ATES vs BTES vs natural gas or green hydrogen peaker with heat pumps, $/MWh_th (real 2024)



Cheaper seasonal storage than the alternatives:

ATES can be 2–6x cheaper per unit of delivered heat than seasonal storage from new gas peakers (~$170 per MWh-th) and 3–8x cheaper than green hydrogen (~$250 per MWh-th). BTES has a higher cost but could still be cheaper than alternatives in many places.

UK 2050 seasonal balancing value (summer charge / winter discharge), Daily average heat demand – GW-e; TES level – TWh-th

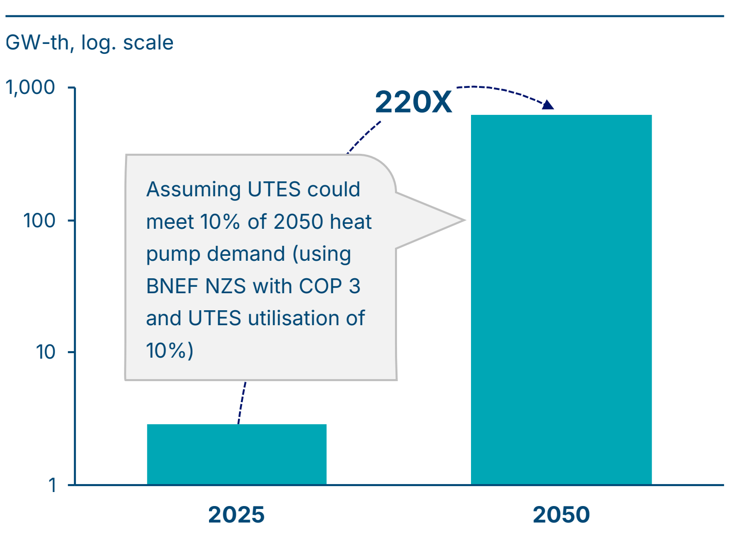


High system value in wind-dominated systems:

In the UK, 20 TWh-th of seasonal underground TES (~10% of 2050 heat demand) could cut peak winter power demand by ~5% and save ~$5 per MWh-e in system costs vs. green-hydrogen storage. Benefits are lower in less seasonal, solar-dominated systems.

Deployment prospects: Underground Thermal Energy Storage is a proven technology and has significant untapped potential, particularly in "Windbelt" systems, with rising seasonal balancing challenges and with existing or planned heat networks.

Global UTES estimated market potential (BNEF NZS & ETC estimates)



Limited installed base today:
~2.9 GW-th of underground TES worldwide across ~3,000 active ATES sites and delivering ~2.5 TWh of heating and cooling per year; seasonal BTES is limited to a handful of demonstration projects.

Strong geographic concentration:
85% of ATES capacity is in the Netherlands, with some capacity in Sweden, Denmark and Belgium; BTES demonstrations notably in Canada, Germany and Denmark.

Large 2050 potential:
Seasonal underground TES has a large untapped potential, particularly in district heating and industry. It could potentially meet ~10% of annual heating and cooling demand in seasonally-variable energy systems (e.g., Northern Europe, Eastern Europe, North America, China, Japan, South Korea).

Barriers to deployment: Financing, permitting, hydrogeology and district-heat anchors.

High upfront CAPEX & financing
High upfront costs deter developers and long-duration storage is hard to finance. Lifetime economics are favourable, but the capital structures to carry the cost are missing.

Siting & hydrogeology
Suitable hydrogeology (permeable aquifers for ATES) is unevenly distributed; BTES is more widely viable but costlier. Limited subsurface data constrains siting in many locations.

Regulatory & permitting barriers
Aquifer-use permits and thermal-impact assessments vary widely across jurisdictions; revenue frameworks that monetise seasonal flexibility are absent in all markets today.

Missing district-heat anchors
The district-heating infrastructure needed to anchor projects is absent in most markets. Network anchor projects (e.g., hospitals) and better cross-project data are key to lowering costs.

UTES has limited environmental risks – these are not a deployment barrier.

– Aquifer thermal disturbance is the main residual concern for ATES: Seasonal heat injection and extraction can alter local groundwater temperatures and microbiology – managed through standard permitting and operating practice.
– Subsurface protection: Well-integrity standards and thermal-impact assessments address groundwater quality and impacts on other groundwater users.

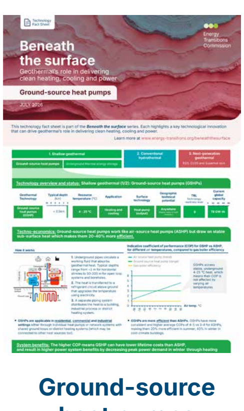
Policy actions: Policymakers should address financing and regulatory barriers to capture seasonal storage value.

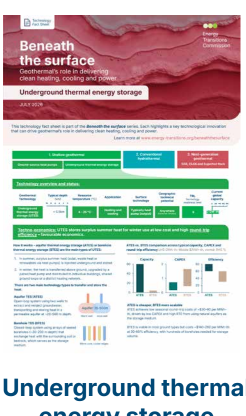
Underground TES enabling actions and lead actors

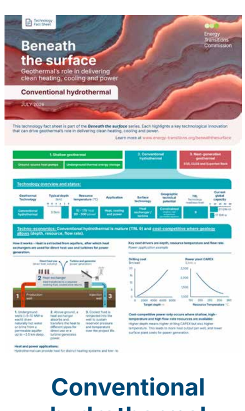
	Action	Lead actors
1	**Harmonise subsurface permitting** Align aquifer-use permits and thermal-impact assessments to reduce current high variation across jurisdictions.	National and sub-national regulators, environmental agencies, building-code authorities.
2	**Create revenue frameworks that monetise the seasonal flexibility system benefits for consumers** Reward avoided ultra-long-duration storage and firm-capacity buildout, absent in all markets today.	Electricity and gas regulators, system operators, distribution network operators, utilities.
3	**De-risk long-duration project finance** Provide long-tenor infrastructure debt, utility bill inclusion and third-party loop-as-a-service.	Treasuries, green investment banks, infrastructure investors, utilities.
4	**Anchor projects in district-heating networks** Use network anchor projects (including hospitals, universities, supermarkets) to lower the marginal cost of subsequent connections.	Utilities, project developers, municipalities, property developers, district-energy operators.
5	**Build reservoir-engineering capacity and cross-project data** Develop scarce reservoir-engineering skills and improve data collection and reporting.	Training providers, trade associations, standards bodies, district-energy operators.

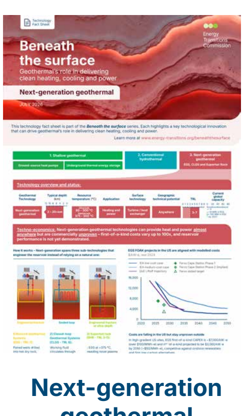
Further reading In the Beneath the Surface series


Beneath the Surface Insights Briefing
Main Report


Ground-source heat pumps
Technology Fact Sheet


Underground thermal energy storage
Technology Fact Sheet


Conventional hydrothermal
Technology Fact Sheet


Next-generation geothermal
Technology Fact Sheet

Sources and notes

The ETC's energy transition vision: ETC (2025), *Carbon in an electrified future: Technologies, trade-offs and pathways*.
Techno-economics: M. Janiszewski (2019), *Techno-economic aspects of seasonal underground storage of solar thermal energy in hard crystalline rocks*; M. Herrmann (2025), *Capital costs of aquifer thermal energy storage (ATES): a review.*
Cost competitiveness and system benefits: Systemiq analysis for the ETC (2026); Energy Transitions Commission (2025), *Power Systems Transformation: Delivering Competitive, Resilient Electricity in High-Renewable Systems*; NESO (2022), *Future Energy Scenarios 2022 (FES 2022)*; Brown C.S. (2024), *Assessing the technical potential for underground thermal energy storage in the UK.*
Deployment prospects: Systemiq analysis for the ETC (2026).
Barriers to deployment: Systemiq analysis for the ETC (2026); BNEF (2026), *New Energy Outlook*.
Policy actions: Systemiq analysis for the ETC (2026).

Energy Transitions Commission

SYSTEMIQ