Major Technological Trends

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Report on major technological trends

Katrin Kieling, GFZ

Philippe Dumas, Giulia Cittadini, EGEC

With contributions from Laurent André (BRGM), Guido Blöcher (GFZ), Romain Chassagne (BRGM), Marton Farkas (GFZ), Luc Pockelé (RED), Javier Urchueguia (UPV), Gerdi Breembroek (RVO).

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ORCID:	Katrin Kieling 0000-0003-0182-5090

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1 Executive Summary

To answer the challenges set in the EU Climate & Energy framework 2030 of an exponential growth of the share of renewable energy including geothermal for the next ten years, a geothermal strategy at EU level must be established. Such program will cover the various technologies of the geothermal sector, which are at different stages of development. The development of a European Geothermal Strategy also encompasses a presentation of the technological trends, market trends and an analysis of the competitiveness of the geothermal industry.

This report looks at research and innovation trends for geothermal systems producing heat & cold and generating electricity. It also takes into account trends in storage technologies and extraction of minerals from geothermal fluids. The main focus of the report is on the last five years, 2019-2024.

The identified research topics and innovation trends are classified in terms of Technology Readiness Levels (TRL). Case studies illustrate the different systems. In view of the fact that there is a multitude of research and innovation activities ongoing, this report can never be exhaustive. However, updates of the report are foreseen and the authors are thankful for contributions from the geothermal community.

As a whole, the main innovations trends reflect the large interest of the society for geothermal energy for district heating and cooling. A wide range of technologies and research projects aim at more cost efficient and secure provision of heat and unlocking geothermal resources in more divers geological settings. Innovation trends also show the opening of the geothermal market for wider applications, with underground thermal storage as a key technology for the heat transition and co-production of critical minerals as a major opportunity to increase the returns on investment for geothermal plants while contributing at the same time to the goals of Europe's Critical Raw Material Act. Finally, research projects are aiming at the application of the ever increasing digital and computational methods for the optimising of geothermal exploration, resource assessment, resource development and operation and monitoring of geothermal systems.

2 Research trends

2.1 Low TRL

2.1.1 Utilisation of Machine Learning and Artificial Intelligence Tools in geothermal exploration and operation

More robust and quantitative approaches to resource and risks characterisation can be achieved with the development of more computational geothermal tools, including machine learning and AI[1] tools. The automatization of some cumbersome procedures (e.g., data cleaning and enhancement) along with a quantitative integration of multiple types of data (*e.g.,* seismic, gravity and well data) holds the promise to improve the exploration of geothermal systems, enable better operational decisions during the exploration process and finally allow for a high drilling success rate. On the other hand, digitalisation of geothermal production processes, linking to models, and deployment of AI enable real-time analysis and decisions.

Currently considered research topics include:

- data assimilation workflows[2], leading to a more quantitative decision-making in geothermal exploration
- integration of multiple data types (e.g. seismic, gravity, electromagnetic and well data as well as other geological information) with advanced AI algorithms
- developing novel, fast AI-based techniques for predicting geothermal attributes directly, such as fluid circulation, heat gradient, and risks
- forward modelling methods, including stratigraphic forward modelling (SFM), diagenesis forward modelling (DFM) and fracture network forward modelling (FFM)

AI is still under intense study and should be developed alongside classical models to enhance understanding and quantify uncertainty.

2.1.2 Digitization and Digital Twins

The term 'digitalisation' refers to the construction of computer models intended to improve production and efficiency. The 'digital twin' can be considered as one of the core concepts of the digitalisation, with the digital/IT infrastructure that provides bi-directional connection between the real plant and its virtual twin. For geothermal energy production and underground, heat storage digital twin systems combined with real time data analysis and AI-aided decision making during operation of geothermal systems are currently developed.

The MALEG project[3] digital twins of three different geothermal sites are developed and combined with a machine learning algorithms to predict the geochemical composition and the scaling potential based on live measurements of the geothermal brine optimizing the individual power plant. To train the AI, an on-site demonstrator 'hardware-twin' as well as a 'digital twin' are developed. The 'hardware-twin' emulate power plant process, brine treatments and mineral extraction to investigate the occurrence

[1] J. Moraga, H.S. Duzgun, M. Cavur, H. Soydan (2002), The Geothermal Artificial Intelligence for geothermal exploration, 1867408.

[2] D Obidegwu, R Chassagne, C MacBeth (2017), Seismic assisted history matching using binary maps, Journal of Natural Gas Science and Engineering 42, 69-84, Seismic assisted history matching using binary maps.

[3] MALEG, The MALEG project, https://maleg.eu/project/.

of scaling and corrosion. The 'digital-twin' simulates the geochemical processes of these potential hazards.

As another example, in the GEMINI project[4], an advanced simulation tool is developed that combines physics-based models, chemistry models, data-driven models and physics-informed AI models, which are all brought together into one flexible web-based framework. The models are standardised and, in the future, can be replicated to work with other systems in other industries. The digital twin continuously monitors and analyses system performance, enabling inefficiencies, potential bottlenecks and failures to be promptly identified and corrected.

2.1.3 Advanced exploration tools

Although methods of exploration and investigation of geothermal resources are numerous and well described in the literature, there is still a need reduce the uncertainties affecting location, size, and productivity characteristics of a given resource. Recent trends in geothermal exploration include:

Fibre Optic Sensors: The development and use of fibre optics as distributed or point sensors is constantly growing in geoscientific and geotechnical applications. Above all, the introduction of distributed temperature sensing (DTS), distributed strain sensing (DSS), and distributed acoustic/vibration sensing (DAS/DVS) is allowing spatially and temporally continuous monitoring of (geo-)technical systems and facilities. Distributed chemical sensing and distributed pressure sensing (DPS) methods have also been demonstrated in test environments. Point sensors, on the other hand, are advantageous in applications involving high-resolution monitoring of specific system components.

Soil gas Surveys: The monitoring of diffuse degassing has been used extensively for different purposes, e.g., study of seismically active faults, detection of structures in volcanic systems in connection with geothermal exploration, and monitoring of geothermal systems under energy production. Therefore, area-wide soil gas surveys constitute a powerful tool for geothermal exploration campaigns as they enable the fast investigation of large areas in a short time. Further development in these areas promises to improve the speed of surveys and the coverage, in order to aid the selection of potential drilling locations.

Urban seismic geothermal exploration: Existing exploration methods are not suited for reservoir characterization in urban contexts. The URGENT[5] project addresses this gap by providing sustainable and affordable solutions for urban seismic exploration of geothermal resources. Low-impact innovative technologies, consisting of an electric seismic source and novel MEMS based sensors integrated into autonomous nodes, will be designed, built, and tested on 3 sites: Balmatt (BE), Konin (PL), Batta (HU). They will enable high-quality data recording including low frequency signals resulting in high resolution imaging up to 4000m of depth. Also, survey designs will be optimised, including compressive sensing and simultaneous shooting.

Forward modelling method for more accurate pre-drilling predictions of geothermal reservoir properties: Forward modelling methods originally developed for hydrocarbon exploration, including stratigraphic forward modelling (SFM), diagenesis forward modelling (DFM) and fracture network forward modelling (FFM), are adapted to be used for exploration in different geothermal

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[4] TNO, GEMINI: intelligent decision support system for geothermal assets, https://www.tno.nl/en/newsroom/insights/2023/11/intelligent-support-system-geothermal/.

[5] CORDIS, Sustainable and affordable Urban Geothermal Exploration Novel Technologies and workflows, https://cordis.europa.eu/project/id/101147467.

settings. For example, the GO-FORWARD[6] project tests and calibrates such approaches in areas with abundant subsurface information and production data, to prove conceptually the applicability of the methods and reproducibility of the results, to optimise and de-risk geothermal exploration. Calibrated model approaches are subsequently applied in areas with limited data availability to demonstrate their capability to increase pre-drill Probability of Success (POS).

These innovative methods and technologies will improve the knowledge of the various geothermal systems, contributing to increase the success rate of drilling and consequently reduce the overall exploration expenditures.

2.1.4 Using a subsurface working fluid other than water (e.g. CO_2) for advanced geothermal systems or UTES

The idea behind using supercritical carbon dioxide (sCO_2) as a working fluid is based on its more advantageous thermodynamic properties compared to groundwater or brine-based geothermal systems. These include favourable subsurface transport properties, strong buoyancy effect, decreased likelihood of scale precipitation as well as the possibility of direct use of CO_2 in turbomachinery (Brown 2000[7]; Randolph and Saar 2011[8]). Therefore, the integration of geothermal energy with carbon capture and storage (CCS) may deliver more heat and/or power with higher efficiency at lower costs. Existing concepts can be grouped as follows (Kervévan et al. 2023[9]):

- Use of supercritical CO_2 as heat transfer medium (working fluid) for geothermal energy production such as CO_2-plume geothermal (CPG), CO_2-Enhanced Geothermal System (EGS), heat production from depleted oil and gas reservoirs, CPG-Energy Storage, and Earth Battery. All these concepts are at a low TRL currently and require field demonstration to prove feasibility.
- Water-based geothermal concepts with CO_2 (re-)injection dissolved in the geothermal brine. The source of CO_2 is either from an external source in CO2-DISSOLVED and Geothermal-Bioenergy with CCS, or from the geothermal plant, e.g., CarbFix project in Iceland. These concepts have lower technical complexity compared to the previous one. Several demonstration experiments can be expected in France, Croatia, Italy, New Zealand and Turkey in the coming years.
- Synergetic uses, such as CCS with improved efficiency by using geothermal energy, e.g. CLEAG-AATG project in Croatia.

A novel concept for renewable energy storage in terms of electrothermal energy and geological carbon dioxide storage is being investigated in the CEEGS[10] project. The flexible balance between supply and demand of intermittent wind and solar energy can be provided by the CO_2-based Electrothermal Energy and Geological Storage (CEEGS) system. During the charge process, electrical energy is converted into thermal energy and mechanical energy in terms of CO_2 being injected into a subsurface reservoir. During discharge period, the stored mechanical and thermal energy are converted back to

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[6] CORDIS, Geothermal exploration and optimization through forward modelling and resource development, https://cordis.europa.eu/project/id/101147618.

[7] Brown, D., A Hot dry rock geothermal energy concept utilizing supercritical CO2 instead of water, Proceedings of the 25th Workshop on Geothermal Reservoir Engineering, SGP-TR-165, Stanford, California, 2000.

[8] Randolph, J. B., Saar, M. O. (2011), Combining geothermal energy capture with geologic carbon dioxide sequestration, Geophysical Research Letters, Vol 38, Combining geothermal energy capture with geologic carbon dioxide sequestration - Randolph - 2011 - Geophysical Research Letters - Wiley Online Library.

[9] IEAGHG (2023), Prospective integration of Geothermal Energy with Carbon Capture and Storage (CCS), 2023-02+Prospective+Integration+of+Geothermal+Energy+with+Carbon+Capture+and+Storage.pdf.

[10] CEEGS, Novel CO2-based electrothermal energy and geological storage system, https://ceegsproject.eu/.

electricity, which can then be fed into the grid. Preliminary results suggest that the concept can be tested at a higher TRL in terms of pilot demonstration.

2.1.5 Coupled thermal, hydraulic, mechanical, chemical (THMC) and microbiological system models

Coupled thermal, hydraulic, mechanical, chemical (THMC) are being developed, to quantitatively predict the process interaction in the area of influence (reservoir, near-borehole area and in the borehole) of medium-depth heat storage as well as deep geothermal systems just like hydrothermal or enhanced geothermal systems. Possibly future co-production of raw materials additionally intervenes in the equilibrium systems, and also here exemplary model calculations contribute to the development of sustainable and stable production of geothermal energy and raw materials.

On this basis of THMC simulations, the short- and long-term dominant processes during the operation of open geothermal systems can be quantified on a site-specific basis, including the interactions of the target reservoir with the surrounding formations as well as the influence of operating conditions on the considered processes. Commercial and Open-Source coupled THM simulators are already existing and widely used. However, the coupling of reactive processes in THM simulators is tricky because of the complexity of geothermal fluids (often hot and saline brines) and their interaction with formation rocks (in fracture or in porous media). In most cases, the parameterization of the hydrogeochemical models must be simplified and standardized. This simplification may imply a certain inaccuracy in the prediction of chemical reactivity and consequently the evolution of porosity and permeability of the reservoir.

There are partial solutions for the representation of reactive transport modelling in porous media in both the commercial sector and the open-source sector that have been used with success on many applications of the subsurface. A standardization on a common standard such as PhreeqC[11] or Reaktoro[12] for reactive transport has not yet taken place. There are several recent or ongoing European or national projects that are developing or improving packages for coupled modelling such as REFLECT[13] (coupling OpenFOAM® with PHREEQC to porousMedia4Foam), THC-PROGNOS[14] (coupling Golem with PhreeqC or alternatively with Reaktoro), DECOVALEX[15] (validating reactive transport modelling with OpenGeoSys against laboratory experiments).

Finally, microbiological processes have recently been investigated in the context of thermal storage, but also hydrothermal energy production. In the future, the challenge is to include in the modelling the chemical (precipitation, corrosion) or mechanical (biofilm formation) changes that are caused by microbiological processes. Microorganisms can inhibite/catalyze the chemical reactions and their activity must be included in the kinetic rate laws of chemical reactions. This integration of microbial constraints will require extensive work to calibrate the models using laboratory and field data. For example, in the ongoing PUSH-IT[16] project geochemical modelling is used to represent microbiological processes during heat storage at elevated temperatures.

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[11] USGS, PHREEQC Version3, https://www.usgs.gov/software/phreeqc-version-3.
[12] Reaktoro, https://reaktoro.org/index.html.
[13] Reflect, Redefining geothermal fluid properties at extreme conditions, https://www.reflect-h2020.eu; https://www.reflect-h2020.eu/wp-content/uploads/2022/01/d4.2_reflect.pdf.
[14] Enargus, THC-Prognos, https://www.enargus.de/search/?q=THC-Prognos.
[15] DECOVALEX, Development of Coupled models and their Validation and their experiments, https://decovalex.org/.
[16] Push it, Piloting underground storage of heat in geothermal reservoirs, https://www.push-it-thermalstorage.eu/.

2.1.6 Smart monitoring and assessment techniques for reservoir monitoring, well integrity and pump lifetime

The operation of geothermal system represents the longest phase of the development chain of a geothermal project and ensures the financial revenue of the high start-up investments. To ensure a sustainable and efficient operation and to guarantee longevity of geothermal production and storage, monitoring must be conducted in the context of the geological resource and the technical installations.

To determine the current state of the plant and make predictions, smart monitoring and assessment techniques and strategies have to be developed.

Given the challenging operation environment of pumps (large variations in flow rate, direction and temperature) in high temperature heat storage projects, pump monitoring systems is needed to monitor pump operation and generate a condition monitoring leading to failure warnings in an early stage. For this purpose, a specialised sensor will be tested in the PUSH-IT[12] project. At the same time, efforts are made to develop second-generation geothermal pumps with prolonged lifetimes under aggressive fluid conditions. Finally, alternative lifting technologies are discussed, such as gas lifting.

With regard to well integrity, current research develops and tests robot-assisted and AI-assisted drilling (e.g. the OptiDrill[17] project) and casing-setting technologies which ensure HSE, well integrity a and adaptation to specific geothermal environments (temperature, pressure and rock characteristics to increase lifetime. Intelligent drilling and completion technologies can be categorized into two branches: intelligent algorithms and intelligent equipment. Intelligent algorithms use AI algorithms to solve nonlinear and other complex problems and provide optimization and control schemes, providing necessary instructions and assistance for intelligent equipment. Intelligent equipment provides data sources and hardware support to establish and verify intelligent models.

In the 2022 edition, the winner of the Ruggero Bertani European Geothermal Innovation Award 2022 was Baker Hughes with its its innovative Corrosion Resistant Podded Electrical Submersible Pump & Completion System. This project, designed and developed by Baker Hughes Artificial Lift Systems and by ECW Geomanagement BV (ECW) has successfully executed an industry-first well completion that allows geothermal production to continue, and the casing to be protected against both localised and general corrosion.

2.1.7 Extraction technologies for co-production of critical raw materials

While co-production of lithium form geothermal fluids is already advanced in first pilot projects by the industry, see section 0, there many research topics that aim at facilitating and optimising the co-production of critical raw material (CRM) from geothermal brine in general.

First results have shown, that the performance of extraction technologies is heavily dependent on the type of brine including the trace elements included. Extraction technologies are often based around selective membranes, ion exchange or ion absorption, to allow the selective removal of only CRM compounds from the fluids. However, research is also investigating other options, such as gas-diffusion-electrocrystallisation, or microbiological approaches such as biosorption or bioprecipitation, for example in the LiCORNE[18] or the CRM-geothermal[19] project. Various companies have developed

[17] OptiDrill, OptiDrill: optimisation of geothermal drilling operation with Machine learning, https://www.optidrill.eu/.

[18] Licorne, Building up strategic reserves of Lithium to ensure the green and digital transformation of the European economy, https://www.licorne-project.eu/ .

[19] CRM geothermal, Raw materials from geothermal fluids, https://crm-geothermal.eu/ .

their proprietary extraction technologies, e. g. the French company GEOLITH has developed an active material (ion sieve/adsorption) capable of selectively capturing lithium from any liquid source.

The CRM-geothermal project is also collecting information on other elements that might be suitable for co-production and investigating extraction methods for strontium, helium, caesium and rubidium.

Ongoing research is considering the sustainability of the extraction process, i. e. to which extend the depleted brine is “recharched” with the CRMs after injection during cycling back to the production well. Finally, technologies for enhanced recovery by injection of additives into the reservoir were investigated, for example in the CHPM2030[20] project.

2.1.8 Crystalline rocks

In Central Europe, the largest geothermal potential resides in the crystalline basement rock with important hotspots in tectonically stressed areas. To better harvest this energy form under sustainable, predictable and efficient conditions, new focused, scientific driven strategies are needed. Similar to other geo-technologies, the complex processes in the subsurface need to be investigated in large-scale facilities to ensure environmental sustainability.

Research for utilising the crystalline basement includes laboratory experiments at high pressure to obtain unique data on the complex coupled thermal, hydraulic, mechanical and chemical processes with the challenge of simulation in-site stress filed and temperature. However, there are also several effort to close the research gap between laboratory and field scale via underground research laboratories.

The BedrettoLab[21] (Bedretto Underground Laboratory for Geosciences and Geoenergies) is a unique research infrastructure run by ETH Zurich making it possible to take a close look at the Earth’s interior. It is located in the Swiss Alps 1.5 kilometres below the surface and in the middle of a 5.2 kilometres long tunnel connecting the Ticino with the Furka railway tunnel. Equipped with the latest technology, the BedrettoLab offers ideal conditions to conduct experimental research focusing on the behaviour of the deep underground when accessing and stimulating it.

A new underground research laboratory GeoLaB[22] (Geothermal Laboratory in the Crystalline Basement) is set-up by the Helmholtz Association will address the fundamental challenges of reservoir technology and borehole safety. In the underground research laboratory, individual caverns will be accessed via an approx. 1 km long access tunnel. From the caverns, additional drilling will be performed. This will allow for controlled high flow rate experiments, CHFE, in fractured rock and developing and calibrating smart stimulation technologies without creating seismic hazard. The first phase of setting up the underground research laboratory is planned to finish until 2029.

2.2 High TRL

Regarding, High TRL (TRL: 6-9) for geothermal technology and Innovation, the trends in technology demonstration in relevant environment, system prototype demonstrated in operational environment, system complete and qualified and system proven.

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[20] CHPM2030, CHPM2030 project, https://www.chpm2030.eu/.

[21] BedrettoLab, Bedretto Underground Laboratory for Geosciences and Geoenergieshttps://bedrettolab.ethz.ch/en/home/ .

[22] KIT, GeoLaB - Research lab geothermal energy, https://www.geolab.kit.edu/english/.

2.2.1 Novel drilling technologies

According to the EGEC Geothermal Market report 2023, there are approximately 50 geothermal power projects in various stages of development and 316 district heating projects under active investigation. All these projects require drilling which is the most expensive part of the geothermal deployment. Consequently, there is an enormous innovation effort targeting the reduction of drilling costs. A few examples shall be highlighted here:

- The ORCHYD[23] project develops an improved drilling method using a high-pressure water jet (HPWJ)-enhanced mud hammer[24]. The objective of this project is to increase the drilling rates in deep hard rocks (> 4 km) by 4 times as compared to conventional rotatory techniques. The fully fluid driven ORCHYD system is combining two innovative rock breaking technics: slotting circumferential relieving grooves on the hole bottom with High-Pressure Water jets (up to 200 MPa) and fluid driven percussion drilling delivering high-energy impacts dozens of times per second.
- GA Drilling has developed a new deep drilling tool, ANCHORBIT®, a downhole walking system that prevents vibrations and improves stability when drilling with rotary systems in the hard and abrasive formations commonly encountered in deep and hot geothermal projects. In these conditions, ANCHORBIT® should double the rate of penetration and bit lifetime since the tool allows for the stabilization of the bit in the wellbore and thus applies more weight to the bit. The company has also developed the PLASMABIT® drilling platform which combines the thermal energy of plasma with mechanical force & weakens the rock which enables faster drilling. The Pulse Plasma Drilling Head doesn't require contact or rotation with the formation. Hence, it is inherently less prone to any mechanical wear.
- Strada has developed a Dual Circulation Water Hammer Technology, which delivers the safety and hole cleaning properties of mud rotary drilling with the ROP of percussion drilling. A weighted flushing fluid of required properties is pumped down the inner tube of Dual Circulation Drill Pipe while a clean power fluid to drive the hammer is pumped down the outer tube. Flushing & power fluids combine at the drill face and conventionally circulate cuttings to surface. Using a clean operating fluid addresses erosion of critical hammer parts, thus achieving hammer longevity and reliability. The dual circulation system has been successfully tested at the Merredin Western Australia Test Site.
- The DEPLOI the Heat[25] project develops the Directional Steel Shot Drilling technology of Canopus, which is expected to be able to create multiple long drainage holes in any desired direction entirely within a reservoir. It combines conventional mechanical drilling action with the impulse of pressure accelerated steel shots. The steel shot action can be controlled with respect to the orientation of the drilling bit resulting in a novel rotating directional drilling system that simplifies the creation of complex borehole geometries. Extensive laboratory testing and optimizations at the Rijswijk Centre for Sustainable Geo-Energy (RCSG) of TNO under laboratory conditions. A field trial took place in the Hagerbach test site (VSH) in

[23] Orchyd, Novel drilling technology combining hydro-jet and percussion for ROP improvement in deep geothermal drilling, https://www.orchyd.eu/ .

[24] Gerbaud, L., Jahangir, E., Velmurugan, N., Sellami, H., & Cazenave, F. (2023), Enhancing drilling performance of mud hammers by combining high pressure water jets slotting. In ARMA US Rock Mechanics/Geomechanics Symposium (pp. ARMA-2023). ARMA.

[25] DeepU, Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation, https://www.deepu.eu .

Switzerland, led by ETH Zurich. Two directional wells were drilled using the DSSD technology and surveyed to examine system performance, borehole quality, and control mechanisms[26].

- The DEEP-U project [27]is developing a new combination of new laser drilling and cryogenic gas technology in order to extract energy from deep (>4 km) U-shaped closed-loop systems. Laser-drilling experiments were performed on granite, sandstone and limestone, including N_2-assisted thermal spallation drilling. Main finding of the project are that melting-evaporation laser drilling is possible but inefficient. In contrast, thermal spallation laser drilling is possible and efficient for wide range of lithologies. The vitrified walls of the borehole formed during the melting process are fractured and permeable.
- In the DeepLight[28] project, develops a contactless drilling technology based on Electrical Pulsed Power (EPP) technology, also named Electro Impulse Technology. The method is based on the effect of electrical discharges that are led through the material/rock to be destroyed. The active electrode is subjected to high-voltage impulses of up to several 100 kV. The electrodes only have loose contact with the rock and are surrounded by a liquid. In the case of very fast voltage impulses, the dielectric strength of liquids is greater than the dielectric strength of solids. Therefore, extreme short pulses are required to cut through the rock in an efficient way. The novel EPP drilling technology will be capable of drilling much deeper wells with larger diameters than current drilling technology. Because there is no mechanical contact for torque and weight on the bit for rock breaking, no heavy equipment is needed, and no trips for bit replacements are required. The project will also investigate EPP drilling with integrated casing placement.
- The OptiDrill project combines novel downhole sensor for measurement while drilling with and AI-based advisory system. Sensors in the bottom hole assembly measure WOB, RPBM, ROP and torque. The project also tested AI tools based on Neural Networks as wells tree-based approaches like Random Forest techniques to predict WOB, ROP and lithology. Additionally, an unsupervised machine learning is used to detect drilling problems in real time. Up to now, the approach was tested during drilling a 150 m deep well in Bochum and successfully provided recommendations for optimal rig operation.

2.2.2 Materials for Geothermal installations

Ongoing R&D focuses on materials adapted to the geothermal to ensure higher performance and resistance. This is done especially with a view to extreme environments, such as high-temperature and high-saline fluids.

The GEO-COAT[29] project develops specialised corrosion- 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 forms of HVOF / Laser cladding). These coating are specially developed to provide the required bond strength, hardness and density for the challenging geothermal applications.

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[26] Knebel et al., Novel "Directional Steel Shot Drilling“ – technology from Canopus Drilling Solutions B.V. – Preparation and results of an extensive lab and field test (2023), Der Geothermiekongress DGK 2023, Essen, Germany https://deploitheheat.eu/wp-content/uploads/2024/07/07-DGK-Knebel-DSSD_v1.0_DGK2023_Langfassung_eng.pdf.

[27] DeepU, Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation, https://www.deepu.eu .

[28] Geothermica Initiative, Deeplight, https://www.geothermica.eu/project/deeplight, https://deeplight-project.eu/

[29] Geo-Coat, Geo-coat project, https://www.geo-coat.eu/ .

The GEOHEX[30] project develops advanced material with anti-scaling and anti-corrosion properties for cost-efficient and enhanced heat exchanger performance for geothermal applications. The consortium developed materials for three different heat transfer mechanisms used in heat exchangers, including single phase heat transfer, condensing surface and boiling surface. For example, TiO_2 coatings were applied on a carbon steel substrate using suspension plasma spray (SPS). In addition, a sustainability model, using parametric lifecycle assessment, and a cost model were developed in order to identify the environmental and cost performance of the materials.

2.2.3 Full reinjection power plants in Italy

A viable, safe, and cost-efficient technology to improve the environmental performance of high-temperature geothermal power systems is the complete reinjection of fluids into the reservoir with total and complete control of non-condensable gases. The release of steam and potentially hazardous chemical compounds from high-temperature geothermal resources and into the atmosphere and ecosystems can be avoided through technology for the capture, sustainable use, abatement or reinjection of Non-Condensable Gases (NCGs), including the selection of the most advanced materials capable of operating in harsh environments.

First demo plants are currently developed in Italy as models for the rest of Europe and globally. Full reinjection case studies have been investigated in the GECO[31] project at the site in Castelnuovo (Italy), Hveragerði (Iceland), and Kızıldere (Turkey)[32].

2.2.4 Underground thermal energy storage

While several demonstration projects on Underground Thermal Energy storage are currently ongoing or already completed (see section 3.2.1) there are a number of enabling technologies that are still in earlier stages of development. For example, research in the ongoing PUSH-IT project includes:

- drilling and completion technologies such as expanded diameter drilling and completion, composite (glassfiber re-enforced epoxy (GRE) and vacuum casings)
- integration of UTES in the heating system: STORM district heating network controller making use of machine learning; co-simulation of underground and surface system to optimize system integration
- monitoring: glass fiber based geomechanical and thermal monitoring of open systems; monitoring of thermal and influence on shallow groundwaters; monitoring of microbiological changes in the reservoir and investigation of microbiological processes in the lab as well as by modelling
- performance assessment: hot push-pull tests for open systems and enhances geothermal response tests for BTES systems are improved and demonstrated at the investigated sites.
- for borehole thermal energy storage systems as well as for borehole heat exchangers, newly formulated cementitious grouts have been developed in the GEOCOND project with the aim of enhancing the thermal conductivity. GEOCOND investigated the integration of expanded

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[30] Geohex, Geohex project, https://www.geohexproject.eu .

[31] GECO, lower emissions from geothermal power generation by capturing them for either reuse or storage, https://geco-h2020.eu.

[32] Mainar-Toledo, M. D. et al. (2023), Environmental benefits for a geothermal power plant with CO2 reinjection: case study of the Kizildere 3 U1 geothermal power plant, Energy Storage and Saving, Vol. 2 Issue 4, https://doi.org/10.1016/j.enss.2023.08.005.

graphite (EG)-based hybrid additives synthesized by building chemical bridges between silica particles and EG in the presence of amino functional silane coupling agent[33].

2.2.5 Geothermal heat pump systems

On shallow geothermal systems, several research projects brought technologies to high TRL level. Drilling designs are market ready technologies, but recent innovations in software and designs allow to develop large systems as illustrated in section 3.1.2.

This research brought geothermal HP technologies at a higher TRL for:

Pipes:

Three R&I projects can be highlighted with regard to piping. The HIPRESS borehole heat exchanger (BHE), a novel technology developed by Jansen (EGIA award) for applications in depths of 300+ meters, allows the exploitation of high temperatures at greater depths improving, at the same time, the efficiency of the heat pump.

The GEOCOND[34] project, mentioned above, worked on developing new geothermal pipes by improving thermomechanical ageing resistance and surface properties. It consists in high thermal Conductive HDPE pipes and fitting elements.The EU Horizon 2020 GEOCOND project established three main lines of work, the first of them focused on developing plastic pipes with improved conductivity. Using a PE100 matrix with specific additives, it increased the plastic's conductivity from 0.4 (standard) to between 1.0 and 1.1, while maintaining key properties such as flexibility, hardness, and coiling capability. This achievement has led to scientific publications and a patent in the approval process. Furthermore, GEOCOND opened new research opportunities to improve the efficiency of underground heat exchangers. A new, termed "trilobular", geometry was designed to optimize heat exchanger performance. This design includes a central tube of low conductivity surrounded by three high-conductivity tubes, which increases the heat exchange capacity by two to three times per meter, thereby reducing the necessary length and depth of the exchange systems. This solution can lead to a decrease in CAPEX larger than 20% in comparison with SOA.

Cheap-GSHPs [35]developed steel co-axial heat exchangers, installed with a piling methodology patented in Italy. This technology was further optimized in the GEO4CIVHIC [36]project achieving 20 – 30 % higher energy extraction efficiencies. Cheap-GSHPs project also developed a co-extruded basket type heat exchanger using aluminum foil as dead fold material to reduce the diameter of these baskets and achieve depths up to 20 meters using an auger drilling method. Such very shallow geothermal heat exchangers could supply sufficient energy in area's where drilling depths are limited to 20 meters by legislation.

Grouting

New additives for grouting were developed by GEOCOND project with Phase Change Materials (PCMs) with various range in the transition temperatures. It includes high thermal conductivity grout for BHE applications.

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[33] Berktas et al. (2020), Synergistic Effect of Expanded Graphite-Silane Functionalized Silica as a Hybrid Additive in Improving the Thermal Conductivity of Cementitious Grouts with Controllable Water Uptake,*Energies*, *13*(14), 3561; https://doi.org/10.3390/en13143561.

[34] CORDIS, Advanced Materials and processes to improve performance and cost-efficiency of Shallow Geothermal systems and Underground Thermal Storage, https://cordis.europa.eu/project/id/727583.

[35] Geo4Civic, https://geo4civhic.eu/cheap-gshp/.

[36] Geo4Civic, https://geo4civhic.eu/cheap-gshp/.

Regarding grouting materials, the research results bring a range of combinations with stable thermal properties and improved workability, surpassing current standards. These results allowed one company in the GEOCOND project incorporated these enhancements to produce badges of material in the order of tons.

Lastly, the project explored the inclusion of phase change materials (PCM) in the grouting, which increases thermal storage capacity in BTS (diurnal thermal storage) systems. This innovation, demonstrated in laboratory settings and documented in several publications, shows that PCM can be highly effective in optimizing thermal storage.

Rigs

First developed in the CHEAP-GSHP project (see above), the GEO4CIVHIC project developed an innovative compact drilling machine tailored for the built environment, with a power-full vibrating-rotating compact drill head and semi-automatic feeder. This versatile drilling machine allows rotating the mast 180° and inclining the mast to drill several boreholes in one spot without having to displace the rig. This vibrating-rotating drill head is commercialized in different power ranges.

Heat pump

Cheap-GSHPs developed a two-stage high temperature heat pump with CO_2 refrigerant in one stage to avoid replacing high temperature terminals. GEO4CIVHIC project further optimized this heat pump. Also in the GEO4CIVHIC project, a high temperature heat pump with CO_2 as refrigerant supplied high temperature terminals placed in series with low temperature terminals at COP's of 3.3 thereby avoiding partial replacement of radiators. A novel hybrid heat pump, always with CO_2 as refrigerant, used air and ground as sink to cool and air or ground as source to heat an historical monument. These solutions make geothermal heat pumps comply with existing and upcoming F-gas regulations.

2.3 Social science and Humanities

Geothermal energy has a major role to play in moving the EU away from our reliance on fossil fuels, hence the Geothermal WG and the ETIP geothermal have set ambitious goals concerning the role out of geothermal technologies for the energy transition. At the same time, the European Green Deal aspires to a "just and inclusive" transition where communities and citizens can work in partnership with institutions and organisations in energy decision-making. However, societal engagement tends to be neglected in strategic documents on upscaling geothermal technologies. In this area of tension, recent research projects link SSH (Social Sciences and Humanities) and STEM (Science, Technology, Engineering, and Mathematics) expertise with the aim of developing tools to identify public perceptions and to establish practices for societal engagement and evaluate their effectiveness.

The aim of the CROWDTHERMAL[37] project was to empower the European public to directly participate in the development of geothermal projects with the help of alternative financing schemes (crowdfunding) and social engagement tools. It has developed guidelines for public engagement, and adapted the theoretical concept of the Social License to Operate (SLO) to geothermal systems. Ongoing research within the CRM-geothermal project takes up the SLO concept and adapts it to projects aiming for the co-production of energy and critical minerals from geothermal fluids. Consultations are used to understand the environmental, social, economic and technical issues that can constrain or support the long-term, sustained acceptance of such projects and identify potential external triggers that can reinforce or undermine social license to operate (SLO). Tools and concepts are implemented at pilot sites in Cornwall in close cooperation with the operators. Similarly, within

[37] Crowdthermal, Development schemes for geothermal energy, https://www.crowdthermalproject.eu/.

the PUSH-IT project[38], societal engagement strategies are testes at demonstration sites for underground thermal storage and the impact and influence of different participation measures is monitored and evaluated. Differences are examined concerning how public understanding and support of high temperature underground heat storage differs over time and among social groups.

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[38] Push it, Piloting underground storage of heat in geothermal reservoirs, https://www.push-it-thermalstorage.eu/.

3 Innovation trends

For technologies, that are already closer to market in their development, several trends can be observed for both the subsurface part and the surface system of the geothermal plant.

New equipment such as heat pumps (HP) and Organic Rankine Cycle (ORC) plants allow to increase the efficiency of the systems, new designs aim at increasing productivity of the plant and innovation reveals new opportunities such as for cooling and storage solutions.

3.1 Market ready technology

3.1.1 Large and high temperature Heat Pumps

Traditional geothermal district heating systems are based on a doublet of wells, one well for production and the other one for reinjection. Drilling these wells at deep depth increases the uncertainty to find suitable geological conditions with high temperatures and high permeability. One trend is to target shallower resources at medium temperature, that are already better explored and bear a reduced exploration risk, and use large heat pumps to increase the temperature to the target temperature needed by the heat consumer.

Large heat pumps are available in the capacity range 1 to 20 MW_{th}. Heat is extracted from a source - for example the geothermal brine - and transferred to a so-called refrigerant, which vaporises due to its low boiling temperature. This is then compressed before the heat is transferred via a heat exchanger to a carrier medium such as water at a higher temperature level, which is then used to provide heat. The temperature release causes the refrigerant to liquefy again and is expanded before the process starts again. This can be used in case of district heating to fit for the temperature required by the building stock, without renovating or changing radiators. It is also used in industrial processes to bring the geothermal brine at the temperature required for the industrial process heat. Industrial heat pump covers now from small- to large-scale applications in the temperature range from low (around 50°C) to medium temperature for industries (>90°C until 150°C): Chemical, petrochemical and refinery, Food and beverage, Pulp & Paper, IT data centers.

Geothermal district heating plant in Vélizy-Villacoublay (France) with large heat pump

The geothermal district heating in Vélizy-Villacoublay is an example for the usage of a large heat pump in combination with innovative drilling technology. The Véligéo geothermal plant, inaugurated on 7 December 2021, employs cutting-edge multi-drains drilling technology. This innovative technique, traditionally used in the oil and gas sectors, enhances access to geothermal heat reservoirs, significantly increasing the system's efficiency. The plant supplies 60% of the 19 km district heating network, providing space heating and hot water to 12,000 homes and saving 22,800 tons of CO_2 annually.

With a capacity of 16 MW, the Véligéo heat plant has dramatically reduced the city's total energy consumption from 170 GWh to 110 GWh. Heat pumps elevate the 63°C geothermal heat to 85°C, and 3 km of the distribution network were upgraded to accommodate lower-temperature heat flows. The project, costing €25 million, received €9 million in subsidies from the Île-de-France Region and ADEME.

3.1.2 Large-scale geothermal HP systems

Cities in Europe, and worldwide, are composed by different types of buildings: size, age, thermal efficiency, number of apartments or offices, adapted to local climate conditions.

If geothermal HP systems were firstly developed for individual installations such as family houses, the trend is to see larger systems providing heat, cold and hot water to buildings complex, block of buildings at a very a large installed capacity to be able to answer the demand profile. The trend is moving from single geothermal probes to borehole heat exchanger fields of hundreds of boreholes with heat production starting from 50-kW up to several MW.

Large scale geothermal HP project in Ferney-Voltaire, France
In 2023 work has started on a shallow geothermal heating and cooling network, assisted by heat pumps, in Ferney-Voltaire in Ain, France, near the Geneva Airport. Celsius Energy, in partnership with Dalkia, will be working on the geothermal heating project. Celsius will drill 173 wells to depths of about 230 meters. Hot water maintained at the subsurface will supply the heat exchangers. A heat plant and several substations will distribute 20 GWh of heat and 6 GWh of cold. The system will be equipped with sensors, which will allow Celsius to have a digital twin for permanent monitoring with the operator.

3.1.3 Low temperature heating systems - 5th generation district heating and cooling

There is a major trend to reduce the temperature of district thermal networks. Urban heating is moving from traditional centralised high-temperature to lower temperature supply. Reducing the temperature of district thermal networks brings efficient, environmental-friendly and cost-effective community thermal supply. Decrease of the supply temperature level allows more efficient operation (e.g. less heat losses), better integration and greater variety of renewables/waste heat sources.

One trend is to renovate buildings and construct buildings complying with Energy Performance of Buildings Directive (EPBD). It brings systems with heating at low temperature for individual buildings, collective buildings, DH networks and some industrial process heat.

5th generation district heating and cooling (5GDHC) networks are an example of these low temperature heating systems: They are characterised by low temperature supply (i.e. close to ground temperature), bi-directional operation (i.e. it can provide heating and cooling simultaneously), decentralised energy flows (i.e. it allows multiple heat sources and heat sinks in the network), and heat sharing (i.e. it can

5th generation geothermal DH in Vridsløsemagle (Denmark) and Bad Nauheim (Germany)
The lighthouse project Vridsløsemagle (Denmark): local district heating company (Høje Taastrup Fjernvarme) converted a small village (110 users) with individual oil boilers to district heating with geothermal heat pumps connected to a thermonet with a centralized field with 23 shallow geothermal probes and a pumping station. The plan is for the district heating company to supply the households through individual heat pumps, connected to the thermonet via branch pipes. The expectation is from the termonet to be able to supply 585 kW, while the heating demand is estimated to 475 kW, which leaves 20 percent of the capacity as a buffer. Another example is the local heating network in Bad Nauheim (Germany): The Bad Nauheim municipal services supply the new Bad Nauheim Süd development area with an 5th generation heating system, using low transfer temperatures. A geothermal collector extracts heat from the ground at a depth of one and a half to three meters using an environmentally friendly carrier fluid. The low-temperature local heating network has a total length of around 64 kilometers. In the new buildings, highly efficient heat pumps increase the water supply temperature from around 10 degrees to 55 degrees for the domestic hot water and to 35 degrees for the underfloor heating. In summer, this system works in exactly the opposite way. Instead of heating, the buildings can be cooled naturally, thus eliminating the need for additional air conditioning units.

recover waste heat and share it with different users [39]). These features enable 5GDHC systems to be solely fuelled by RES. Geothermal resources at shallow depth typically supply heating at temperature below 30°C. They can be assisted by heat pumps and form an ideal source for 5GDHC networks.

3.1.4 New casing materials - Composite Downhole Tubulars for completion

New casing materials are developed with the aim of longer well lining lifetime, and easier to clean. Glass Reinforced Epoxy are field proven in geothermal environments replacing costly steel grades.

Huisman Geo received the European Geothermal Innovation Award 2023 with their project **Composite Downhole Tubulars.** The innovation of the project lies in the fact that no full composite downhole tubulars were available before its launch. Additionally, the HCT system carries unique features, such as a full composite pipe body and strong yet slender threaded connections. An exceptional application for which the product is used, is in injection wells for highly corrosive carbonized salt water into basaltic bedrock, to capture the CO_2. Notably, it was also developed and tested specifically for downhole applications. After years of development, the innovative Huisman Composite Tubulars are now successfully used in various applications such as geothermal, oil & gas, and carbon storage wells.

Similarly, the GRE-GEO[40] project has developed a cost-reducing glass-fiber reinforced epoxy piping that is especially designed for geothermal well application (GRE-GEO) with relatively large inside diameter and smaller outside diameter. This especially concerns the pipe coupling, which would allow an installation in new wells as well as utilization for workover of old wells. Furthermore, the project's results include the much-needed guidelines and tools for the design, qualification and installation of the GRE piping system.

3.1.5 New drilling, well designs and equipments

3.1.5.1 Sub-horizontal drilling designs

New drilling design for geothermal wells aims at improving the productivity of the system.

Five generations of deep drilling techniques for geothermal have been seen since the first development of geothermal power in 1913 and district heating, mainly after the 1960s. The trend has always been to allow cost reduction, while improving efficiency and reliability. The first generation saw two vertical wells drilled from two distant drill pads, while the second introduced deviated wells and single drill pads. The next generations were focused mainly on improving the design of deviated wells until deviated symmetric wells were developed.

The fifth generation proposed for the first time (sub) horizontal wells for deep geothermal pioneered in Cachan (South Paris Basin, France). This is, for example, the technology currently used in the Paris basin for new geothermal district heating systems.

In 2021, the sector has seen a new development with multi-drains. This innovative technology has been developed in Vélizy-Villacoublay, in the western Paris basin. The principle of the system is that the wellbore comprises three drains, enabling the productive levels to be tapped to a greater extent and maximising the volume drained naturally from the reservoir.

[39] Buffa et al. (2019), 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*, 104, https://doi.org/10.1016/j.rser.2018.12.059.
[40] Gre-Geo, https://www.gre-geo.org/about-gre-geo.

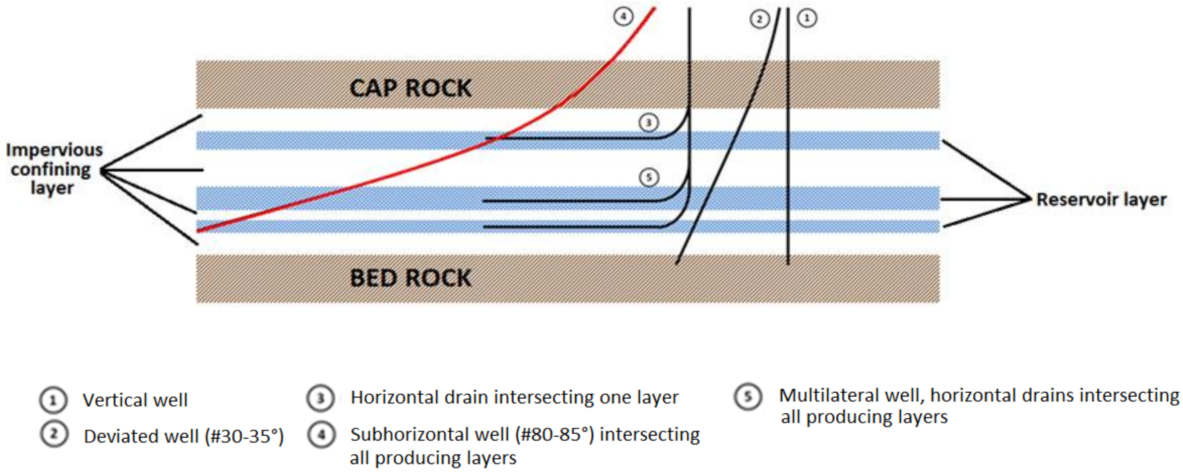

Figure 1: Subhorizontal well concept illustrating the 5 generations of well design (source Ungemach, Antics, GPC IP 2019)[41]

Sub-horizontal drilling design in Cachan, Paris
The Cachan geothermal plant in Paris employs a multi-well system to provide heating to the local district, showcasing efficient use of geothermal resources in urban settings. The project's success in Cachan, marks a significant advancement in geothermal technology, opening new possibilities for geothermal development in densely populated areas with moderate reservoir performance. On December 13th, 2017, the first subhorizontal geothermal well, designed and supervised by GPC IP, was completed for DALKIA (EDF Group). This well, a world premiere in geothermal engineering, features a 1,001-meter long, 87° slanted openhole drain in the Dogger/Bathonian oolithic limestone reservoir at a true vertical depth of 1,550 meters. This well, capable of a 450 m^3/hr nominal discharge and a 16 MWth rated capacity, was complemented by an injection well of similar design, forming a doublet that replaces two aging geothermal doublets from 34 years ago. The second doublet improved flow rates and heat production, providing at least 400 m^3/hr of hot water, compared to 300 m^3/hr from the old wells.

3.1.5.2 Multi wells drilling

New drilling technologies developed in the oil and gas sector could be replicated for geothermal: multi-well pad, new vertical drilling systems etc.

In top, project portfolio approach to drill a series of wells for one or several projects in the same area is both an innovative technique and an innovative business model to de-risk project.

The aim of drilling multi wells is to have larger installed capacity while decreasing costs by drilling development. In the Innargi project depicted below, it consists in 17 wells: 7 production wells & 10 injection wells.

[41] Antics et al. (2019), Subhorizontal Well Architecture Enhances Heat Production, The Cachan Milestone. European Geothermal Congress, http://europeangeothermalcongress.eu/wp-content/uploads/2019/07/339.pdf.

Multi wells by INNARGI in Aarhus
A new geothermal district heating plant is under construction in Aarhus, Denmark, poised to become the largest in the European Union. Directed by Innargi in collaboration with AffaldVarme Aarhus and Kredsløb, the project features a 31-meter tall drilling rig set to reach depths of 2.5 kilometers, with the first facility in Skejby expected to begin delivering heat by 2025. This plant represents a significant advancement in 5th Generation District Heating and Cooling (5GDHC), a demand-driven system that enables simultaneous heat and cooling exchange among customers while storing excess energy for future use. The innovative approach involves 17 wells and 7 installations equipped with heat exchangers and heat pumps to harness geothermal energy. Approximately 1,500 cubic meters of geothermal water, with surface temperatures of 75 °C, have already been extracted, showcasing the system's capability to provide a sustainable source of warmth for Aarhus residents. The plant is scheduled for completion by 2029.

3.1.5.3 Novel drilling equipments

Novel drilling technologies focus on new drilling bits, innovative control technologies during drilling and the combination of multiple drilling techniques to increase ROP.

TOMAX anti stick-slip tool AST mitigates stick-slip through regulating weight-on-bit (WOB) to maintain constant torque on the bit. Stick-slip is a major cause of down hole tool failures, bit damage and slow rate of penetration. As the bit engages the rock face any torque fluctuations will be managed by the AST. Excess torque causes the tool to contract along the internal helical splines. This contraction will decrease the weight on bit and prevent the onset of stick-slip. The system has been successfully demonstrated in the context of oil wells.

3.1.6 Larger ORC turbine

On average, current ORC turbine in operation have a capacity lower to 10 MWe. There is a trend to upscale this capacity. Binary turbine dominates the market in regions with low and medium temperature fields, but the trend is to install binary turbines also in high temperature fields, to allow better reinjection or to install air cooler instead of water cooling tower. Moreover, it improves reliability, availability and grid-balancing flexibility.

The application of binary turbines in high temperature fields leads to the installation larger ORC turbines. There are currently ambitions to develop advanced binary plants for geothermal exploitation at different temperature level.

3.1.7 District cooling

Cooling demand is still a niche market in comparison to the heat market (1%-99%), but the cooling market is a fast growing one. And as for district heating network, district cooling must be smart grid. A new type of demand is coming from data centres requesting large amounts of cooling.

Geothermal can supply cold via individual system and free cooling, through small scale cooling network supplying cold to a block of buildings, data centres, and with cooling network for a district or a city.

3.2 First demonstration – close to market

In this chapter, technologies close to market ready level, with first demonstration projects are highlighted. It can be expected to have these technologies on the market before 2030.

3.2.1 Medium and high temperature UTES

Underground thermal energy storage (UTES) involves the temporary storage of thermal energy in the subsurface. The technologies can be widely applied in energy infrastructures supplying sustainable and low carbon heat to industry, agriculture and district heating grids. Especially (district) heating networks with temperature ranges between 25 and below 100 ˚C are highly suitable. The main advantage of medium and high temperature UTES compared to low-temperature systems (< 25 °C) is that the heat that is retrieved can be used directly for heating purposes and is suitable for more applications without a heat pump. For industrial heating networks and networks with higher temperatures the technology could be applied in combination with heat pumps.

Technologies for which medium and high temperature storage is tested include:

- Aquifer Thermal Energy Storage (ATES): open systems consisting of at least one hot and one cold / luke warm well that target a fluid bearing aquifer formation in which heat/cold is stored
- Borehole Thermal Energy Storage (BTES): closed systems of wells that are arranged in a field of boreholes to store heat by conduction in a certain rock volume
- Mine Thermal Energy Storage (MTES): open system in existing water-filled mine shafts and drifts

The main objective of ongoing demonstration projects is to implement commercial projects, lowering the cost, reducing risks, improving the performance of these UTES (~25°C to 100°C) and to optimize heat network with demand side management (DSM).

Demonstration of UTES is currently ongoing in the PUSH-IT project, with aquifer thermal storage being demonstrated in Delft (NL) and Berlin (DE), borehole thermal storage in Darmstadt (DE) and Litomerice (CZ), and mine thermal storage in Bochum (DE) and Cornwall (UK).

In the following, already operating projects are highlighted for each technology.

ATES in Middenmeer, The Netherlands
In 2021, the first full scale high-temperature aquifer thermal energy storage (HT-ATES) system became operational in Middenmeer, the Netherlands. Agriport A7 is a large-scale greenhouse area. The local energy company ECW provides geothermal heat (92ºC, from 2 km depth) to the greenhouses through a heating network. The geothermal systems have significant overcapacity in the summer period while in winter they can provide only ~25% of the heat demand, resulting in a strong dependence on fossil fuels. ECW has built a full-scale High Temperature Aquifer Thermal Energy Storage (HT-ATES) system, which facilitates the large-scale storage of surplus heat (overcapacity in summer) and its recovery in winter time. Heat is stored in an unconsolidated sand aquifer at nearly 400 m depth, with a maximum flow rate of 150 m^3/h. Each summer, up to 28,000 MWh of thermal energy (>100.000 GJ) can be stored, the bulk of which is recovered in winter. Risks identified in former small-scale HT-ATES pilot-projects were investigated within the GEOTHERMICA HEATSTORE project, and the results contribute to the quality of the full-scale HT-ATES system. The test drilling performed in 2019 has offered a detailed image of the subsurface properties and the risks associated with it. A highly detailed system was designed, and successfully installed. Clogging risks are tackled by a special CO_2 dosing unit and groundwater will be monitored on chemical and microbial changes.

BTES fields in Köping, Sweden

Volvo's Powertrain plant in Köping is the largest BTES system in Sweden. Volvo invested in geothermal cooling and heating system to reduce energy consumption. It also wanted to improve comfortable working environment for its employees, of whom around 1,850 work at the five factory complex. The first storage unit with 125 boreholes was commissioned in 2014. Volvo invested € 5 million in the system that was expected to reduce electricity and heating use by 5,000 MWh per year, equivalent to the annual energy consumption of around 300 homes with district heating. The system has continuously been expanded and today comprises a total of 215 boreholes with an average depth of 270 m. This adds up to a total borehole length of 58 km.

The challenge of great space cooling needs on the one hand and great heating needs on the other is typical for a factory. UTES is a solution that can both balance and capitalise on the different needs. The system is used for cooling the buildings in summer, storing warmth from this process in the boreholes, and reutilising it for heating in winter. In early 2023, the latest geothermal storage was added to the system. It comprises 60 boreholes for the cooling of a new factory section. For the first time, a heat pump was connected to the thermal storage to additionally provide domestic hot water. Overall, borehole storage in Köping has been proven to be both stable and flexible.

MTES Mijnwater-project in Heerlen, Netherlands

An already completely flooded and no longer accessible mine layout was accessed through directional drilling technology in Heerlen, the Netherlands..

From 2003-2008, a pilot project was developed with the support of the European Interreg IIIB NWE programme and the EC-REMINING-lowex project. The pilot included two hot wells in the northern part of Heerlen, which reached depths of 700 metres below the surface to extract hot water, and a temperature of about 28°C. On the other side of town, two 250m-deep cold wells were created for the extraction of cold mine water with a temperature of about 16°C. A fifth well was used to inject the used cooled-down warm water and the used warmed-up cold water (18-24°C) back into the system.

At the pilot stage, the system provided both heat in winter and cooling in summer to two buildings: the Central Bureau of Statistics (22,000 m^2 large), and the Heerlerheide Centrum, a complex with shops, office and apartments (about 30,000 m^2). This relatively easy system also comprised a bivalent energy station with heat pumps for base loads, and gas boilers and chillers for peaks.

Once the pilot proved that it was possible to use mine water for district heating, the municipality decided to expand the system. However, up to the point, the system used mine water purely as an energy source, with limited capacity for further expansion. To avoid overusing the heating source, while still scaling up the system, the project opted to investigate using mine water for energy storage instead of as an energy source. Accordingly, starting in 2013, the process was changed quite significantly so that mine water was heated up (for heat storage) and cooled down (for cold storage) before being pumped back into the ground via bi-direction wells.

The upgraded 2nd stage of the Mijnwater project provided heat for 200,000 m^2 of building equivalents in four connected cluster grids. For example, in 2017/18 the grid delivered 5.1 GWh/a of heating, and 5.2 GWh/a of cooling, with an electricity input of 2.3 GWh/a.

High Enthalpy Aquifer Technology (HEAT) in Tromsø, Norway

In UTES, another trend is to develop technology with high temperature storage above 100°C. A first attempt is done in Tromsø (Norway) injecting residual heat at 120 °C from a waste incinerator. An underground fracture system is established between injector(s) and producer(s) to maximize contact area between circulating water and bedrock. 11 wells reaching 300 m depths are foreseen for the project in order to store at least 10 GWh. HEAT has the potential to become the largest heat storage option and be an integrated part of the energy system in large parts of Europe.

3.2.2 Single well

Deep closed loop technologies embrace several applications to develop technologies for heat extraction solutions that rely entirely upon fluids circulating within deep boreholes.

Among these technologies currently developed are closed single well systems: deep borehole heat exchanger (DBHE), fully closed U-shaped systems, or (semi-)open single well systems. These technologies can also bring solutions for non-productive geothermal wells or repurposing oil & gas wells.

The concepts are at different TRL levels. DBHEs are being used as a source for district heating at a few locations (see Info-box on Eden project). The thermal output strongly depends on the design and completion of the well. In case of an existing (repurposed) well, the design and completion may not be optimal, but the lower energetic performance may be compensated by lower investment costs.

The (semi-)open single well system is being used as low temperature heat source in combination with heat pumps at a few locations in Switzerland.

The closed, U-shaped system (Eavor LIte™) is currently being tested at Rocky Mountain House in Alberta, Canada. Two deep vertical boreholes, an injection and a production well, connected by a horizontal borehole at depth and an insulated pipeline at the surface, establish an effective closed-loop system. New concepts of drilling and completing long (semi-) horizontal wells and wand small diameter laterals are being developed and tested by several companies.

Single well project at Eden (UK)

The geothermal system of the Eden project uses a vacuum insulated tube (VIT) inserted to a depth of 4,000 meters. Hot water is pumped to the surface using a submersible pump and passes through a heat exchanger, delivering heat at 85°C. The cooled water is then recirculated to be reheated, in a continuous coaxial system. This £22 million project has been made possible through funding from the European Union, Cornwall Council, and Gravis Capital Management. Drilling of the deep geothermal well, EG-1, began in May 2021 and reached completion in October of the same year. The well extends to a vertical depth of 4,871 m, with a total length of 5,277 m.

The implementation of a single well heat exchanger and a 3.8km heat main has been a critical component of the project. This system links the geothermal site with the Eden Project's heat loads, ensuring efficient heat distribution. The heat main consists of two steel pipes, heavily insulated, that transport hot water to and from the geothermal plant. At the Eden Energy Centre, plate heat exchangers extract the heat for use in Eden's heating circuits.

3.2.3 Deep closed loops of multilateral well systems

A second innovation of deep closed loop technologies are closed multilateral well systems.

Equally to the DBHE or U-shaped systems, these closed-loop solutions primarily aim to extract heat through heat conduction at the borehole-rock interface. Multilaterals increase the volume of rock that is harvested for heat, owing to the slowness of conductive heat transfer. High drilling costs per meter are reduced since the fixed costs (vertical wells, access, land, etc.) are spread over more energy-mining laterals.

A fluid circulates within the closed loop, heating up as it travels through the depths of the earth. Thanks to the significant temperature difference between the subsurface and the surface, the heated fluid naturally rises, requiring no additional energy input. Once at the surface, the heat can be directly fed into the district heating network or converted into electricity. The cooled fluid then descends back through the second vertical pipe to be reheated, creating a continuous and efficient cycle. This innovative approach offers several advantages over traditional geothermal systems. It eliminates the need for thermal water extraction and reinjection, thus minimizing the risk of seismic activity and environmental impact.

This technology is supposed to allow unlocking of vast geothermal resources that are stored in impermeable deeply buried, compact sediments and hot crystalline rock which otherwise remain largely unexploited.

Eavor-Loop™ project in Geretsried, Germany

In the town of Geretsried, the Eavor-Loop™ project is set to supply the region with district heating and significant electrical energy. The Eavor-Loop™ is a closed-loop geothermal system that operates like a vast underground heat exchanger. It consists of two vertical boreholes connected by 24 horizontal boreholes at depths of 4,500 to 5,000 meters, forming 12 loops in total.

In Geretsried, the Eaver Loop™ is aiming at producing 8,2 MW electric power and 64 MW thermal output, leading to a total CO_2 reduction of 44.000 t per year. In March 2023, the company announce a drilling progress of 7000 m, while the construction of the powerplant is in progress at the same time.

3.2.4 Cooling for industrial purposes

Every summer several EU cities are already experiencing problems linked to the overload of the electricity grids due to the widespread use of inefficient cooling devices at building and industry (including data centres) levels. In this context, geothermal (free and active) cooling technologies represent a solution which is renewable, efficient and cost-competitive and can cool even intense sources of heat. Data centres are gluttons for energy, requiring an immense amount of power not only to generate the computers, but also to cool them down.

Renewable cooling in data centre in Strasbourg, France
Geothermal solutions to cool the data centre in the University of Strasbourg: Two geothermal doublets (2 boreholes + 2 discharges) ensure that the facilities continue to operate. Free cooling is based on the direct use of the subsoil as a source of coolness, without the need for a heat pump, and provides exceptional energy efficiency, reaching levels of 50/1, i.e. 50 kWh of cold production for 1 kWh of electricity.

Renewable cooling in data centre in Bergamo, Italy
Renewable cooling in the new Euronext data centre in Bergamo: In 2022 Euronext, the pan-European market infrastructure, has completed the migration of its Core Data Centre and related services to the Aruba Global Cloud Data Centre IT3 in Bergamo, Italy. In the new Euronext Data Centre, the cooling system uses ground water extracted from redundant wells and sent to redundant heat exchangers. The piping system serving each data room is made with 4 lines with a quarter of the total Computer Room Air Handler (CRAH) connected to each line. Using groundwater as the main cooling energy source enables Euronext data centre to reduce energy waste. The main advantage is having a constant temperature of the water which, at groundwater level, remains at around 9°C all year round.

3.2.5 Co-production of critical raw materials

Some geothermal fluids are known to carry significant amounts of critical raw materials, such as Lithium. Recently, several projects have started with the objective to develop novel and potentially disruptive technological solutions of raw material extraction from geothermal fluids, that can help satisfy the European needs for energy and strategic metals and other economic non-metallic materials. Geothermal plants may optimize the production of both energy and metals/materials in a single interlinked process according to the market demands, exploiting deep geological formations. By exploiting mineral production, geothermal plants will also become more economically competitive, create new market and supply chain opportunities, and reduce their impact with a circular economy approach.

Specifically, regarding lithium, geothermal plants will also contribute to the reduction of the environmental footprint of lithium production compared to standard extraction methods (like hard rock and evaporation pond mining) which are significantly more harmful to the environment and CO_2 intensive than geothermal lithium.

Co-production of lithium in Landau, Germany and Cornwall, UK
Vulcan Energy Resources has successfully started the production of climate-neutral lithium chloride at its plant in Landau, Germany, in April 2024. In February 2023, the company published the results of a feasibility study for the first phase of its lithium project. Vulcan plans to initially produce 24,000 tons of lithium hydroxide monohydrate per year, which will be achieved through a multi-stage process from lithium chloride. The LEOP ("Lithium Extraction Optimization Plant") in Landau has been operational since August 2023. It is used for product qualification, optimization, and training of the operating team for subsequent commercial production. The LEOP follows from Vulcan's pilot plants in Insheim, which have extracted lithium chloride from Vulcan Energy's producing drill sites over the past three years. The application of Direct Lithium Extraction by Adsorption has enabled efficiencies of over 90 percent in the extraction of lithium from geothermal brine, the company reports. Cornish Lithium Ltd. is piloting lithium extraction from geothermal water at the site in United Downs, Cornwall. Cornish Lithium began drilling in November 2019, completing two diamond boreholes to approximately 1 km each. Cornish Lithium used a bespoke sampling method which isolated individual permeable structures at depth, and proved that they contained lithium-enriched geothermal waters. Direct Lithium Extraction technologies were tested on site to evaluate the best extraction technology for the low-saline, lithium-rich water that is produced from the pilot wells.

4 Conclusions

The main innovations trends reflect the large interest of the society for geothermal energy.

A wide range of technologies and research projects aim at more cost efficient and secure provision of heat, and unlocking geothermal resources in more divers geological settings.

Innovation trends also show the opening of the geothermal market for wider applications, with underground thermal storage as a key technology for the heat transition and co-production of critical minerals as a major opportunity to increase the returns on investment for geothermal plants while contributing at the same time to the goals of Europe's Critical Raw Material Act.

Finally, research projects are aiming at the application of the ever increasing digital and computational methods for the optimising of geothermal exploration, resource assessment, resource development and operation and monitoring of geothermal systems.

The multitude of trends in research and innovation stemming from European or national R&I projects also shows very clearly, how European and national funding instruments impact the technology development and ensure that technologies pass the valley of death. In many cases, European cooperation has been instrumental in ensuring the piloting and demonstration of novel methods and concepts.

References

- Antics et al. (2019), Subhorizontal Well Architecture Enhances Heat Production, The Cachan Milestone. *European Geothermal Congress*, http://europeangeothermalcongress.eu/wp-content/uploads/2019/07/339.pdf.
- Berktas et al. (2020), Synergistic Effect of Expanded Graphite-Silane Functionalized Silica as a Hybrid Additive in Improving the Thermal Conductivity of Cementitious Grouts with Controllable Water Uptake,*Energies*, *13*(14), 3561; https://doi.org/10.3390/en13143561.
- Brown, D., A Hot dry rock geothermal energy concept utilizing supercritical CO2 instead of water, Proceedings of the 25th Workshop on Geothermal Reservoir Engineering, SGP-TR-165, Stanford, California, 2000.
- Buffa et al. (2019), 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*, 104, https://doi.org/10.1016/j.rser.2018.12.059
- Gerbaud, L., Jahangir, E., Velmurugan, N., Sellami, H., & Cazenave, F. (2023), Enhancing drilling performance of mud hammers by combining high pressure water jets slotting. In ARMA US Rock Mechanics/Geomechanics Symposium (pp. ARMA-2023). ARMA
- IEAGHG (2023), Prospective integration of Geothermal Energy with Carbon Capture and Storage (CCS), 2023-02+Prospective+Integration+of+Geothermal+Energy+with+Carbon+Capture+and+Storage.pdf.
- Mainar-Toledo, M. D. et al. (2023), Environmental benefits for a geothermal power plant with CO2 reinjection: case study of the Kizildere 3 U1 geothermal power plant, Energy Storage and Saving, Vol. 2 Issue 4, https://doi.org/10.1016/j.enss.2023.08.005.
- J. Moraga, H.S. Duzgun, M. Cavur, H. Soydan (2002), The Geothermal Artificial Intelligence for geothermal exploration, 1867408.
- D Obidegwu, R Chassagne, C MacBeth (2017), Seismic assisted history matching using binary maps, Journal of Natural Gas Science and Engineering 42, 69-84, Seismic assisted history matching using binary maps.
- Randolph, J. B., Saar, M. O. (2011), Combining geothermal energy capture with geologic carbon dioxide sequestration, Geophysical Research Letters, Vol 38, Combining geothermal energy capture with geologic carbon dioxide sequestration - Randolph - 2011 - Geophysical Research Letters - Wiley Online Library.

Projects

- BedrettoLab, Bedretto Underground Laboratory for Geosciences and Geoenergieshttps://bedrettolab.ethz.ch/en/home/ .
- CEEGS, Novel CO2-based electrothermal energy and geological storage system, https://ceegsproject.eu/.
- CHPM2030, CHPM2030 project, https://www.chpm2030.eu/.
- CORDIS, Geothermal exploration and optimization through forward modelling and resource development, https://cordis.europa.eu/project/id/101147618.
- CORDIS, Sustainable and affordable Urban Geothermal Exploration Novel Technologies and workflows, https://cordis.europa.eu/project/id/101147467.
- CORDIS, Advanced Materials and processes to improve performance and cost-efficiency of Shallow Geothermal systems and Underground Thermal Storage, https://cordis.europa.eu/project/id/727583.
- CRM geothermal, Raw materials from geothermal fluids, https://crm-geothermal.eu/ .

- Crowdthermal, Development schemes for geothermal energy, https://www.crowdthermalproject.eu/.
- DECOVALEX, Development of Coupled models and their Validation and their experiments, https://decovalex.org/.
- DeepU, Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation, https://www.deepu.eu .
- Enargus, THC-Prognos, https://www.enargus.de/search/?q=THC-Prognos.
- GECO, lower emissions from geothermal power generation by capturing them for either reuse or storage, https://geco-h2020.eu.
- Geo-Coat, Geo-coat project, https://www.geo-coat.eu/ .
- Geohex, Geohex project, https://www.geohexproject.eu .
- Geothermica Initiative, Deeplight, https://www.geothermica.eu/project/deeplight, https://deeplight-project.eu/
- Geo4Civic, https://geo4civhic.eu/cheap-gshp/.
- Gre-Geo, https://www.gre-geo.org/about-gre-geo.
- KIT, GeoLaB - Research lab geothermal energy, https://www.geolab.kit.edu/english/.
- Licorne, Building up strategic reserves of Lithium to ensure the green and digital transformation of the European economy, https://www.licorne-project.eu/ .
- MALEG, The MALEG project, https://maleg.eu/project/.
- OptiDrill, OptiDrill: optimisation of geothermal drilling operation with Machine learning, https://www.optidrill.eu/.
- Orchyd, Novel drilling technology combining hydro-jet and percussion for ROP improvement in deep geothermal drilling, https://www.orchyd.eu/ .
- Push it, Piloting underground storage of heat in geothermal reservoirs, https://www.push-it-thermalstorage.eu/.
- Reaktoro, https://reaktoro.org/index.html.
- Reflect, Redefining geothermal fluid properties at extreme conditions, https://www.reflect-h2020.eu; https://www.reflect-h2020.eu/wp-content/uploads/2022/01/d4.2_reflect.pdf.
- TNO, GEMINI: intelligent decision support system for geothermal assets, https://www.tno.nl/en/newsroom/insights/2023/11/intelligent-support-system-geothermal/.
- USGS, PHREEQC Version3, https://www.usgs.gov/software/phreeqc-version-3.