The potential of next-generation geothermal for heating in Europe

Standpoint by Future Cleantech Architects

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Introduction

Geothermal is a renewable form of energy generation that works by drilling into the earth to extract heat which is naturally present underground, keeping the surface footprint low. Depending on its temperature, this heat can be used either directly, such as heating a building or an industrial process, or it can be used in a power plant to produce electricity.

The temperature of the heat is determined by depth: the deeper the drilling, the higher the temperature of the rock, which directly translates to both more raw energy available and higher efficiencies of power generation. On average globally, temperature rises by around 30°C per kilometer of depth, with significant variation depending on location. In the best locations, high temperatures are accessible at shallow depths, but geothermal energy is in principle available everywhere as long as sufficiently deep drilling is technoeconomically viable. In fact, at around 7 km of depth, the usable energy contained in a 400 m thick layer of rock at around 250°C is comparable to that in a shale oil deposit[1].

Europe can harness geothermal energy to enhance energy security and provide flexible, carbon-free energy to support the decarbonization of our economies, both for direct heating and electricity generation. Notably, the IEA estimates that Europe has nearly 40 TW of technical potential for enhanced geothermal power generation below 300 USD/MWh, which is equivalent to 35 times Europe's current total installed electricity capacity of all types. Geothermal potential is particularly high in France, Italy, and Central Europe, Member States with significant industrial activity requiring clean energy to decarbonize their industries. This technical brief provides an overview of the new geothermal technologies, with a focus on the potential in Europe for direct heating applications.

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[1] Technical details of this comparison:
Oil: Deposit thickness 100 m, rock density 2600 kg/m^3, total organic carbon (TOC) 4wt%, hydrocarbon to carbon ratio 1.25, transformation ratio (TR) 40%, retained fraction 60%, oil density 850 kg/m^3, extraction rate 15%, energy density crude oil 37.75 MJ/L, electricity conversion efficiency 60%. Calculation: 100m * 2600 kg/m^3 *4% *1.25 *40% *60% /(850kg/m^3) *15% * 37.75 MJ/L *60% = 3.46 TWh / km^2
Geothermal: Fracture network height 400 m, granite heat capacity 0.79J/(g.K), granite density 2630 kg/m^3, ambient temperature 20°C, depth 7 km, thermal gradient 35°C/km, temperature 245°C, heat engine efficiency vs. Carnot efficiency 80%, total temperature reduction 45 K, conservative linear approximation over depth and temperature range. Calculation: 400m *0.79J/(g.K) *2630kg/m^3 *(245K+273.15K-(200K+273.15K)) *((1-(30K+273.15K)/(245K+273.15K))+(1-(30K+273.15K)/(200K+273.15K)))/2 *80% = 3.22 TWh / km^2

Geothermal for heating

Types of geothermal[2]

Conventional geothermal, more specifically known as hydrothermal, started about a century ago in Italy. It requires three conditions: heat in the ground at a depth reachable by drilling; the presence of water in the ground to pick up the heat; sufficiently porous rock such that the water can flow through the rock. This specific set of geological conditions is limited to only a few areas globally, most notably Iceland, and will therefore never scale to meet a noticeable fraction of global energy demand, despite being a fully commercially mature technology. In 2022, only 0.1 GW of new geothermal power generation capacity was added worldwide.

Next-generation geothermal technologies seek to overcome these limitations by artificially creating the conditions for geothermal energy generation (see Fig. 1), such that only the prerequisite of heat remains. This drastically unlocks and expands the resource potential globally: the IEA estimates that the global technical potential of next-generation geothermal below an LCOE of 300 USD/MWh exceeds that of conventional geothermal by a factor of 2000 (specifically enhanced geothermal, see below).

Enhanced geothermal systems (EGS) borrow from the extensive experience of the shale oil and gas industry in the United States: they use horizontal drilling and a variant of hydraulic fracturing (fracking) to artificially create fractures in the rock; water can then be injected in one well and circulate through the cracks in the rock, picking up heat, until it reaches an extraction well that returns it to the surface for heat transfer or power conversion. The main benefit of creating a fracture system is that these cracks provide a large surface area for the water to efficiently and cost-effectively pick up the heat present in the rock.

By contrast to the shale industry however, EGS requires fewer and different additives to fracture rocks, among other reasons because the focus lies on leveraging pre-existing faults in the rock. Additives used to reduce friction and protect equipment can also be found in the biomedical industry (e.g. drug delivery polymers, disinfectant, surfactants), but it is also frequently possible to only use water and sand. In addition, the field has learned much from the fracking industry's history, following specially designed protocols from the US Department of Energy to mitigate the risk of induced seismicity.

By borrowing from the shale industry, EGS has progressed very quickly and is currently around TRL 6-7 according to the IEA (although some startups are probably already at TRL 8; see the overview

[2] Usually in the context of power generation but these apply to heating as well.

in Table 1). The existence of a workforce trained in these techniques, as well as a supply chain for the equipment involved, are significant boosts. The US Department of Energy is a strong supporter, with an Enhanced Geothermal Earthshot initiative that aims to reduce the cost of EGS by 90% to 45 USD/MWh by 2035 for power generation.

By contrast with EGS, closed-loop systems (also known as advanced geothermal) do not involve any fracking, which fully allays residual concerns on seismicity. However, this relies on more drilling to get enough area for the circulating fluid to pick up heat from the rock. Accordingly, the technology is slightly less mature, around TRL 5-6 according to the IEA, and likely to cost more.

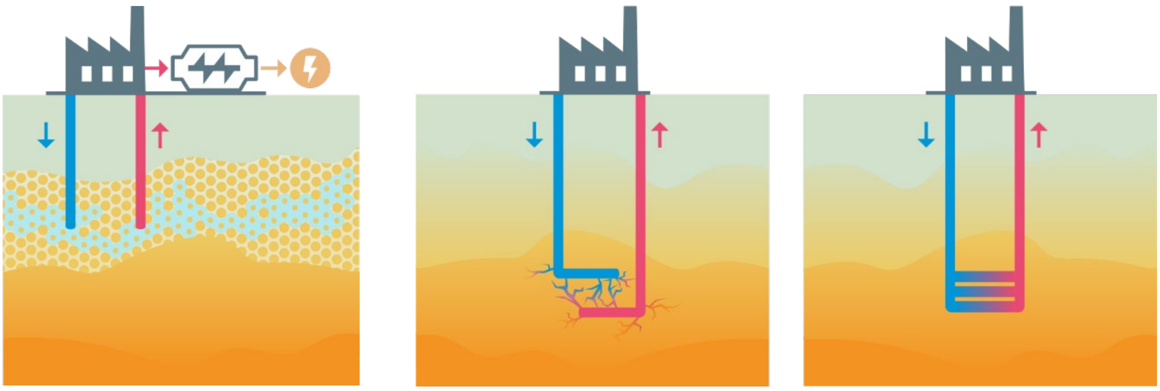

Figure 1: Diagram of the various types of geothermal systems for electricity generation, from left to right: conventional hydrothermal, enhanced geothermal systems, closed-loop. All can be used for power generation or direct heating applications.

Note on scope: this report does not explicitly cover technologies such as ground-source heat pumps which concern shallow depths; the focus is solely on the extraction and direct use of heat from underground. However, there is significant overlap between these two approaches, with the main difference typically being depth (i.e. temperature); ground-source heat pumps can operate at much shallower depths (up to 500 m) since they then efficiently boost the temperature of the heat extracted by using electricity.

Uses cases for geothermal heating

The lowest-temperature application of geothermal is for heating of buildings and water. This can be implemented through district heating networks or via individual building heating, but the latter is more typically done through ground-source heat pumps rather than direct use of the geothermal heat. The scale of geothermal direct heating projects (in terms of drilling and capital investment) typically makes them better suited for large installations such as district heating networks.

Geothermal can also be used to provide heat to industry, which spans a much wider range of temperatures (for example in Fig. 2). This therefore involves drilling deeper to reach higher temperatures. Overall, geothermal's contribution will be limited to the lower-temperature side of industrial heat demand (around 200°C, up to 400°C when ultra-deep drilling matures); nevertheless, this is still a significant market, with process heating demand below 200°C making up 37% of the total for industry in Europe today.

Note that for all of these applications, geothermal is far from the only clean technology available. Heat pumps and e-boilers are the most notable other technologies and FCA strongly supports their deployment, including for industrial heat (heat pumps especially are endowed with much higher efficiency, although they will target lower temperatures, up to around 200°C).

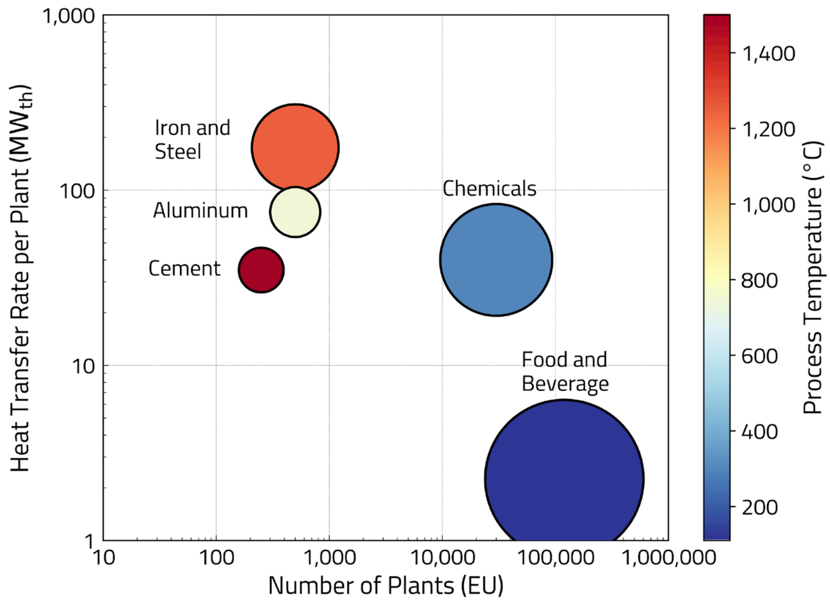

Figure 2: Number and size of industrial plants in the EU for various sectors; geothermal heating could serve the low-temperature sectors. NB: the size of the bubble represents uncertainty in the data. Source: FCA analysis

Infobox: geothermal for electricity generation[3]
If the temperatures are high enough, geothermal heat can also be used in a power plant at the surface to generate clean electricity to be sent to the grid or directly to a dedicated customer. This is the main application of conventional geothermal energy plants today. These can be run as baseload (i.e. near-constant operation at a high capacity factor, typically around 80% for geothermal) or with more flexibility in ramping up and down depending on hourly prices on the grid. This flexibility (also known as dispatchability) is particularly valuable for grids with ever higher penetrations of variable wind and solar, since geothermal could complement these sources at times when they are not available, rather than directly competing with them when they are abundant. Geothermal power generation is attracting considerable private interest, with multiple startups progressing fast (see Table 1). The demand for clean power from hyperscalers in the race to build data centers is boosting this development globally, with several offtake agreements already signed totaling hundreds of MW in the development pipeline (Meta will buy 150 MW_e from Sage Geosystems, Google will buy 115 MW_e from Fervo). Project InnerSpace and the IEA estimate that Europe has nearly 40 TW of technical potential for EGS up to 8 km deep, accessible at costs below 300 USD/MWh; this is equivalent to 35 times Europe's current total installed electricity capacity of all types. At less than 2 km, the potential is very limited; most of it is in the 5-8 km range.

Potential in Europe

Resource in Europe

Geothermal potential is relatively spread across the EU, with "hot spots" in France, Italy, and parts of Central Europe. The map in Fig. 3 illustrates this, although the reality is more complex, with the geothermal resource being a function not only of location but also the state of the art in terms of

[3] Geothermal sometimes has other co-benefits such as the potential to co-extract valuable resources like lithium from geothermal brines in the Rhine valley on the border between Germany and France.

drilling technology. If the latter improves, both technologically and in terms of cost, then developers can drill deeper and therefore hotter, thus opening up more suitable regions across Europe. As result, the landscape of the technoeconomically feasible resource is evolving over time.

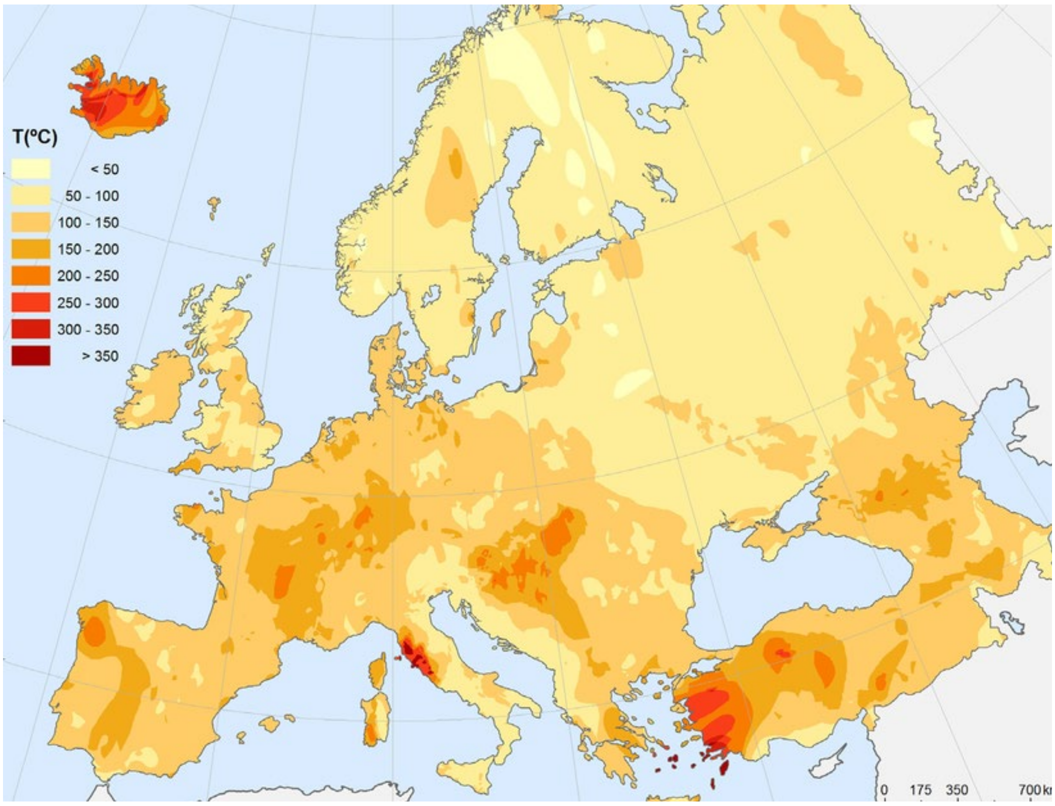

Figure 3: Calculated temperatures at 4.5 km depth across Europe (for illustrative purposes i.e. where the "best" resource is). Source: Chamorro 2014

Improvements

Some of the technology improvements in geothermal come from enhancing the efficiency of heat extraction from underground, either with different well lining materials or different working fluids circulating in the rock. However, most of the current and future improvements center around better drilling technology, usually drilling faster and/or autonomously, since this is one of the main cost drivers of projects (drilling time is responsible for 75% of total well cost). Encouragingly, the learning rates for geothermal seem to be high, up to 35% in the case of Fervo's EGS wells. This is partly thanks to the geothermal sector piggybacking off of knowledge transfer from the fossil fuel sector: for every dollar invested in geothermal, 65-80% has a significant overlap with the skills and expertise of the oil and gas industry. With no plateau in sight yet, geothermal still has much room for improvement.

For ultra-deep drilling (say beyond 5 km) to reach high temperatures (450°C), highly innovative methods are actively being investigated, such as high-pulsed-power drilling, thermal-shock drilling, millimeter-wave laser drilling, percussive drilling, high-pressure water jet drilling, directional steel-shot drilling, and plasma drilling.

Table 1: Leading companies in next-generation geothermal (non-exhaustive overview).

Company	Origin	Purpose	Technology
Borobotics	Europe	Heating	Compact autonomous drilling robot for shallow depths for ground-source heat pumps
Dig Energy	US	Heating	Compact water-jet drilling rig
Innovia Geo	US	Heating	Shallow drilling
Bedrock Energy	US	Heating	Ground-source heat pumps
Dandelion Energy	US	Heating	Ground-source heat pumps
Canopus Drilling Solutions	Europe	Heat & power	Directional steel shot drilling
Eavor	Canada	Heat & power	Closed-loop geothermal
Eden Geopower	US	Heat & power	Electrical reservoir stimulation to enhance permeability
XGS Energy	US	Heat & power	Closed-loop geothermal, pipe-in-pipe heat exchanger
Zanskar	US	Heat & power	AI & geoscience-enabled exploration
Fervo Energy	US	Power	Enhanced geothermal
Sage Geosystems	US	Power	Enhanced geothermal and subsurface energy storage
GeoX Energy	US	Power	Superhot rock geothermal
Mazam Energy/AltaRock	US	Power	Superhot rock enhanced geothermal
Rodatherm	US	Power	Closed-loop
Factor2 Energy	Europe	Power	CO_2 geothermal working fluid
Quaise	US	Power	Millimeter wave drilling
GA Drilling	Europe	Power	Advanced drilling

Finally, an important and beneficial characteristic of the geothermal heating sector is its gradual nature, as opposed to one with sharp thresholds: the deeper we drill, the higher the temperature, which unlocks progressively better performance and new target applications. This allows geothermal as a sector to grow organically, where it progresses to ever larger markets in a smooth way and spurs itself on in a virtuous cycle.

Policy recommendations

The EU and Member States have several policy tools at their disposal to encourage the development of next-generation geothermal.

- **Expand and diversify energy supply:** make building next-generation geothermal plants a priority (e.g. streamlining permitting; granting projects status under PCI "project of common interest").
- **Characterize the resource:** high-quality public data characterizing geothermal resources across Europe (i.e. geological maps of temperature and depth) can help to reduce exploration cost uncertainty, thus derisking more projects and lowering the barrier to entry for new players in the industry. Supporting a centralized EU geothermal database and mapping with open access, like the GeoMap initiative of Project InnerSpace, would benefit the whole sector.
- **Foster social acceptability:** communicate and get local communities involved in projects; highlight successful geothermal projects; share profits and benefits; mitigate seismic risks from drilling where they might exist. This will help accelerate the permitting process.
- **Transition from fossil to geothermal:** compared to wind and solar, fossil fuel companies (specifically the services companies, including European ones) have many key assets required for geothermal such as drilling technology and workflows, capital, and trained labor. According to the EU's Joint Research Centre report on geothermal, the EU is underrepresented in drilling services, but has a strong manufacturing base for above- and below-ground equipment.

- **Attractive financing:** geothermal is a CAPEX-heavy technology, so the cost of financing has a major impact on the levelized cost of electricity (LCOE). Derisking mechanisms like public guarantees can also help lower perceived financial risks by investors, especially for early-stage projects.
- **Support further R&D** for deep drilling techniques and testing innovative technologies, since faster, cheaper, and deeper drilling is key to unlocking higher temperatures and lower costs.
- **Start here, then export globally:** this is a technology with global potential. Not only does this increase the spill-over impact for emissions reductions, it also represents an economic opportunity as a technology export, if Europe catches up to the US, who are currently leading.
- **Include geothermal** as a core component of upcoming clean energy strategies, whether for direct heating or for electricity generation.

As a clean, safe, and reliable energy source, geothermal is worth pursuing as part of Europe's heating plans. Geothermal has a high potential for scaling up (both technically and economically), with a significant addressable market spanning district heating and industry.

About

Future Cleantech Architects is a climate innovation think tank dedicated to closing the innovation gaps in hard-to-abate sectors through research and development, and policy and advocacy. To this end, our experts conduct comprehensive, science-based analyses and modelling of these sectors and drive high-level research consortia on critical technologies. We advocate for policymakers to prioritize and incentivize research and development to accelerate technological solutions for transitioning to a sustainable net-zero future.

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