Geothermal Innovation Trends 2025

EGEC GEOTHERMAL

ETIP Geothermal

Geothermal Innovation Trends 2025

Contents

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Executive Summary

In 2025, the Nobel Prize in Economics was awarded to three researchers (Joel Mokyr, Philippe Aghion and Peter Howitt) for their work on how innovation drives economic growth. Their combined research for some years provides a framework for better understanding the relationship between three elements: science, technology and economic prosperity. In the geothermal sector we fully appreciate and demonstrate this.

The geothermal sector is one of the most innovative sectors in Europe's economy. Every year, new research and innovation, also in terms of business models, help geothermal to provide better solutions to decarbonize our economy. Geothermal also supports local economic development by supplying electrical power, heating, cooling, thermal storage and minerals to industry and communities.

To accelerate the market development of geothermal energy technologies, research and innovation allows these technologies to be less costly, more efficient, and easier to install anywhere.

The aim of EGEC's annual report on Geothermal Innovation Trends is to describe all these technological developments. The first report on major technological trends, published in 2024, consisted of Major Technological Trends 2024 and the Report on major market trends, both of which were published in the framework of the Geotherm Fora project. These reports covered not only developments in 2024 but also the trends of the decade 2020-2030.

This 2025 report on Geothermal Innovation Trends covers general trends with a particular focus on innovations in terms of 'market ready' technologies and first demonstrations of 'close to market' technologies.

Technologies that are in the early stages of development (low TRL) are seeing significant progress - especially new drilling technologies. Artificial Intelligence (AI) is increasingly being used in the development of geothermal energy projects. Several geothermal technologies that are in advanced levels of development (high TRL) are currently being demonstrated and will soon be commercialised.

Examples of innovation in the domain of geothermal project development and business models include: the project portfolio approach to de-risk investments with several geothermal projects in the same area; signing long-term heat purchase agreements with consumers, and the supply of 'heat as a service', which can be an efficient way to finance geothermal heat pump systems.

1. Introduction

Five themes are shaping the new generation of geothermal projects from 2020 to 2030:

I. **Increasing capacity** of geothermal installations with more diversified and multi-purpose applications, such as geothermal heat pump systems and mini heat grids (capacity > 0.5 MWth), geothermal district heating networks in cites (> 100 MWth), trigeneration with Combined Heat and Power plants, extraction of minerals such as lithium, potassium, etc..

II. **Adapting the depth to be reached**, with some 'deep geothermal' projects becoming less deep, taking advantage of greater efficiency of production at lower temperature, and some 'shallow geothermal' projects becoming deeper to access higher temperatures;

III. **Adapting the number of wells to be drilled** with multiple wells for geothermal heat pump systems and district heating networks, and with new drilling design such as deep sub-horizontal wells, in order to improve the sustainability of the production system and resource performance to supply heating, cooling, hot water and electricity;

IV. **Expanding to 'greenfield' areas**, moving into previously unexplored areas and expanding geothermal assets through the use of new exploration techniques; and supplying energy to new sectors such as low & medium temperature industrial processes, data centers, etc.;

V. **Innovative business models and approaches**, such as the project portfolio approach with several projects developed in parallel, which contributes to the de-risking of geothermal investments, as well as long term heat purchase agreements or 'heat as a service' contracts in relation to geothermal heat pump systems.

In order to provide a comprehensive overview the innovation trends, the report looks at all geothermal technologies and geothermal project development phases.

Geothermal technologies

Geothermal energy is accessible on a continuous basis, 24 hours per day, making it a reliable and efficient solution for energy consumers, including a wide range of industrial applications. From heating and cooling to electricity generation and even lithium extraction, geothermal plays a crucial role in the transition to clean energy for buildings, cities and industries. The agricultural sector can also benefit significantly from geothermal energy: numerous greenhouses already use geothermal heating as a renewable and reliable source of energy.

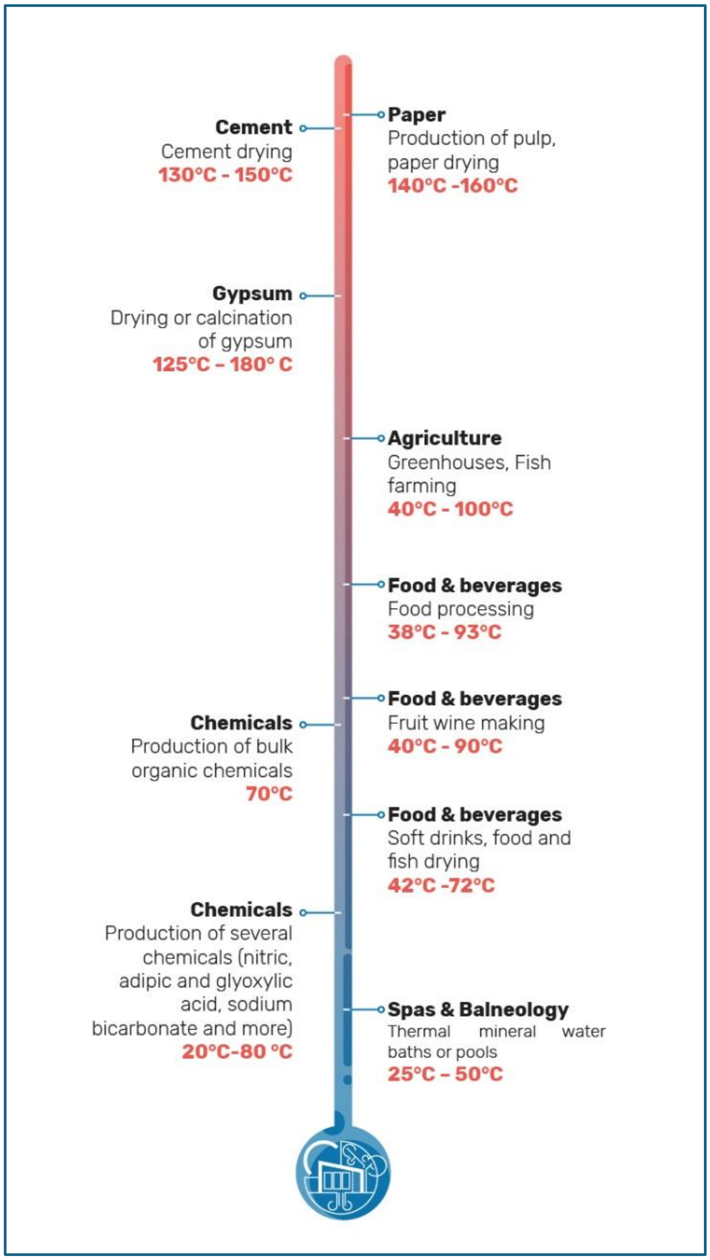
Supplying heat, cooling and hot water

Geothermal energy can be exploited via various technologies to supply heat, cold and hot water to buildings, services, industry and agriculture. Notably, geothermal heat pump systems can provide heating, cooling and hot water on a small scale for individual homes (capacity of 10-12 kWth), at medium scale (>50 kWth) for larger buildings, and on a large scale (>500 kWth) for networks of buildings and services as well as facilities such as data centres (which have become increasingly relevant with digitalisation, leading to greater cooling demand and pressure on grids).

Geothermal district heating and cooling (DHC) systems are another way of supplying heating and cooling. Traditional doublet systems range from 1 to 20 MWth while larger scale systems with multiple wells can supply more than 100 MW of heating capacity.

Geothermal heating and cooling systems can supply heat for industrial applications from low to medium temperature range (25°C – 160°C).

Figure 1: Thermometer of industrial heat applications suitable for geothermal



Generating electricity

Geothermal power plants generate a continuous supply of electricity using energy from geothermal sources, with capacities ranging from 1 MW to more than 100 MW. Geothermal plants are suitable for providing baseload power (24-7) and can produce both power and heat simultaneously (CHP). Several technologies exist to generate electricity using medium (>100°C) or high temperature (>200 °C) geothermal resources, and next generation technologies including Enhanced and Advanced Geothermal Systems (EGS and AGS) and 'superhot' sources (>400°C).

Storing heat underground

Underground Thermal Energy Storage (UTES) is a technology focused on storing heat below ground for short-term and long-term periods. Storage is possible in aquifers (ATES) or boreholes (BTES), and there are also projects storing heat in mine water.

Supplying critical raw minerals

It is possible to extract critical raw materials from geothermal brine. In particular, geothermal lithium is receiving increased attention and a plant in Germany already produces lithium, while several other projects are under development. Lithium and other critical raw materials are essential parts of the energy transition and the possibility of having European sources of these materials is highly promising.

Project Development

Geothermal projects pass through the following stages of development:

1. Site investigation, feasibility studies, securing finance and obtaining exploration permits;
2. Exploration for resource assessment, obtaining drilling permits;
3. Drilling and subsurface engineering, obtaining exploitation permits;
4. Utilisation and management of the resource to generate electricity and/or heating & cooling;
5. Operation and maintenance for a sustainable management of the resource over 50+ years, maintenance and replacement of equipment as required;
6. Decommissioning the project after the end of its useful life.

2. Research Trends

Research trends can be measured by Technology Readiness Levels (TRLs). The primary purpose of these is to provide a standardised framework for assessing and communicating the maturity of technologies. Table 1 shows descriptions of TRL levels 1-9 according to the definitions used by the EU's Horizon Europe programme.

Table 1: Technology Readiness Levels (TRLs) (adapted from Scaling Up Ideas, 2025)

TRL	Description
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in a lab
TRL 5	Technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in an operational environment
TRL 8	System completed and qualified

Technology Readiness Levels can be completed by other Readiness Levels (see table 2). Indeed, the TRL scale has inspired several complementary frameworks: from Manufacturing to Commercial, Integration, Service, and even Policy levels.

Table 2: the 14 Readiness Level Frameworks and their scales

Technology and systems	Manufacturing and commercialization	Specialised readiness frameworks
Technology Readiness Level TRL 1–3 (basic principles → proof of concept), TRL 4–6 (lab validation → relevant environment prototype), TRL 7–9 (operational prototype → flight-proven system).	**Manufacturing Readiness Level** MRL 1–3 (manufacturing implications → proof of concept), MRL 4–7 (lab process validated → prototype production), MRL 8–10 (pilot line proven → full-rate production).	**Data Readiness Level (DRL A1–C4)** A1–A4 (raw/unverified → structured), B1–B4 (cleaned → labeled), C1–C4 (validated → monitored in production).
System Readiness Level SRL 1–3 (system concept → architecture defined), SRL 4–6 (integration feasibility → subsystems integrated), SRL 7–9 (prototype integrated → mission-proven system).	**Commercial Readiness Level** CRL 1–3 (concept → business plan defined), CRL 4–6 (value proposition validated → repeatable sales), CRL 7–9 (competitive positioning → established market presence).	**Policy Readiness Level (PRL 1–9)** PRL 1–3 (problem defined → draft concept), PRL 4–6 (pilot designed → evaluated with stakeholders), PRL 7–9 (policy validated, governed, implemented).
Integration Readiness Level IRL 0–2 (no integration → conceptual integration), IRL 3–6 (interfaces defined → demo in relevant environment), IRL 7–9 (prototype integrated → proven in mission).	**Market and Technology Readiness Level (MTRL)** MTRL 1–3 (early tech concept + market need), MTRL 4–6 (validated demand + scalable prototype), MTRL 7–9 (mature technology with established market).	

Design Readiness Level DRL 1–3 (conceptual design → requirements defined), DRL 4–6 (preliminary/detailed design reviews → design verified), DRL 7–9 (design validated → frozen for production).	**Operational Readiness Level** ORL 1–3 (concept → use case defined), ORL 4–6 (processes, training, logistics validated), ORL 7–9 (trials → sustained operations).	
Science Readiness Level SRL 1–3 (hypothesis → concept model), SRL 4–6 (data gathered → peer-reviewed findings), SRL 7–9 (operational validation → mission-grade science).	**KTH innovation readiness (multi-axis radar)** Technology, market, team, IP, funding, customer. Each axis scored 1–9 to show gaps and progress.	

Geothermal technologies in early stages of development

Basic research on geothermal technologies (low TRL activities) is subject to constant developments over long timeframes. In 2024/25, trends for low TRL geothermal technologies are in line with the trends identified in the first edition of the Geothermal Innovation Trends report (consisting of Major Technological Trends 2024 and the Report on major market trends, both of which were published in 2024 in the framework of the Geotherm Fora project).

The utilisation of **Machine Learning and Artificial Intelligence Tools** in geothermal exploration and operation are being developed to identify and reduce risks and improve drilling success rates. These tools enable real-time analysis of large amounts of data to support decision making. Current research topics focus on data assimilation workflows[1], integration of multiple data types with advanced AI algorithms, developing novel, AI-based techniques for predicting geothermal attributes directly and forward modelling methods, including stratigraphic forward modelling (SFM), diagenesis forward modelling (DFM) and fracture network forward modelling (FFM). AI tools continue to evolve and their use across many different applications is spreading rapidly.

Digitalisation, including one of its core concepts - **Digital Twins** (real and virtual plants in mutual connection) - can improve production and efficiency. Such systems are currently developed for geothermal energy production and underground heat storage combining real time data analysis and AI-aided decision making during the operation of geothermal systems. The MALEG project[2] has developed digital twins for three different geothermal sites. These have been combined with a machine learning algorithm to predict the geochemical composition and the scaling potential based on live measurements of the geothermal brine at each power plant. Another example is the GEMINI project[3], which includes the development of an advanced simulation tool that combines physics-based and chemistry-based models, data-driven models and physics-informed AI models, which are all brought together within a common web-based framework.

[1] Seismic assisted history matching using binary maps (D Obidegwu, R Chassagne and C MacBeth), Journal of Natural Gas Science and Engineering 42 (2017), pages 69-84.
[2] The machine learning for enhancing geothermal energy production (MALEG) project (https://maleg.eu).
[3] GEMINI: intelligent decision support system for geothermal assets (TNO, 30-11-2023).

Advanced **exploration** tools will allow project developers to reduce uncertainties relating to the location, size, drilling success rate and productivity characteristics of a geothermal resource.

- The development and use of **Fibre Optic Sensors** as distributed or point sensors is constantly growing in geoscientific and geotechnical applications. For spatial and temporally continuous monitoring of (geo-)technical systems and facilities, distributed temperature sensing (DTS), distributed strain sensing (DSS), and distributed acoustic/vibration sensing (DAS/DVS) will be particularly important. Distributed chemical sensing and distributed pressure sensing (DPS) methods for test environments and point sensors in applications involving high-resolution monitoring of specific system components are under development.
- **Soil gas Surveys,** the monitoring of diffuse degassing has been used extensively for various purposes, e.g., study of seismically active faults, identification of structures in volcanic systems in connection with geothermal exploration, and monitoring of geothermal systems under energy production. Further development promises to improve the speed of surveys and the coverage, in order to aid the selection of potential drilling locations.
- **Urban seismic geothermal exploration** is addressed by the URGENT[4] project, which aims to provide sustainable and affordable solutions for urban seismic exploration of geothermal resources. An electric seismic source and novel MEMS (Micro-Electro-Mechanical Systems) based sensors integrated into autonomous nodes, will be designed, built, and tested at 3 sites: Balmatt (Belgium), Konin (Poland) and Batta (Hungary). They will enable high-quality data recording including low frequency signals resulting in high resolution imaging down to a depth of 4000 metres. Also, survey designs will be optimized, including compressive sensing and simultaneous shooting.
- **Forward modelling methods** will allow for more accurate pre-drilling predictions of geothermal reservoir properties, including stratigraphic forward modelling (SFM), diagenesis forward modelling (DFM) and fracture network forward modelling (FFM). For example, the GO-Forward[5] project tests and calibrates such approaches in areas with abundant subsurface information and production data.

Crystalline rocks have the largest geothermal potential in central Europe. Laboratory experiments to obtain unique data and simulation are conducted in ongoing research projects. Additional efforts are undertaken to close the gap between laboratory and field scale research, such as the use of underground research laboratories.

Combined thermal, hydraulic, mechanical, chemical (THMC) and microbiological system models are being advanced to better quantify how different processes interact within the zones affected by medium-depth heat storage and deep geothermal operations - ranging from the reservoir

[4] URGENT - Sustainable and affordable URban Geothermal Exploration Novel Technologies and workflows (project supported by Horizon Europe - Climate, Energy and Mobility)
[5] GO-Forward - Geothermal Exploration and Optimization through Forward Modeling and Resource Development (project supported by Horizon Europe - Climate, Energy and Mobility)

to the near-wellbore region and the borehole itself. The potential future extraction of raw materials could further shift these equilibrium conditions. To address this, representative modeling studies are being used to support the design of long-term, sustainable strategies for jointly producing geothermal energy and valuable raw materials.

Using a **subsurface working fluid other than water** for Advanced Geothermal Systems or UTES refers to the use of supercritical carbon dioxide (sCO_2) as a working fluid being more thermodynamic than groundwater or brine. Hence, integrating geothermal energy and carbon capture and storage (CCS) has the potential to increase efficiency and reduce costs. It includes the use of sCO_2 as a heat transfer medium (working fluid) for geothermal energy production, and water-based geothermal concepts with CO_2 (re-)injection dissolved in the geothermal brine, as well as synergetic uses, such as CCS with improved efficiency by using geothermal energy[6]. The CEEGS project[7] investigates electrothermal energy and geological carbon dioxide storage.

Smart monitoring and assessment techniques for well integrity and pump lifetime.

Extraction technologies for the co-production of critical raw materials including lithium build on existing technologies and aim at facilitating and optimizing the co-production of critical raw materials (CRM) from geothermal brines. Studies show a high dependence on the type of geothermal brine. The CRM-geothermal project[8] is collecting data and investigating extraction methods for various critical raw materials including strontium, helium, caesium and rubidium.

Geothermal technologies in advanced stages of development

Several new geothermal technologies have been validated in laboratory and are currently at the demonstration stage (high TRL activities). Of particular interest are:

Novel **drilling technologies**, such as the solution developed at Mines Paris – PSL University (France) in the framework of the ORCHYD project[9], which combines a high-pressure water jet (HPWJ) and percussion to achieve a faster penetration rate through hard rock (granite) compared to conventional rotary techniques. Since the ORCHYD project ended in 2024, two follow-up projects have been launched. The HyPerDrill project[10] (supported by the French National Research Agency - ANR) aims to improve the drilling performance of ultra-deep geothermal wells in hard rock formations, with a particular focus on the crystalline basement. Meanwhile, the GEOSIS project[11] (supported by ADEME - the French Agency for Ecological Transition) aims to develop an innovative seismic approach to characterize geothermal reservoirs with greater precision.

[6] Prospective Integration of Geothermal Energy with Carbon Capture and Storage (IEAGHG, 2023)
[7] CEEGS - Novel CO_2-based electrothermal energy and geological storage system
[8] CRM-geothermal (project supported by Horizon Europe)
[9] Accessing geothermal energy with drilling innovations (CORDIS website, 07-02-2025)
[10] HyPerDrill - Hybrid Percussion Drilling for Deep Geothermal Applications
[11] GEOSIS - Characterization of geothermal reservoirs with real-time seismic data during drilling

Material research for geothermal installations aims at higher performance and resistance – particularly valuable for extreme environments. For instance, the Geo-Coat[12] project has developed specialised corrosion-resistant and erosion-resistant coatings, based on selected High Entropy Alloys (HEAs) and Ceramic/Metal mixtures (Cermets), to be applied through thermal powder coating techniques (primarily High-Velocity Oxygen Fuel / Laser cladding). Additionally, the GEOHEX[13] project works on advanced material with anti-scaling and anti-corrosion properties for cost-efficient and advanced heat exchanger performance for geothermal applications.

Sustainable power plants projects in Europe have seen some developments in Iceland, Italy, Portugal and Turkey. But no new innovations can be reported at that stage.

With increased use of renewable energy, storage increases in importance. High temperature Underground thermal energy storage promises highly efficient results when adapting to supply and demand differences. The PUSH IT[14] project has conducted mud and well integrity tests, providing new insights and allowing for improved drilling precision.

Versatile geothermal heat pump systems are highly relevant solutions to ensure the heating and cooling transition succeeds in all environments. The EU-funded HOCLOOP project[15] has been developing a horizontal closed-loop geothermal solution that can operate in both shallow and deep geological formations. Developing alternative working fluids, including CO_2-based fluids, rather than just water, will improve heat extraction. The aim is to make geothermal viable in regions that don't have conventional hot aquifers, by using innovative drilling and loop design.

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[12] Geo-Coat - Development of novel and cost effective corrosion resistant coatings for high temperature geothermal applications (project supported by Horizon 2020)

[13] Geohex - Advanced material for cost-efficient and enhanced heat exchange performance for geothermal application (project supported by Horizon 2020)

[14] PUSH-IT - Piloting Underground Storage of Heat In geoThermal reservoirs (project supported by Horizon Europe) (see Mud and well integrity tests performed at TU Delft – PUSH-IT)

[15] HOCLOOP - An environmentally friendly geothermal energy solution based on a horizontal closed loop (project supported by Horizon Europe)

3. Innovation Trends

Following the first report on geothermal innovations (Major Technological Trends 2024) published last year, the Geothermal Innovation Trends 2025 report presents the innovation trends of the decade with a particular focus on developments in 2025.

2020-2030 trends in innovative geothermal technologies

For the current decade, we can divide the major innovation trends in two categories:

Market-ready technologies

- **The use of large and high temperature heat pumps** to increase the temperature of geothermal brine for District Heating grids or industrial processes
- **Installing large-scale geothermal heat pumps** at shallow depths (typically <250m deep), with high numbers of wells (up to 200 or more) providing hot water, space heating and passive cooling to large buildings and services
- **Low temperature heating network systems** (5th generation District Heating networks) for refurbished and new buildings and services at street or district level
- **New drilling techniques, well designs and drilling equipment** for improving the productivity of the subsurface system
- **New casing materials** for increasing the lifetime of geothermal wells, with composite downhole tubulars for completion
- **Larger turbines** to install binary turbines in high temperature fields and for next generation geothermal technologies
- **Geothermal (or passive) cooling** for buildings, districts, data centres (to reduce electricity demand) and cities (to counter the 'urban heat island' effect).

First demonstration or 'close to market' technologies

- **Medium and high temperature underground thermal energy storage (UTES)**
- **Single deep well** at medium depth or deeper
- **Deep closed loops** of multilateral well systems
- **Robot drilling** for shallow geothermal projects
- **Electricity, heating and cooling for industrial purposes -** including Data Centres
- **Co-production of critical raw materials**.

Innovation Trends in 2025

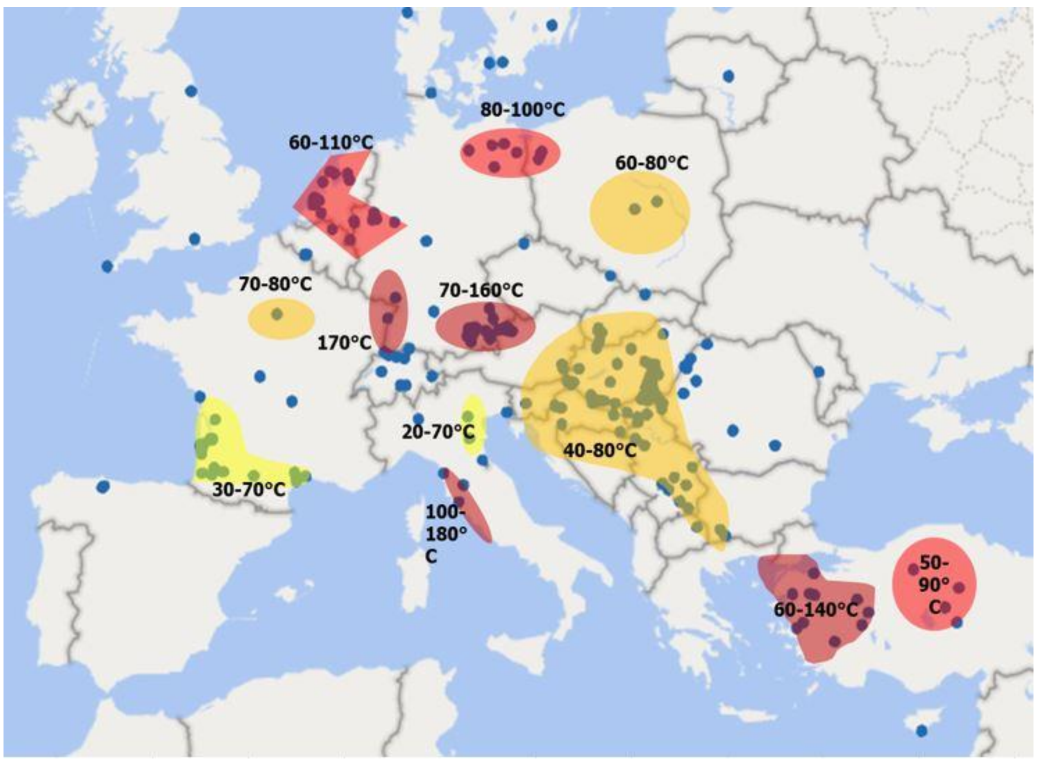
To gain an overview of innovation in the geothermal sector in 2025, we can look at both market-ready technologies and first demonstration or 'close to market' technologies.

Market-ready technologies

- **Use of large and high temperature heat pumps** to increase the temperature of the geothermal brine for District Heating grids or industrial processes.

This becomes increasingly common as geothermal district heating projects tap into lower temperature geothermal reservoirs, especially in previously undeveloped (or 'Greenfield') areas, as shown in figure 2.

Figure 22: Map of main geothermal district heating and cooling reservoirs with existing systems and temperatures



The geothermal district heating plant in Aarhus (Denmark), developed by Kredsløb and Innargi, has officially started supplying heat in 2025[16]. To supply up to 20% of Kredsløb's district heating needs, the total capacity of the geothermal system will be around 102 MWth. It is already assisted by a 10 MW electric heat pump, provided by Aalborg CSP in collaboration with Solid Energy A/S. The heat pump station in Skejby will have a capacity of up to 18 MW of heat and provide temperatures up to 95°C to Kredsløb's district heating network.

[16] Geothermal heat in Aarhus signals new momentum for Europe (Think GeoEnergy, 14-11-2025)

- **Installing large-scale geothermal heat pumps** at shallow depths (typically <250m deep), with high numbers of wells (up to 200 or more) providing hot water, space heating and passive cooling to large buildings and services.

Hungary is seeing the installation of its largest geothermal heat pump systems with 1680 kWth capacity for heating and 1527 kWth for cooling. MBH Bank has developed a project aiming to build its new headquarters in the existing AGORA office park. The proposed geothermal heat pump system consists of 235 wells at 130m deep, representing over 30km of boreholes in total.

- **Low temperature heating network systems** (5th generation District Heating networks) for refurbished and new buildings and services at street or district level.

The Nice Méridia smart grid project, in France, inaugurated in 2021, saw new development and a significant expansion in 2025. The current network (operated by IDEX) consists of a geothermal system of 12 wells drilled to 50m depth, targeting the aquifer, for a district heating and cooling (DHC) network of 5km, supplying heat at 63°C and cold at 8°C to around 3,000 housing units. The DHC network is being expanded to cover a grid of 12km, requiring €42.2 million of investment (including a public support of €16.5 million). GéotherNice will notably supply heating and cooling to the ice skating rink for the upcoming 2030 Olympic Winter Games.

- **New drilling techniques, well designs and drilling equipment** for improving the productivity of the subsurface system, and **new casing materials** for increasing the lifetime of geothermal wells, with composite downhole tubulars for completion;

Halliburton has developed **new electric submersible pump (ESP) technology** for geothermal applications, offering a blend of high performance and robust durability. Key features include: hybrid technology that combines the resilience of induction motors with the efficiency of permanent magnets; High Power Output (1120 kW in a single-piece motor, optimized for demanding geothermal environments; Temperature Tolerance (engineered to operate at internal temperatures up to 204°C, ensuring reliability in high-heat conditions), and High Efficiency (achieves up to 94% in power factor and efficiency, setting a new benchmark for ESP system performance).

The novel patented technology of Flexible Couplings has been in development within ÍSOR (Iceland GeoSurvey) since 2015. Flexible Couplings are designed to mitigate failures in production casings of high-temperature geothermal wells, that may be caused by constrained thermal expansion. By implementing **Flexible Couplings in the production casing**, each casing joint (around 12 m long) is allowed to expand. Thermal straining of the casing is prevented and the risk of casing failures minimized, thereby increasing the reliability of wells. In early 2025, ON Power made use of Flexible Couplings in a well drilled in Nesjavellir (Iceland). Casings with conventional casing connections have no room for thermal expansion. Therefore, the casing material develops permanent plastic deformations during the first warm-up of the well after being drilled. These permanent deformations can cause severe casing failures, particularly if the well cools down, e.g. during workover. The novel

Flexible Couplings allow the casing to expand into the connection without developing permanent plastic strain, thereby allowing the casing material to work within its elastic range.

A new geothermal installation was being built for the EPCG in Champigny-sur-Marne (near Paris in France) in 2025 by Coriance Group. This project is of particular interest due to the **innovative use of fiberglass in the wells**, replacing the traditional steel. Thereby, corrosion and material remains are limited – a well-known hurdle in geothermal plants. While the use of fiberglass is not new as such, only a few wells are equipped with this highly advanced material.

Using cementation technology – an innovative shallow geothermal technology - Averne Group launched in 2025 a research project to enhance surface geothermal probe installation. The project is supported by BRGM and ADEME as part of the Sustainable Energy initiative. Project coordination is covered by BRGM and AFPG, the French geothermal association. The objective is to improve installation techniques for geothermal probes by **enhancing cementation quality** while reducing material use for environmental gains and work efficiency. Two test campaigns have been launched.

- **Larger turbines** to install binary turbines in high temperature fields and for next generation geothermal technologies.

A new milestone was reached by Exergy International, which unveiled its new GEMINI turbine[17] in October 2025. This innovative configuration combines the power of two turbines into a single high-capacity unit delivering up to 60 MWe. Conceived and developed entirely by Exergy's turbine team in Italy, the Gemini sets a new benchmark for efficiency, scalability, and competitiveness in large-scale geothermal power generation, making it the ideal match for next-generation Enhanced and Advanced Geothermal Systems (EGS and AGS).

- **Geothermal (or passive) cooling** for buildings, districts, data centres (to reduce electricity demand) and cities (to counter the 'urban heat island' effect).

One of the best-known examples of a geothermal district cooling system is seeing new developments. The district cooling network that was installed for the Olympic 2024 village in Saint-Denis (near Paris) is being extended to connect 189 new housing units by 2027. These buildings will then benefit from the SMIREC district heating and cooling network in the Pleyel district, which makes use of biomass and geothermal energy.

[17] Exergy unveils Gemini Turbine: The new frontier in large-scale geothermal power generation

First demonstration or 'close to market' technologies

- **Medium and high temperature underground thermal energy storage (UTES)**

Following the 2024 milestone reached in Tromsö (Norway) with an underground thermal energy storage (UTES) facility injecting residual heat from a waste incinerator at 120 °C, new development has been seen in Finland. QHeat worked on the integration of heating and storage wells to a waste burning facility. The Lounavoima geothermal energy system is an innovative geothermal solution providing both heating and cooling for the facility while storing excess thermal energy for later use. In collaboration with QHeat, Lounavoima decided in 2019 to commission a geothermal energy system consisting of six deep coaxial heat wells. These wells help Lounavoima store the surplus heat energy the power plant generates during the summer and utilize it during the colder months of the year. The 6 deep coaxial heat wells were finalised and fully working by the end of 2025.

The system also allows Salo's district heating company to replace fossil-based peak energy production with stored energy, thereby reducing emissions and costs. The system extracts maximum efficiency from stored heat, temporarily cooling the well during periods of high-demand, when energy is usually at its most expensive and carbon-intensive.

- **Single deep well** at medium depth or deeper

One of the few deep single wells, at the Eden Project in Cornwall (UK) has seen in 2025 a new development. Eden Geothermal have entered into an agreement with Baker Hughes to collaborate in exploring the opportunity to further develop the existing Eden Geothermal facility and bring it to its full potential as a high-profile demonstration of the technology's benefits and uses.

To extract heat from EG-1 – the UK's longest deep geothermal well (with a total length of 5,277m), Eden Geothermal created a single well heat exchanger and installed a new 3.8km heat main to link the geothermal site with the heat loads on the Eden Project site. The single well heat exchanger has been created by installing a coaxial circulation system in the well itself. Vacuum-insulated tubing was installed to a depth of 3,850m in the centre of the well.

- **Deep closed loops** of multilateral well systems

In December 2025, Eavor Technologies announced that the Eavor-Loop™ project in Geretsried (Germany) has started to generate electricity.[18] The plant has a capacity of approximately 8.2 MW electrical power combined with 64 MW thermal output. The ORC turbine for the power plant was completed in November 2024. The closed loops form a radiator composed of 12 legs per vertical, 24 legs in total connected in pairs at 4.500 m deep (see figure 3).

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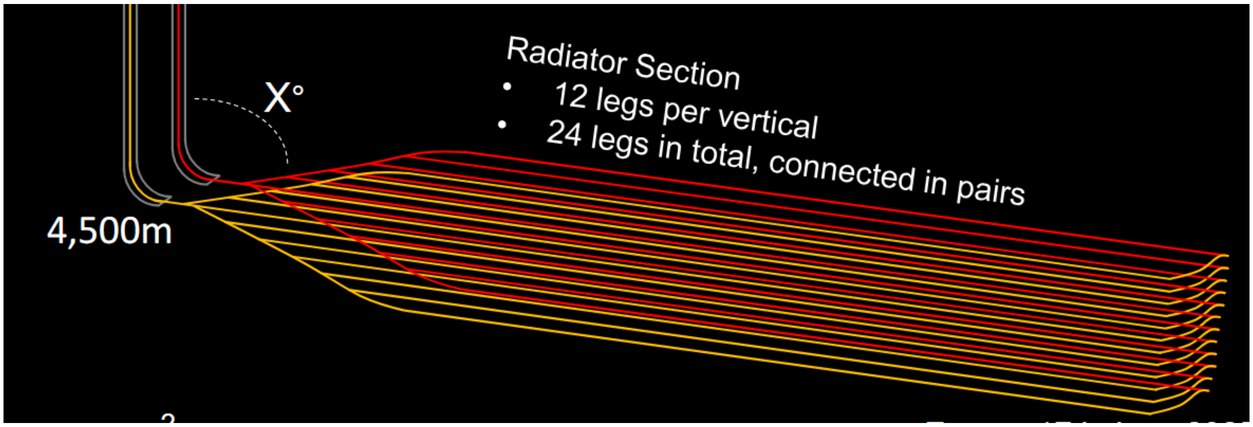
[18] Eavor Technologies Achieves First Electricity Production at Geretsried Site (Press Release, 04-12-2025)

Figure 33: Eavor-Loop 1.0 at Gerestried, Germany



In response to growing interest in Eavor-Loop™ technology, Eavor has announced that similar projects are already being planned at two other sites in Germany: Hanover and Neu-Ulm.

2025 has also seen new developments at Green Therma's closed loop project in Denmark. In January 2025, Green Therma announced a partnership with Aalborg Forsyning to demonstrate their Heat4Ever™ solution in Aalborg. Then in June, it was announced that Green Therma would receive about €11 million in funding from Denmark's Energy Technology Development and Demonstration Programme (EUDP) to help implement this project[19]. The demonstration plant has an estimated capacity of around 2 MW, utilizing Green Therma's patented DualVac™ technology, and the drilling of wells for the plant is expected to start in the autumn of 2026.

- **Robot drilling for shallow geothermal projects**

In Switzerland, Borobotics has developed an autonomous drilling robot named Grabowski, which is the first geothermal drill to be completely automated[20]. In 2025, a new hammering design enabled the robot to reach a first milestone of 20 meters of depth. In the coming months, the aim is to drill deeper with the current setup: with a 135 mm diameter and a length of 2.5 m, Grabowski weighs less than 150 kg. The focus now shifts towards lose ground drilling in anticipation of the introduction of the extrusion unit to the system in April 2026.

[19] Green Therma receives EUDP funding for Heat4Ever demonstration in Aalborg (Think GeoEnergy, 25-06-2025)
[20] Swiss firm develops autonomous drill machine to tap shallow geothermal energy (Interesting Engineering, 19-01-2025)

- **Electricity, heating and cooling for industrial purposes** (including data centres)

Several projects in Europe are planned to supply energy for industrial heat applications. They include electricity, heating, cooling and energy storage solutions for data centres.

For this report, we have chosen to highlight two projects that were realized and developed in 2025, using two different geothermal technologies.

The first one is a geothermal heating project for a liqueurs and syrups production plant in France. Celsius Energy has signed an agreement with the Giffard company to build its new production site, representing an investment of €30 million for a 10,000 m^2 building. The geothermal heat pump system for the Giffard plant covers 97% of its heating costs with geothermal energy, with 17 boreholes drilled, each to a depth of 170 metres. The heating and cooling supply aims at ensuring the maceration to produce liqueurs and syrups, and for other processes such as cold storage rooms, ventilation systems, and air compression systems.

The second project, in Austria, features geothermally powered cascade heating and cooling grids for industrial, commercial and housing use. In the current NEFI project CASCADE, they are using the innovative method of gradual heat utilization. This technology makes it possible to use thermal energy not just once, but in successive stages or "cascades" for various purposes, from heat for industry to heating buildings, with decreasing temperatures. It starts with the industrial use of geothermal energy in the Gmunden dairy farm. The heat is used in the dairy production facilities and is then integrated into the Gmunden heating network. Some of the geothermal heat is used by the Hofstetten brewery at St. Martin im Mühlkreis, where it replaces fossil fuels.

- **Co-production of critical raw materials**

Following the Lithium extraction demonstrated by the Eugeli project in France, and the first lithium production by Vulcan Energy in Germany, new developments have been seen in 2025.

The innovation of the CASCADE process by Energie Baden-Wuerttemberg AG is about the use of a second reactor column with higher-performing absorbents. The resulting precursor has a significantly higher purity and concentration of lithium compared to standard technologies and allows the extraction of solid lithium salts with ‘battery grade’ purity. The CASCADE process (a patented technology) was intensively tested at the Bruchsal geothermal plant under real conditions, albeit with low flow rates. A test system was developed for this purpose and put into operation on site in January 2024. This plant allowed the evaluation of different process schemes through the use of three test reactors that can be started up in parallel or in series.

Lithium de France started to drill in November 2025, and aims to reach a depth of 2400m. The geothermal doublet will be used for supplying heat to the town of Betschdorf (France), and the project will also extract lithium from geothermal brines. The collaborative project is supported by BPI France and the equipment was designed together with DG SKID. The overall goal of Averne Group is to reach an annual production capacity of 4 TWh of geothermal heat and 27,000 tonnes of geothermal lithium by 2031.

Altamin has secured in 2025 a €2 million grant for research on critical minerals from geothermal brine in the Lazio region of Italy[21]. The BRAIN project looks at innovative process to demonstrate the feasibility of producing commercial-grade potassium sulfate (Sulphate of Potash) to be used as a plant fertilizer, alongside lithium and boron using geothermal energy.

Planning permission was granted in 2025 to Cornish Lithium for their commercial geothermal lithium production facility based in Cornwall (UK)[22]. Phase One of the project will involve drilling and testing two 2,000-metre-deep wells, which will build on the exploratory drilling completed in 2023. Lithium-enriched geothermal waters will be extracted from the first well using state-of-the-art Direct Lithium Extraction (DLE) technology. In Phase Two, a temporary demonstration plant will be constructed to validate the production of lithium compounds at the Cross Lanes site. This phase will evaluate the opportunity to provide samples for battery and electric car manufacturers. Cornish Lithium intends to construct a commercial plant at this location.

Also in Cornwall, the United Downs Deep Geothermal Power is on track to become the first fully operational geothermal electricity plant in the UK. After changing the ESP pumps in November 2025, it plans to produce electricity. The United Downs geothermal brine is also well suited for Direct Lithium Extraction (DLE) with a significant presence of lithium (> 300 ppm) and low TDS. The development of the DLE plant consists of two stages: bringing a Lithium Carbonate Equivalent (LCE) demonstrator online, followed by full-scale expansion of Lithium extraction.

The United Downs geothermal power plant site in Redruth, Cornwall (UK)

[21] Altamin secures grant for research on critical minerals from geothermal brine in Italy (Think GeoEnergy 22-09-2025)

[22] Planning permission granted for UK's first commercial geothermal lithium production facility (Global Mining Review, 13-03-2025)

Highlights of a 2025 innovation trend: Exploration Campaigns

Recent years have seen steady growth in the number of exploration activities being undertaken in Europe. In 2024, a record of more than 17 seismic surveys were conducted, compared to only 10 in 2023. Numerous other 3D seismic and other exploration campaigns have been carried out in 2025. Meanwhile, we have observed the continuing transfer of exploration technologies from the oil and gas industry to the geothermal energy sector. While project developers relied mainly on legacy data or regional geological surveys to develop projects in better known areas, 3D seismic surveys are increasingly being conducted in order to identify suitable locations for drilling.

Seismic exploration campaigns in Europe

Switzerland saw a huge amount of surveying activity: EnergeÔ carried out a seismic survey covering 400 km^2, Invert-Geoscience has conducted a survey near Lucerne, and Geo2X used STRYDE nodes to survey an area of 104 km^2. Hydro-Geo Environnement, a company that specializes in geological surveys, carried out a survey in Magglingen (Bern) and the surrounding area. GEOOL, which is a joint venture based in Lausanne, conducted a 3D seismic survey covering 170 km^2 and including 43 municipalities.

The De-Risking Enhanced Geothermal Energy Projects (DEEP) project has developed a system that records micro-seismic signals in real-time and uses this data to predict seismic activity in the coming minutes, hours, and days.

In the Netherlands, the publicly funded SCAN agency has developed an approach that is more detailed than 2D seismic surveys, but less expensive than most 3D surveys. The methodology involves drilling a series of small holes, 10 to 40 meters deep, at intervals of 40 to 100 meters. Seismic charges are placed in the holes, which are then sealed with clay and detonated. Geophones are used to gather data and build up a detailed mapping of the subsurface to a depth of 6 km. At the end of 2024, SCAN explored three additional areas for new seismic studies (Brabant West, Amsterdam East, and Apeldoorn-Deventer). Furthermore, SCAN also operates on several drilling test sites in the Netherlands to collect additional data.

Meanwhile, in the Euregio Meuse-Rhine, which covers neighbouring areas in Belgium, Germany and the Netherlands, researchers from the University of Liège (ULiège) and the Royal Dutch Meteorological Institute (KNMI) have carried out seismic surveys as part of the E-TEST project, which is supported by the European Union's Interreg programme. This work also contributes to the 'Einstein Telescope' – an underground observatory where scientists will study the universe by collecting data on gravitational waves.

Geophysical flights

Geophysical flights represent a significant advance for geological exploration. In 2025, Vulcan Energy conducted an exploration campaign over parts of the central and northern Upper Rhine Graben. The measurement campaign is part of the GeoProH joint project, which involves Vulcan Energy, OMV, Eavor Deutschland, the City of Frankfurt am Main, the Karlsruhe Institute of Technology (KIT) and the regional government of Hesse (Ministry of Economy, Energy, Transport and Housing).

Bell Geospace, the UK-based airborne geophysical surveying company, has already undertaken geophysical flights for the geothermal project of ZeroGeo Energy GmbH in the Lower Saxony region.

With this new approach, the insights into geological structures in the subsurface are expected to be improved and the data will be combined with existing drilling and seismic information. Thereby, it will be possible to create a consolidated 3D subsurface model which is an essential basis for planning upcoming renewable energy and carbon-neutral lithium projects.[23]

Bell Geospace Basler BT-67 - C-FTGI aeroplane used for aerial geophysical surveys [Trevor Hannant]

[23] GeoProH: Vulcan Energy und Partner starten geophysikalische Befliegung im Oberrheingraben (Vulcan Energy, 13-11-2025)

4. Market trends

Table 3: Definitions of key concepts for SET PLAN Task Force 5 (Access to Market)

Key concept	Applied definition
Market access (Related terms: access to the market, market entry and entry to the market)	Market access of SET Plan technologies refers to the ability of a technology company or the country to sell goods and services with minimal restrictions or barriers to the market. Market access is thus about overcoming barriers and hurdles.
Market uptake (Related terms: market adoption, market penetration commercial, and consumer and industry acceptance)	Market uptake of SET Plan technologies refers to the extent to which a technology is adopted and used by consumers or businesses after having received access to the market. It involves the processes and factors that influence the acceptance and integration of innovations into market.
Market competitiveness (Related terms: Dominant and high market shares)	Competitiveness of SET Plan technologies include the capacity of the technologies to compete in the market, and reach a stage of competitive pricing, quality, innovation, security and sustainability enabling sustainable productivity growth.

Market trends in Europe

Geothermal energy usage is increasing throughout Europe.

Based on the **geothermal power plant**'s long lifetime and them being local, resilient and dispatchable, continuous growth can be observed in the sector after a period of stagnation, largely due to unstable regulatory support. Europe currently has over 3.5 GWe of installed geothermal electricity capacity (1 GWe in the EU Member States), generating around 20 TWh in 2024 (7 TWh in the EU). In 2024, three new geothermal power plants were inaugurated - two in Türkiye and one in Austria. External shocks have created additional challenges. Since 2020, the COVID-19 pandemic and the ongoing war in Ukraine have delayed permitting, disrupted supply chains, and inflated energy and equipment costs. While energy prices fell in 2023, financing remains difficult due to high interest rates and inflation - especially for smaller developers lacking the financial resilience of large utilities.

Nonetheless, we expect to see a growth in the deployment of geothermal electricity generation in the coming years, with the use of fossil fuels such as coal decreasing. Around 50 geothermal power plants are currently progressing through various stages of development — from initial exploration and drilling to preparations for grid connection. As of 2024, two additional projects have entered the development phase. Developers are increasingly pursuing clusters of projects, either within the same geological basin or spread across multiple regions, in order to spread risk and streamline development.

The **next generation power** market in Europe presents advanced technologies that are considerably expanding. **Combined heat and power** next to Enhanced Geothermal System (EGS) projects are also expanding in Europe.

In 2024, the **geothermal district heating and cooling** sector in Europe demonstrated steady and diversified growth, with notable progress in emerging markets, while mature markets saw slow or zero growth. Ten new geothermal DHC plants were commissioned in Europe, including 3 in Poland, 2 in the United Kingdom, and 1 in each of France, Greece, Romania, Spain and the Netherlands. A total of 412 geothermal DHC plants were in operation in 2024 across Europe, including 308 in the EU Member States, and several more have begun operating in 2025. Additionally, about 500 projects are under development at different stages. At the end of 2024, the total installed capacity across Europe was more than 6 GWth across 29 countries (including 21 of the EU Member States).

Nonetheless, growth is not as high as it has been in the past. Reasons for this include adverse financial conditions, delays in project development and longer project development duration. As for the upcoming years, there are 400 geothermal district heating and cooling projects under development which – if all commissioned – would increase Europe's total geothermal DHC capacity by over 100%.

The next generation of geothermal district heating and cooling (DHC) systems will include plants with an installed capacity of significant size, systems that make use of repurposed wells, and systems that utilize low temperature heat.

As for **geothermal heat pumps**, the market has suffered a decline in sales, in the context of a general decline in sales of heat pumps of all types. Within the EU, about 11,000 geothermal heat pump units were sold in 2024, which represents a 29% decrease since 2023. At the end of 2024, some 2.43 million geothermal heat pumps were operating in Europe with a total installed capacity of 37.6 GW of heat.

Macroeconomic factors, subsidized gas prices, uncertainty relating to electrification and permitting issues next to technical barriers have all contributed to reducing the number of geothermal heat pumps being installed. Favourable policy and legislative developments as well as financial incentives at EU and national levels are needed to create the conditions for the geothermal heat pump market to rebound.

Underground thermal energy storage (UTES) is dominated by low-temperature systems, particularly Borehole Thermal Energy Storage (BTES). Thousands of BTES installations are operational across Europe, primarily serving small-scale heating and cooling applications for buildings. High potential is also seen in mine water energy storage with significant opportunities for replication, although it still remains a niche market.

In terms of competitiveness with other renewable energy sources, as well as fossil fuels, the geothermal market is increasing its resilience. However, the costs of geothermal technologies need to be further reduced, which can be supported by fostering research and knowledge of innovative technologies. Many of the trends outlined in this report will contribute to lowering the costs. Additionally, increased deployment will bring down the costs of geothermal installations, making them more attractive and competitive.

Exporting geothermal services will increase the competitiveness of Europe's geothermal sector. With a strong industrial base in Europe, deep geothermal projects already face challenges in accessing the necessary drilling equipment, which is also used by the oil and gas industry.

Turning to the **extraction of critical raw minerals**, in March 2025 it was announced that two geothermal lithium projects have been selected by the European Commission as strategic projects in the framework of the European Critical Raw Materials Act (CRMA). These projects will benefit from streamlined permitting and administrative procedures, as national authorities are required to give priority to facilitating the delivery of strategic projects. Permits for extraction projects should be granted within 27 months, while permits for processing and recycling projects should be granted within 15 months. Strategic projects also benefit from support provided by the European Commission and access to financial institutions to help them secure funding.

Vulcan Energy has advanced its geothermal lithium programme, and in 2025 the company received approval to build its commercial lithium extraction plant in Landau (Germany)[24]. Extracting lithium from geothermal brine is now a clear commercial pathway in the Upper Rhine area and is attracting industrial partnerships and local permitting decisions.

Market trends in the value chain

The EU is a net exporter of geothermal services, particularly for power plants. These services include exploration, subsurface engineering, drilling, EPC (engineering–procurement–construction), and facility construction. Many service companies have extensive experience of projects in the oil and gas sector, and they can provide expertise in areas such as advanced drilling, subsurface engineering, seismic acquisition, monitoring tools, and well-construction techniques.

Several European regions have strong 'service clusters' (such as Celle in Germany, Pau in France or Aberdeen in Scotland) specialised in drilling, engineering and well services.

Growth in demand for drilling

Drilling remains the single biggest cost category and a gating constraint. Market intelligence and rig-market reports show growth in demand for geothermal-capable rigs and associated services for 2024–25. A record number of deep wells drilled in Europe from 2025 to 2030, driven by new exploration campaigns. In 2024, there were a record number of surveys (17), and at least 10 3D seismic campaigns began in the first half of 2025. This increase in exploration is directly feeding into expectations for a strong surge in drilling. Developers are responding to cost pressures through entering into partnerships with rig owners and/or acquiring their own drilling rigs.

[24] Vulcan Energy: Construction permit granted for lithium extraction plant in Germany (Electrive, 03-11-2025)

EU push on equipment and manufacturing

The Net-Zero Industry Act (NZIA) identifies geothermal as a strategic net-zero technology and aims for 40% of EU deployment needs to be manufactured in Europe by 2030. Its adoption is therefore expected to push EU manufacturing capacity and "strategic autonomy" for geothermal components. Implementation activity around the NZIA (which entered into force June 2024) is driving policy and funding to expand EU manufacturing for strategic components. Procurement preferences and industrial programmes are pushing "made in Europe".

The NZIA recognised the following as primary components [25] used for geothermal:

- Heat exchangers resistant to geothermal corrosive operating conditions
- Submersible pumps resistant to geothermal corrosive operating conditions
- Brine re-injection pumps.

The NZIA is expected to strengthen geothermal EU autonomy in some weak areas. Specifically:

- The absence of EU manufacturing of lineshaft pumps.
- Reliance on imported titanium, which is essential for heat-exchanger materials.
- Competition from Chinese manufacturers in the supply of valves, compressors and high-temperature cement.

Services: ongoing transfer from the oil & gas sector

Expertise and contractors from the oil & gas sector continue to migrate to the geothermal sector (including drilling crews, directional drilling experts and reservoir engineers). This strengthens the service layer of the value chain but puts pressure on crew availability and can also lead to increased costs when there is continuing demand for the same services in the oil & gas sector.

Increased attention to next-generation geothermal

The successful deployment of closed-loop Advanced Geothermal Systems (such as the Eavor-Loop™ project in Geretsried, Germany) represents a significant development, reducing the need for deep geothermal energy projects to rely on access to natural hydrothermal resources. As so-called 'next-generation' systems mature, new segments of the value chain will become more important (such as loop design, working fluid management and advanced engineering). Closed-loop systems could reshape operations and maintenance (O&M)) for deep geothermal projects. Instead of managing fluids from naturally permeable aquifers, operators will need to manage circulating working fluids, design for thermal efficiency, and optimise loop architecture.

[25] To identify specific components considered to be primarily used for the production of net-zero technologies, four criteria were applied in the assessment, namely their specific nature; their commercial availability; the fact that they are always primarily used for that production; and their essential character.

5. Conclusions

The geothermal sector is characterised by ongoing innovation, which continues to drive and support the expansion of the European market for geothermal technologies.

Technologies that are in the early stages of development (low TRL) are seeing significant progress - especially new drilling technologies. Artificial Intelligence (AI) is increasingly being used in the development of geothermal energy projects. Several geothermal technologies that are in advanced levels of development (high TRL) are currently being demonstrated and will soon be commercialised.

Technologies that can currently be described as ‘close to market’ include:

- Medium and high temperature underground thermal energy storage (UTES)
- Single well geothermal projects at medium depth or deeper
- Deep closed loops of multilateral well systems
- Drilling robots for shallow geothermal projects
- Cooling for industrial purposes - including Data Centres
- Co-production of critical raw materials.

Some of the relatively new technologies that can be described as ‘market ready’ include:

- The use of large and high temperature geothermal heat pumps to supply heat for district heating grids and/or industrial processes
- Large-scale geothermal heat pumps that provide hot water, space heating and cooling to large buildings and services
- Low temperature heat networks (5th generation district heating networks) for new and refurbished buildings and facilities at street and/or district level
- New drilling techniques, well designs and drilling equipment for improving the productivity of subsurface systems
- Large turbines suitable for use in high temperature fields and for so-called ‘next generation’ geothermal technologies
- Geothermal cooling systems for buildings, urban districts and data centres

Examples of innovation in the domain of geothermal project development and business models include: the project portfolio approach to de-risk investments with several geothermal projects in the same area; signing long-term heat purchase agreements with consumers, and the supply of 'heat as a service', which can be an efficient way to finance geothermal heat pump systems.

European Technology & Innovation Platform on Geothermal

The European Technology & Innovation Platform on Geothermal (ETIP-Geothermal) is an open stakeholder group, endorsed by the European Commission under the Strategic Energy Technology Plan (SET-Plan), with the overarching objective to enable geothermal technology to proliferate and reach its full potential everywhere in Europe. The primary objective is overall cost reduction, including social, environmental, and technological costs.

The ETIP-Geothermal brings together representatives from industry, academia, research centres, and sectoral associations, covering the entire geothermal energy exploration, production, and utilization value chain.

etip-geothermal.eu

European Geothermal Energy Council

The European Geothermal Energy Council (EGEC) is a not-for-profit organisation promoting all aspects of the geothermal industry. Founded in 1998, its objective is to facilitate awareness and expansion of geothermal applications across Europe by shaping policy, improving investment conditions and steering research.

EGEC is listed in the European Transparency Register No. 11458103335-07

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