ISSN 1831-9424

European Commission

CLEAN ENERGY TECHNOLOGY OBSERVATORY

DEEP GEOTHERMAL HEAT AND POWER IN THE EUROPEAN UNION

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS & MARKETS

2023

Joint Research Centre

EUR 31702 EN

Contact information:
Name: Nigel Taylor
Address: European Commission Joint research Centre, Ispra, Italy
Email: nigel.taylor@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC135206

EUR 31702 EN

PDF ISBN 978-92-68-08432-8 ISSN 1831-9424 doi:10.2760/545601 KJ-NA-31-702-EN-N

Luxembourg: Publications Office of the European Union, 2023

How to cite this report: Taylor, N., Diaz Rincon, A., Georgakaki, A., Ince, E., Letout, S., Mountraki, A., Shtjefni, D. and Tattini, J., Clean Energy Technology Observatory: Deep Geothermal Heat and Power in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/545601, JRC135206.

Contents

Abstract

This report takes a closer look at the status of deep geothermal energy in the EU, with a focus on power and direct heat applications. The market for deep geothermal energy is growing globally and, while the EU is underrepresented in drilling services, it has a strong manufacturing base for both above- and below-ground equipment. Despite the potential for this technology, it still faces challenges, such as high upfront costs, limited subsurface data availability, and licensing issues. Geothermal operations also have varying environmental impacts and may affect public acceptance. However, deep geothermal energy has a high potential to supply the EU's district heating and cooling sector. SWOT analysis shows promising opportunities for geothermal energy, including emerging technology for higher temperatures and efficiency, and recovery of critical materials from geothermal brines.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

Acknowledgements

The authors are very grateful for the review and other contributions received from Luca Giovannelli (DG RTD.C.1) and from the JRC Editorial Board reviewer.

Particular thanks to the European Geothermal Energy Council and its general secretary Philippe Dumas for the information provided.

We also thank the other members of the JRC.C. 6 POTEnCIA and POLES-JRC teams: R. Salvucci, J. Gea Bermudez, M. Jaxa-Rozen, A. Schmitz and B. Schade. Thanks also to Giulia Serra and Pablo Riesgo Abeledo (DG ENER.B5) and to Thomas Schleker (DG RTD.C.1) for coordination, support and comments. We also acknowledge the support of the JRC.T.5 Technology Innovation Monitoring service for bibliometrics, provided by colleagues Marcelina Grabowski and Olivier Eurlarts.

Authors

Taylor N,	JRC.C.2
Diaz Rincon, A.	JRC.C.6
Georgakaki, A.	JRC.C.7
Ince, E.	JRC.C.7
Letout, S.	JRC.C.7
Mountraki, A.	JRC.C.7
Shtjefni, D.	JRC.C.7
Tattini, J.	JRC.C.6

Executive Summary

This report is part of an annual series from the Clean Energy Technology Observatory that address the status of technology development and trends, value chains and markets. Here the focus is on deep geothermal energy for power and direct heat applications, in particular district heating systems. Shallow geothermal energy systems are not covered here, but ground-source pumps are addressed in a companion CETO report.

Geothermal energy technologies are very mature. Innovative deep geothermal projects still face the problem of high-risk up-front expenses and often complicated licensing issues. The Horizon Europe project PUSH-IT started in January 2023 with the aim of demonstrating the use of high-temperature geothermal reservoirs to provide energy storage. The Innovation Fund awarded a grant of EUR 91 million for the EAVOR LOOPEN project to set up a closed loop system. Also, availability of subsurface data is often limited and their acquisition costly and time consuming. With a general focus on electricity in the energy discussion, geothermal projects are often at a competitive disadvantage. However, the new urgency for measures to decarbonise heating in national or European energy debates may change this. There is also an ongoing call for integration of geothermal heating and cooling in industry. Geothermal is already providing competitive and stable heat supply at scale to industries that need temperatures up to 200°C: agri-food, paper, plastics, etc. (for more information and examples, see the relevant SET Plan working group).

Globally, deep geothermal energy for electricity generation has seen steady growth in a number of countries, reaching a total installed capacity of 14.9 GW at the end of 2022 and an annual growth rate of 3% over the last decade. The EU's net capacity was 877 MWe in 2022, but growth is well below the global trend. Also, power output dropped slightly in 2022. The European Geothermal Energy Council (EGEC) notes that in Europe as a whole 43 projects are being developed and 140 are investigated. If all of these were to be implemented, it would increase the capacity by 1 GWe to reach an installed capacity of 4.5 GWe and generating 28.3 TWh by 2030?)..

For geothermal heat production in the EU, the outlook is more promising, with a growth rate of 9% in 2022. In particular, the geothermal district heating and cooling (DHC) sector has developed steadily. By the end of 2022 in Europe as whole, 395 systems were in operation—an increase of 14 compared to 2021. With around 5000 DHC systems in operation, there is considerable scope for further development, even if technically not all are suitable for supply by geothermal systems. Current additions in the EU are being driven by projects in France, the Netherlands and Poland. The EU Solar Energy Strategy notes that energy demand covered by solar heat and geothermal should at least triple to reach the EU 2030 targets, implying an increase to approximately 114 GWth (81 TWh).

The EU maintains a strong position for R&D investment, high-value patents and scientific publications in this field. In addition, projects trying to develop enhanced geothermal systems (EGS) did not reach the envisioned maturity and sometimes ran into problems causing a loss of public acceptance, for example when seismic events were induced. Last but not least, public R&D funding for geothermal energy in general has usually been far below that for other technologies.

The value chain for geothermal power in the EU involves above-ground and below-ground activities. Production well drilling and facility construction are the major costs of a geothermal project, and there are few specialized geothermal drilling companies globally. The European market is underrepresented in exploration and drilling services, and there are bottlenecks in rig availability and costs as well as lack of knowledge. The turbine market is dominated by large industrial corporations, with a few major manufacturers accounting for most of the installed capacity. The market for facility construction is competitive, with national (public and) private companies. District heating systems are the largest and fastest-growing direct use application of geothermal energy in the EU. Suppliers of geothermal equipment for the underground part of the installations are mostly from the oil & gas industry. The major providers of pumps, valves, and control systems are mostly from the US and Canada.

Geothermal operations have varying impacts on the environment, including GHG emissions, water use, land use, and ecosystem and biodiversity impact. CO2 emissions are the most common GHG emissions from geothermal operations, with variability depending on geological conditions and power plant technology. Geothermal operation phases have limited land use, with drilling and test phases occupying land for a short period and operation phases lasting for 20-40 years. Geothermal energy is low in water consumption, due to the use of subterranean brines, and re-injects water back into the reservoir after use. Geothermal plants may impact human health through potential emissions into the air. Public acceptance may be affected by hazardous emissions and negative effects on the environment, such as induced seismicity, groundwater contamination, and noise pollution.

Table 1. CETO SWOT analysis for the competitiveness of deep geothermal power and heat

Strengths	**Weaknesses**
– Large potential resource in the EU – Dispatchable power and high capacity factor (80%) – Sector coupling with large-scale underground thermal storage – Extensive EU manufacturing base for below-ground and above ground equipment – Can supply the DHC networks – Established EU R&I – Positive trade balance in services and equipment – Significant local employment	– High CAPEX persists – Licensing delays – Seismic concerns – High-quality resources only available in some EU countries – Availability of drilling expertise and equipment dependent on the oil/gas industry and oil/gas prices
Opportunities	**Threats**
– Enhanced geothermal systems with higher temperatures and efficiencies – Recovery of lithium and other critical materials from geothermal brines – Export of services and equipment – More exploitable resources with better technology and expertise – Emergence of the EU heat market (as opposed to a gas market) – EC policies for accelerated licencing for renewables	– Low/subsidised fossil fuel prices – Low social acceptance – Competition from other technologies investments in the EU, in particular wind and solar for power generation – Shortage of expertise and skills at all levels – Reduced R&I funding

Source: JRC analysis

1 Introduction

1.1 Scope and context

This report is part of an annual series from the Clean Energy Technology Observatory that address the status of technology development and trends, value chains and markets. It is an update of the 2022 report [1]. The focus is on the use deep[1] geothermal energy for electric power generation (Figure 1) and for direct heat applications, in particular district heating and cooling systems (DHC). Shallow geothermal energy systems such as ground-source pumps are addressed in a companion CETO report [2].

Geothermal energy development in Europe has been slow compared to other renewable technologies due to various challenges and obstacles. Ground-source heat pump systems are a mature technology but have faced a lack of capacity in meeting increased demand in the last two years. Deep geothermal projects face high upfront expenses and licensing issues, while geothermal projects for heating and cooling are often at a competitive disadvantage compared to electricity-based solutions including heat pumps However, recent developments such as large oil and gas companies investing in geothermal developments, national roadmaps with ambitious targets, and innovative technologies such as large high-temperature heat pumps and medium-deep geothermal resources have made geothermal energy more attractive. Other new developments include heat and cold storage in the subsurface, extraction of critical raw materials from geothermal brines, and technological advancements in resource assessment and exploration. Potentially disruptive technologies such as the Closed-Loop Geothermal System and geothermal power production using stored CO2 are also under development.

Geothermal power directly supports the decarbonisation policy and the 42.5% target for renewable energy in EU energy consumption by 2030, as agreed for the recast of the Renewable Energy Directive, as part of the Green Deal and Fit-for-55 policies[2].

Geothermal heat has an important role for decarbonising the heating and cooling sector, which accounts for 50% of global energy consumption and contributes 40% of CO2 emissions.[3] The European trade association for geothermal, EGEC, notes that 25% of European cities and industries are located in regions suitable for geothermal H&C [3]. The FF55 package requires an increase of the renewables share in H&C by 0.8% per year to 2026 and 1.1% until 2030, while for DHC the required annual increase would be 2.1%.

In terms of industrial policy, geothermal heat and power is included in the proposed Net Zero Industry Act[4], which will help strengthen the European manufacturing capacity of net-zero technologies and overcome barriers to scaling up the manufacturing capacity in Europe. As such, geothermal technology was also included in the recent ENTEC study on the strategic importance of the NZIA technologies [4]. The analysis was based on three key criteria: overall impact on the EU's climate goals, the need for building manufacturing capacity and its vulnerabilities. The overall composite score was 6 (out of15), i.e., non-critical from a supply chain perspective.

1.2 Methodology and Data Sources

The report has been written following the CETO methodology that addresses three principal aspects:

a) Technology maturity status, development and trends

b) Value chain analysis

c) Global markets and EU positioning

Annex 1 provides a summary of the indicators considered and the main data sources used.

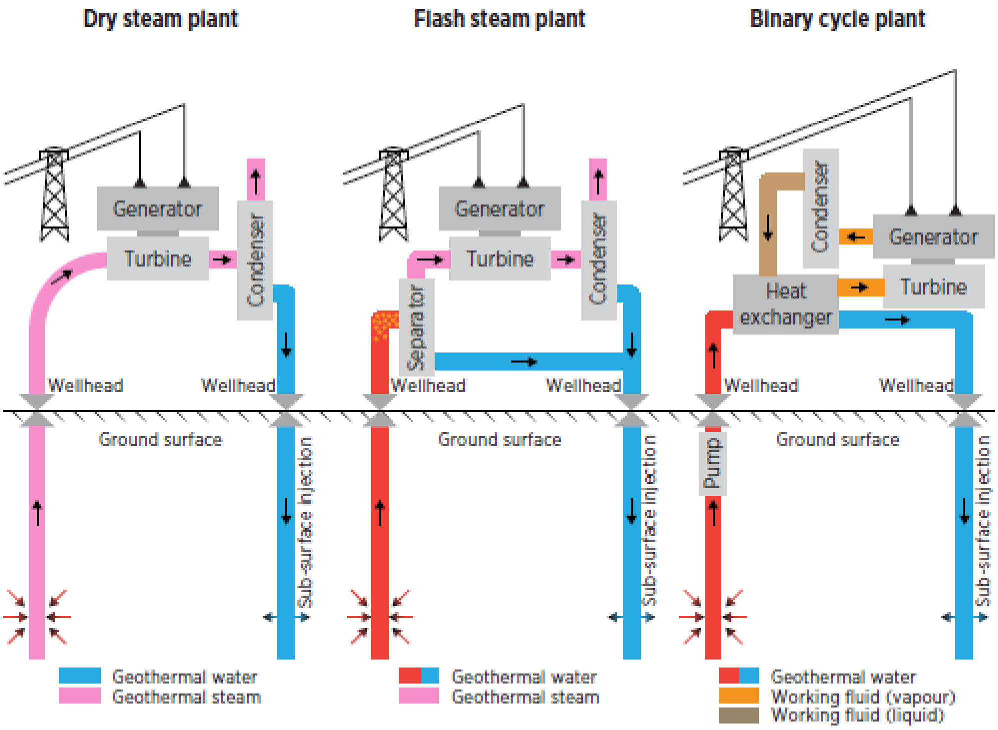
[1] *Deep geothermal is typically defined as any geothermal source below 500m in depth (https://www.bgs.ac.uk/geology-projects/geothermal-energy/). High (>180 °C) and medium (>100 °C) temperature resources can be used for electricity generation, while low- to medium-temperature resources can be used via a heat exchanger to supply industrial processes, district heating systems etc.*

[2] *See https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en*

[3] *IEA, https://www.iea.org/reports/renewables-2019/heat*

[4] *See https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en*

Figure 1 Principal geothermal power plant systems



Source: IRENA [5]

2 Technology status and development trends

2.1 Technology readiness level

Geothermal energy is a mature and commercially proven technology that can provide low-cost energy supply with the highest capacity factor among renewable energy sources (see Box 1). However, unconventional geothermal resources such as enhanced geothermal systems (EGS[5]) or hot dry rocks (HDR[6]) are less mature and have higher costs due to deep drilling requirements and additional stimulation measures. For this there can be synergies with drilling technology for oil and gas, and traditionally geothermal well drilling uses much the same equipment. Availability of comprehensive geothermal resource mapping is a key challenge for development, but initiatives like the database nlog.nl in the Netherlands and government-led mapping and exploration drilling can help reduce project development risks and costs. Global success rates for production wells are improving due to better surveying technology and adherence to best practices. Geothermal installations are site-dependent, and industry knowledge from each project can contribute to developing advanced standards. Adherence to best international practices for survey and management with thorough data analysis is the best risk mitigation tool for developers.

For research and development in general, the Implementation Working Group (IWG) on Deep Geothermal of the SET plan proposed an update of the Implementation Plan in 2020 [6]. The updated Deep Geothermal Implementation Plan includes priorities for research, development and innovation covering a broad range of topics for the geothermal sector across all segments of the value chain (**Table 2**). Also thermal energy storage technology is seen as being of increasing importance as enabler for renewable heating.

Table 2 RD&I priorities for the SET-Plan Deep Geothermal Implementation Plan and current TRL.

Priority	TRL (2022)
– Geothermal heat in urban areas	7
– Integration of geothermal electricity and heating & cooling in the energy system responding to grid and network demands	4-5
– Improvement of overall geothermal energy conversion performance for electricity and heating & cooling generation	5-6
– Closed loop electric and heating & cooling plants integrated in the circular economy	5-6
– Sustainable and efficient production technologies	4
– Development and exploitation of geothermal resources in a wider range of geological settings	4
– Advanced drilling/well completion techniques	4-5
– Innovative exploration techniques for resource assessment and drilling target definition	5-6
– Increasing awareness of local communities and involvement of stakeholders in sustainable geothermal solutions	n/a
– Risk mitigation (financial/project)	n/a

Source: SET-PLAN [6] and authors' elaboration

[5] *Enhanced geothermal systems (EGS) are engineered reservoirs that can provide geothermal power from geothermal resources that were once considered unrecoverable due to lack of water, location, or rock type (https://www.nrel.gov/geothermal/sedimentary-egs.html)*

[6] *Hot dry rock (HDR) is a form of EGS where volumes of rock that have been heated to useful temperatures by volcanism or abnormally high heat flow, but have low permeability or are virtually impermeable. From: Comprehensive Renewable Energy (Second Edition), 2022*

Box 1: Capacity factor for geothermal power plants

Geothermal power plants claim the highest capacity factor among renewable energy sources. The average for European geothermal power plants in 2022 was 79%, but some plants run at 100%, and others much less. The Valle Secolo station in Larderello, Italy has reported 98% for some years. Factors that can reduce the capacity factor include down time can be planned or unplanned maintenance. In installations with high salinity or very acidic geothermal fluids, maintenance may have to be quite frequent and even workovers may be required for cleaning or testing of well integrity. Sometimes the casing can be damaged due to corrosion and/or erosion. A work-over will lead to longer down times. In low temperature areas, where downhole pumps are required for production, maintenance often includes replacement of the pump, which can also take several days. It is noted that usually wells operate for more than 2 decades in the EU, so new drilling is not a factor. Lastly, some plants are combined heat and power plants so they may operate partially to generate electricity and some hours for heating supply.

2.2.1 Electricity supply

The theoretical potential for geothermal power in Europe and the world is very large and exceeds the current electricity demand in many countries. However only a small portion of the heat in place can be realistically extracted for energy production. Traditional geothermal systems currently extract energy at depths up to 3-4 km. EGS systems, if fully developed, could access depths of up to 10 km.

The global installed capacity at the end of 2022 was 14.9 GW, with the addition of 0.181 GW from 2021 [7]. This value represents an increase of 51% from approximately 10.7 GW in 2010 and a compound growth rate of 3.8%.The largest share (37%) of capacity is in Asia and Oceania, where Indonesia, New Zealand and Philippines all have capacities above 1 GW [9]. Global geothermal electricity production is now close to 100 TWh.

In longer term scenarios, relatively few results are available from global analyses, which often bundle geothermal power in an "other renewables" category. The IEA 2022 Net Zero Energy analysis [8] notes 1% geothermal by 2050, which would correspond to approximately 470 TWh. The POLES-JRC Global 2°C Scenario for CETO (see Annex 3) envisages geothermal installed capacity to almost triple in 2030 (46 GW) compared to todays' level and then to reach almost 180 GW in 2050. The IRENA World Energy Transition 2023 report [9] also foresees strong growth in geothermal power, to reach a 151 GW total by 2050.

For Europe, **Table 3** shows the installed capacities per country for both power generation and heating/cooling [3]. Overall European capacity was 3.4 GW, with 142 plants producing at 22 TWh at an average capacity factor of 76%. The EUnet capacity is 877 MW [10], with Italy accounting for almost 90% of it. Total growth since 2010 (Figure 2) has been limited to 12%. Most of the recently installed capacity for electricity in Europe is located in Turkey, with no growth in Italy or Iceland (traditional leaders for capacity in this sector). In Germany, the trend for local and small-scale binary power plants continues, with the addition of two plants of 1 MW and 5 MW respectively in 2021. Eurostat data indicates that EU electricity production was 6.7 TWh in 2020 from 871 MWe installed, but dropped to 6.5 TWh in 2021 and 6.0 TWh in 2022 (Figure 2).

Looking forward, the 2019 Member States' National Energy and Climate Plans (NECPs) target 8 TWh by 2030. It remains to be seen if this milestone is revised in the updated NECPs due in 2023. EURObserv'ER [10] expects a more modest increase to 7 TWh by 2030. The POTEnCIA CETO Climate Neutrality Scenario (see Annex 3) projects that deep geothermal installed capacity doubles (to 1.7 GW) and increases five-fold (3.5 GW) in 2030 and 2050 respectively compared to current level (Figure 3). Besides, electricity production from deep geothermal is projected to grow to almost 11 TWh (Figure 3).in 2030 and 28 TWh in 2050[7].

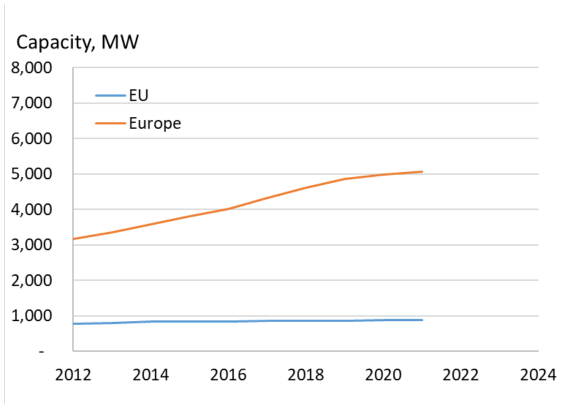
[7] *In the POTEnCIA results, even though capacity increases in certain years, the generation can reduce (as in 2050). Since geothermal plants are mostly used as baseload generators (running with capacity factors above 80%), in the future when there will be much higher penetration of variable renewables, all flexible generators (such as the steam turbine and generator sets used to produce geothermal power) are expected to support the electricity system, even acting as peaking plants if possible. This can result in lower capacity factors than historical values. In time, use of demand flexibility and large-scale deployment storage technologies can mitigate such needs.*

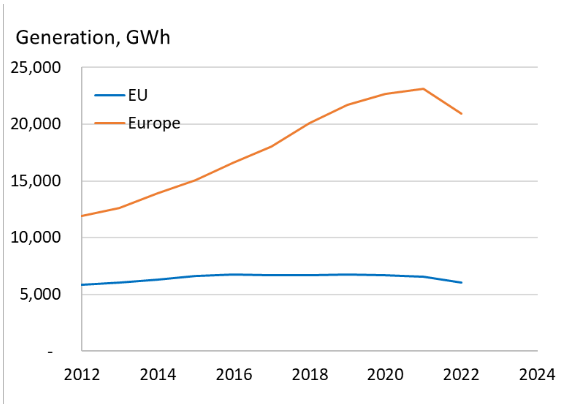
Table 3. Installed total capacity for electricity and for heating & cooling in the EU for 2022

Country	Net Generation Capacity (MW_e)	Electricity Production (GWh)	Heating/Cooling Capacity (MW_{th})
Austria	0.9	0.1	103
Belgium			22
Croatia	10.0	93.7	22
Cyprus			0,6
Czech Republic			8
Denmark			33
Finland			1
France	16.2	133.2	470
Germany	40.0	231.0	356
Greece			17
Hungary	3.0	16.0	256
Italy	771.8	6 026.1	180
Lithuania			14
Netherlands			369
Poland			137
Portugal	29.1	217.2	0
Romania	0.05	0.0	88
Slovakia			17
Slovenia			11
Spain			8
Sweden			44
EU Total	**871**	**6 717**	**2 156**

Sources: JRC elaboration of installed capacities: EGEC Geothermal Market Report, 2021 [3] and net capacity: Eurostat

Figure 2 Eurostat data for geothermal electricity and derived heat production (2022 value based on monthly data).



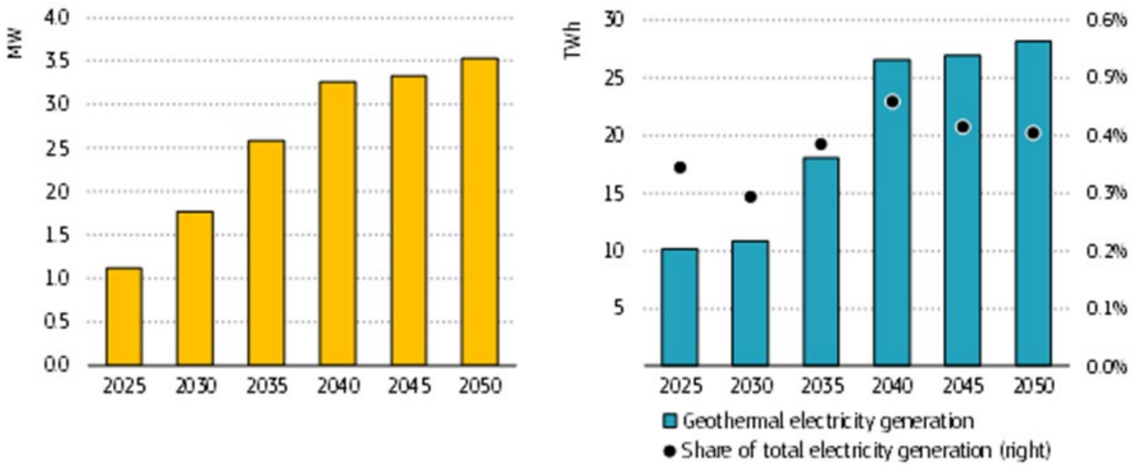


b) installed capacity

b) generation

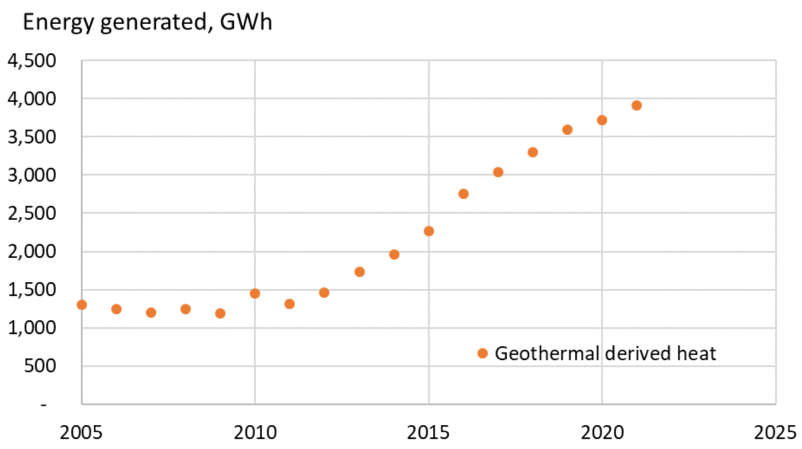
Sources: JRC elaboration of Eurostat data

Figure 3 Projected installed capacity and electricity generation from geothermal under the POTEnCIA CETO Climate Neutrality Scenario in the EU, 2025 to 2050



Sources: JRC, 2023

Figure 4 Eurostat data for geothermal heat production.



Source: JRC elaboration of Eurostat data

2.2.2 Heating and Cooling

Globally, the heating and cooling sector accounts for 50% of global energy consumption and contributes 40% of CO2 emissions. The market for low and medium temperature heat worldwide is estimated at 12,222 TWh, of which 58% for buildings and about 42% for industrial process, with 2,700 TWh for low temperature and 2,400 TWh for medium temperature applications [5]. The role of geothermal up to now is very modest. IRENA [5] indicate that the global installed capacity for geothermal heating and cooling by direct use of geothermal fluids reached 30.1 GWth in 2020[8]. It reports strong growth for the overall sector including heat pumps, but gives no breakdown for deep geothermal. Looking to the future, the IRENA World Energy Transitions Outlook 2023 [9] in its 1.5S scenario indicates that direct geothermal heat for end uses and DHC could rise from a current level of 250 TWh to 390 TWh in 2030 and 617 TWh in 2050. It also notes that current progress is below this scenario trajectory.

For the EU, the use of geothermal derived heat reached 3 900 GWh in 2021 (Eurostat, 2022 data pending). There has been steady growth since 2010 of approximately 9 % per year. However, this derived heat value cover a wide range of uses, including heat for residential buildings and commercial premises, so also heat pumps to some extent.

It should be noted that about 20-25% of the total geothermal electricity generation capacity installed is from cogeneration plants, CHP (Combined Heat and Power), and about 20% of the geothermal district heating and cooling capacity. Cogeneration optimises the benefits from a given geothermal project, by exploiting a larger temperature range of the geothermal fluid before re-injection.

District heating systems represent an important source of demand and are critical vector for decarbonising heat and cooling. EGEC [3] reports that geothermal plants for district heating and cooling systems in Europe continued to grow in 2022. There are now 395 systems in operation, up 14 since 2021 and corresponding to an additional 105 MWth of capacity. The total installed capacity across Europe was 5 608 MWth. In 2021 the EU share was 262 systems with a total installed capacity of 2.2 GWth (the EU has approximately 5000 DHC systems). EGEC also notes the emergence of new large scale geothermal projects which are not necessarily focusing on the development of "deep" high/medium temperature reservoirs.

Looking to future scenarios for geothermal in the EU, the REPowerEU communication underlined the need to accelerate diversification of energy supply for heating and cooling. The 2022 EU Solar Energy Strategy noted that energy demand covered by solar heat and geothermal should at least triple to reach the EU 2030 targets. Based on the EurObserv'ER [10] value of 10.1 TWh for geothermal in 2020, this would imply growth to approximately 30 TWh by 2030. Encouragingly, several EU countries have published development plans or roadmaps e.g. Croatia, German, France Ireland, Netherlands and Poland.

2.2 Technology Costs

Geothermal power plant installed costs are highly site-sensitive, as they are heavily influenced by the reservoir quality, the type of power plant and the number of wells required. The nature, extent, thermal properties and depth of the reservoir and its fluids will all have an impact on project costs. The quality of the geothermal resource and its geographical distribution will determine the power plant type. This can range from flash, direct steam to binary, enhanced or a hybrid approach to provide the steam that will drive a turbine and create electricity (**Figure 1**). Typically, costs for binary plants designed to exploit lower temperature resources tend to be higher than those for direct steam and flash plants, as extracting the electricity from lower temperature resources is more capital intensive.

The total installed costs of geothermal power plants consist not only of the usual project development costs and the cost of the power plant and grid connection. They also include the costs of exploration and resource assessment (including seismic surveys and test wells), as well as drilling costs for the production and injection wells. Total installed costs also include field infrastructure, geothermal fluid collection and disposal systems and other surface installations.

According to IRENA [7], the global weighted average capital cost (CAPEX) for new geothermal power plants in 2022 was USD 3 478 /kW, implying a reduction from the 2021 value of USD 4 300 /kW, but overall, relatively constant for the last decade. This is also consistent with the current value of USD 4 000 /kW overnight

[8] *Total geothermal H&C is reported as 107.4 GWth for 2020, with 72% from heat pumps and 28% from geothermal fluids*

investment cost used in the CETO POLES-JRC and POTEnCIA scenario analyses (see **Figure 6**), which however shows a gradual decrease going forward, reaching USD 2 513 /kW by 2050.

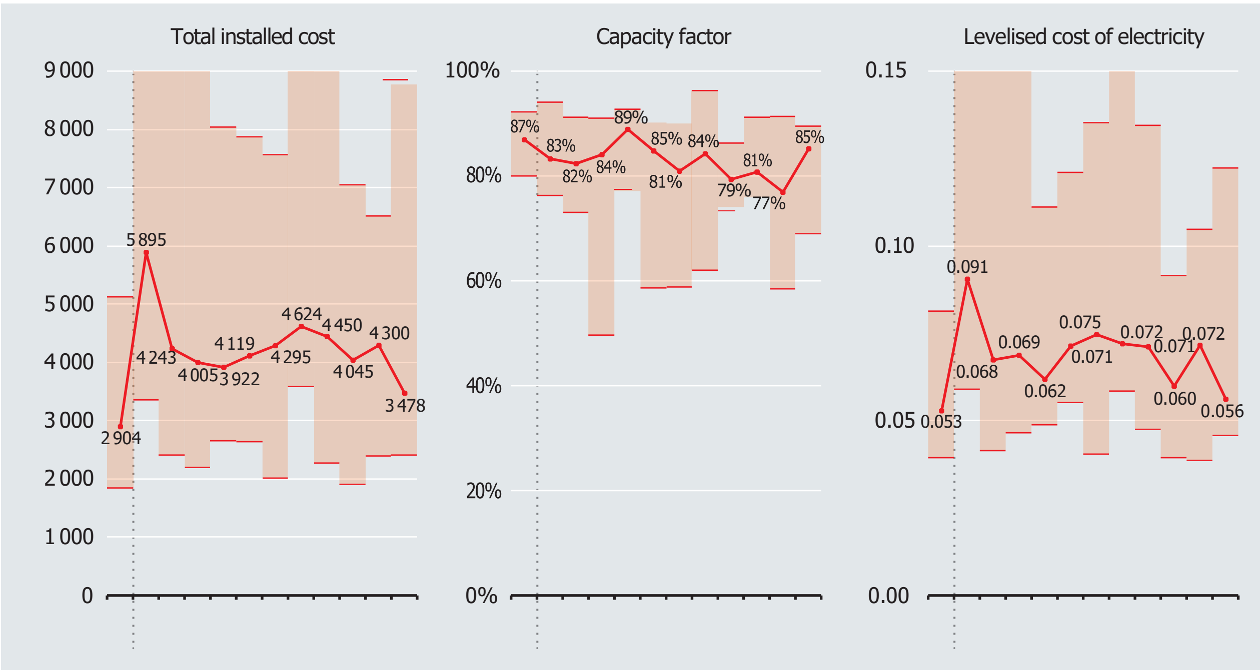
Regarding operational costs, the NREL ATB database [11] gives these in the range of 1.6-2.2% of CAPEX, and plants operate at a capacity factor of approximately 80%. OPEX also needs to take account of drilling additional wells to maintain production pressure in the lifetime of a project (25 years[9]). This can bring OPEX to USD 115/kW/year, based on common practice in high-temperature geothermal areas with steam and flash power plants. In low-enthalpy regions with dominantly heat production or electricity generated in binary power plants, the need to drill make-up wells is less common.

IRENA's global weighted average LCoE for 2022 was 56 USD/MWh, with the same time trend as for CAPEX. Regarding capacity factor, geothermal plants are typically designed to run as often as possible and in 2022 the capacity factor for newly commissioned plants was 85%.

With regard to deep geothermal for heating and cooling, no public cost data has been found so far. For ground source heat pumps (shallow geothermal), CAPEX, OPEX and levelised cost data is included in the 2022 Ademe analysis of energy costs [12], as well as in the IEA comparative analysis for heat for buildings [13].

Lastly, the SET-Plan Implementation Plan for Deep Geothermal targets production costs (including from currently not exploited unconventional resources, such as superhot, EGS, and/or from hybrid solutions) of below 100 EUR/kWh for electricity and 5 EUR/kWh for heat by 2025.

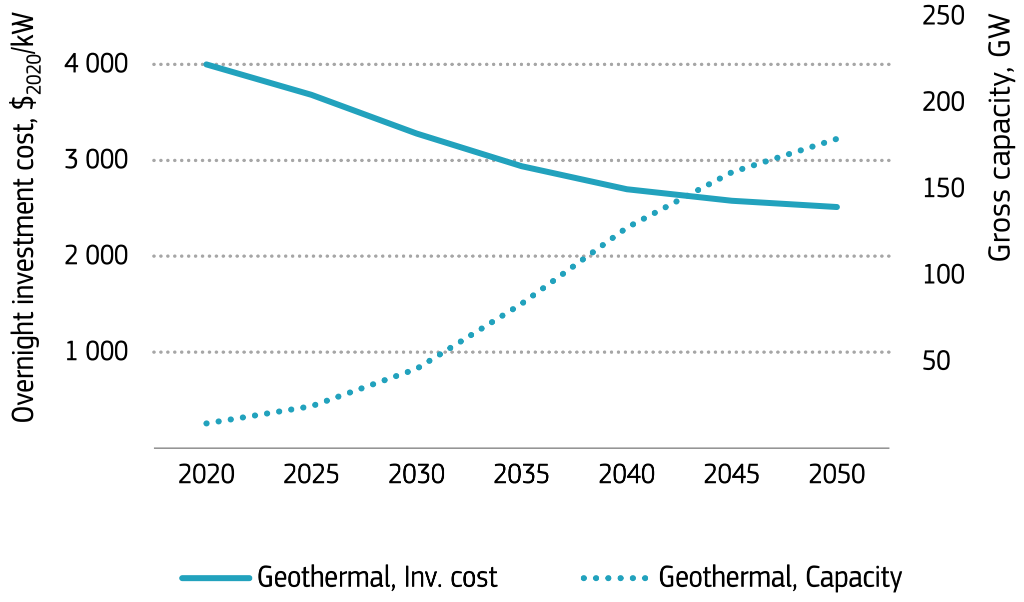
Figure 5. CAPEX, capacity factor and LCOE of geothermal power projects, 2010-2022



Source: IRENA Renewable Cost Database 2022 [7]

[9] *In most European countries projects for heating & cooling are planned for a lifetime of 30 years.*

Figure 6 Projected global installed capacity and overnight investment cost for geothermal electricity under the POLES-JRC CETO Global 2°C Scenario, 2020 to 2050



Source: POLES-JRC, 2023s

2.3 Public RD&I Funding and Investments

2.3.1 Global Public RD&D Funding

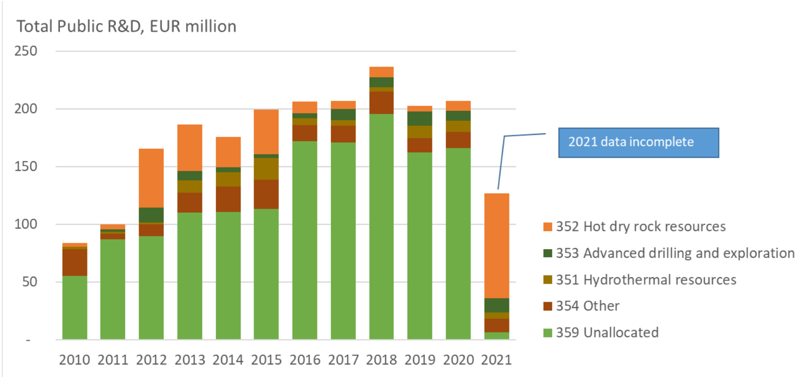
The IEA collects annual data on public R&D investments for clean energy technologies from its members [14]. These data are used here to assess the situation for geothermal energy. The relevant fields are:

- 35 Geothermal energy
- 351 Hydrothermal resources
- 352 Hot dry rock resources (including EGS)
- 353 Advanced drilling and exploration
- 354 Other geothermal energy
- 359 Unallocated geothermal energy

At global level, data is still partial for 2021. Nonetheless it is seen that public investment in EGS technology increased in 2021 compared to previous years (**Figure 7**). The technology is supported in particular in the USA, France, Germany and Switzerland. There is also a significant amount of research funding on theoretical studies on fracture controlled geothermal projects in Norway.

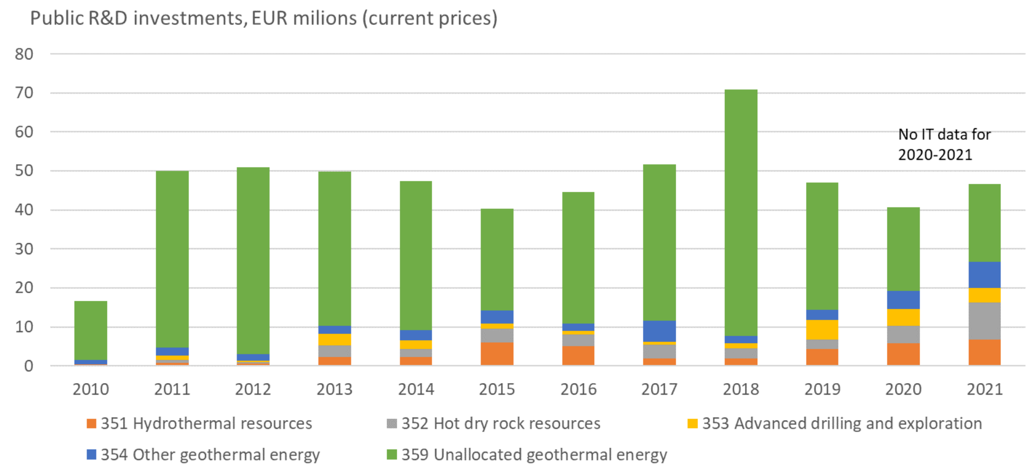
In the EU, spending on geothermal research (**Figure 8**) has been relatively constant over the last decade, implying a decrease in real terms. It represents about 20 to 25% of the global total. The EU member states with the largest geothermal R&D budgets in 2020 were Germany, France and the Netherlands No data was reported for Italy.

Figure 7 Global geothermal: public RD&D funding over the period 2010 to 2020



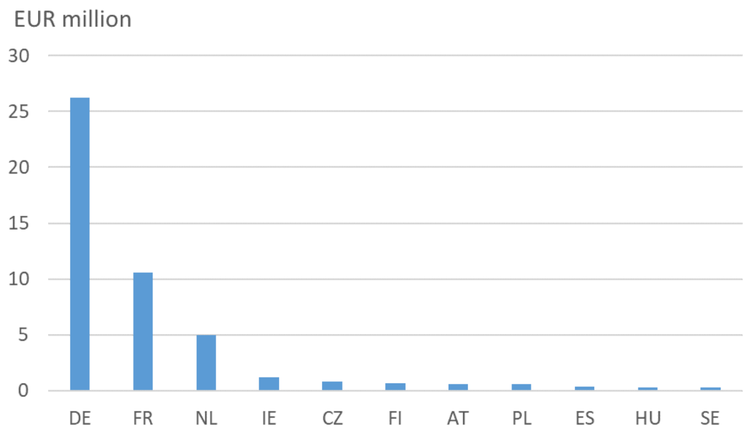
Source: JRC based on IEA

Figure 8. EU public RD&D funding for geothermal energy over the period 2010 to 2021, from data reported to the IEA.



Source: JRC based on IEA

Figure 9. EU member state public RD&D funding for geothermal energy in 2021, from data reported to the IEA: NB Italy did not report data for 2021, but previously has been the 3rd largest in terms of budget.



Source: JRC based on IEA

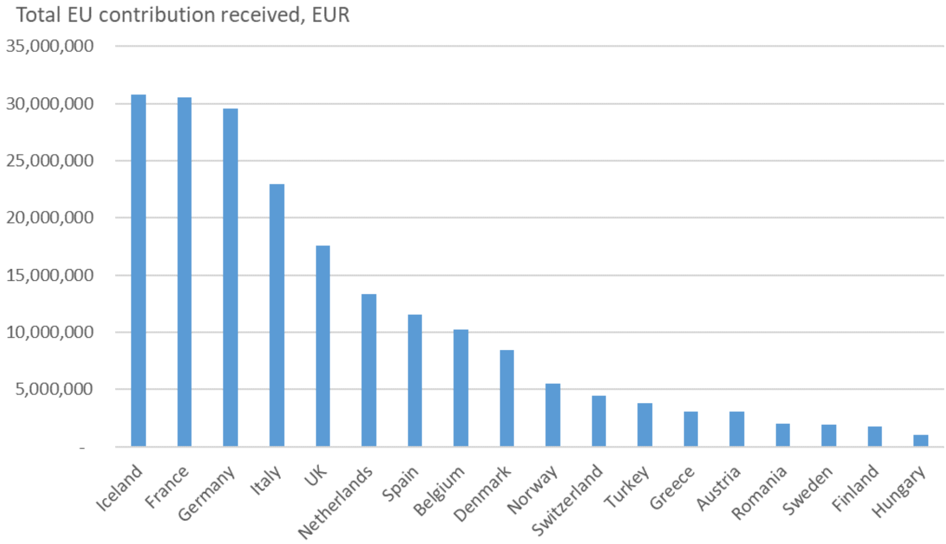
2.3.2 EU Funding

Under Horizon 2020 (2014-2020) the EU has supported 54 geothermal-related R&I projects with approximately EUR 208 million. **Figure 10** shows the total EU contribution per country. Iceland, France and Germany are the largest beneficiaries. Analysis of the number of projects per country indicates a similar ranking. Funding has continued in Horizon Europe (2021-2027), with at least 6 projects approved up to August 2023, and representing a budget of just over EUR 34 million (see Annex 4). In addition, the Innovation Fund has awarded grants to two geothermal projects:

- EAVOR LOOPEN, 2021-2026, Germany Closed loop technology using geothermal energy, grant EUR 91 million
- CCGeo: 2020-2021, Croatia, Closed-loop geothermal power plant, grant EUR 4.5 million.

The 2022 CETO report on deep geothermal [1] includes an extensive review of European and international R&D projects. This analysis will be updated in 2024.

Figure 10. H2020 funding (2014-2020) for geothermal projects - only countries with projects that received >EUR 1 million are shown.

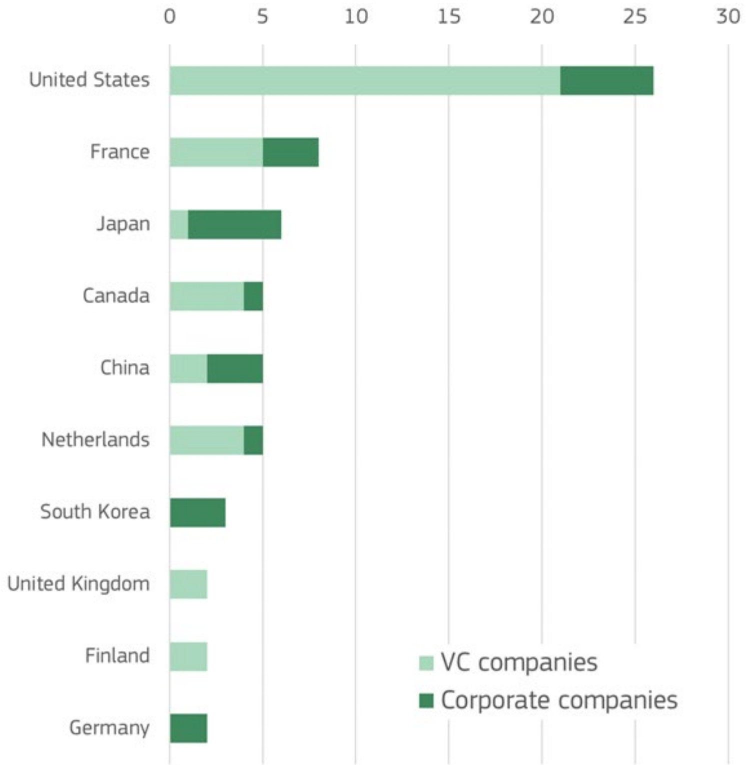


Source: JRC analysis of Cordis data

2.4 Private RD&I funding

As shown in Figure 11, six countries host together 73% of innovating companies active over the 2017-2022 period and the US (1st) alone account for 35% of all active innovators. Start-ups play a significant role in the development of geothermal solutions and they account for 64% of all active innovators. While they constitute most of active innovators in France (2nd), Canada (4th) and the Netherlands (6th), the innovation effort is largely driven by corporate innovators in Japan (3rd), China (5th) and South Korea. Overall, the EU accounts for 32% of innovators active over the 2017-2022 period (mainly in France and the Netherlands).

Figure 11- Number of innovating companies active over the period 2017-2022, by country (Top 10)

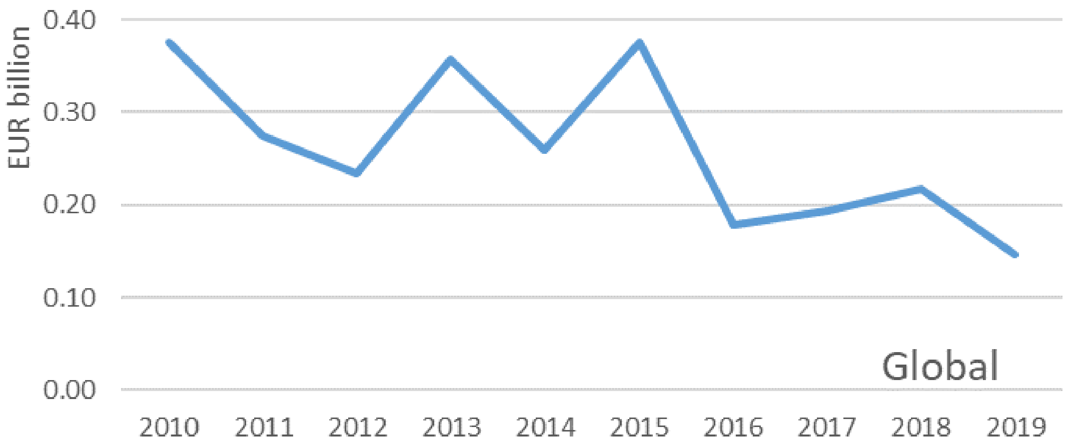


Source: JRC compilation of sources. Active VC companies include start-ups that have been founded or have raised venture capital over the considered period. Active corporate companies include subsidiaries of top corporate R&I investors with relevant high-value patents over the considered period.

2.4.1 Private R&I investments

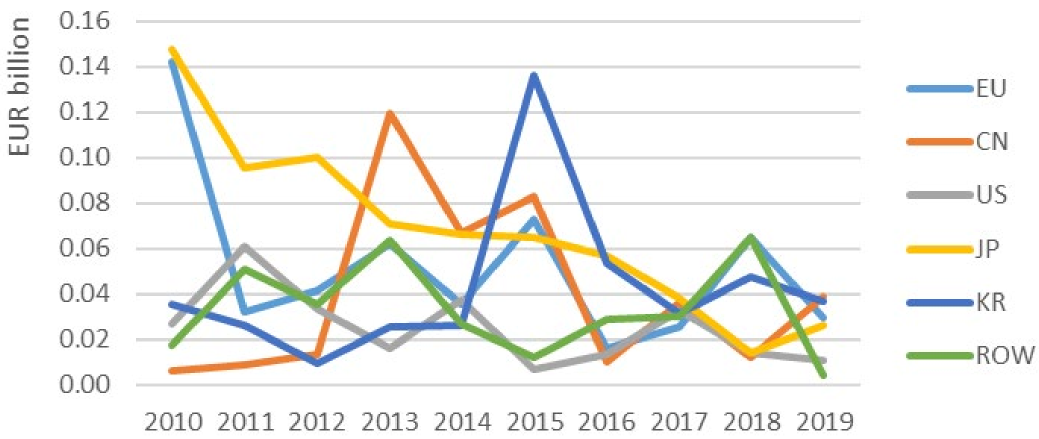
The following gives estimates of private R&I based on the use of patenting data as a proxy [15, 16] and should be interpreted with caution. The data to 2019 (patent data have several years lag) are shown in **Figure 12** and indicate a marked decline in investments over the last decade. **Figure 13** shows the trends at country/regional level. **Table 4** shows the top organisations for R&D investments globally and for the EU.

Figure 12. Overall trend in annual R&D investments by private companies, using patenting data as proxy.



Source: JRC analysis

Figure 13. Trends in annual R&D investments for the EU and major economies.



Source: JRC analysis

Table 4. Top organisations globally for geothermal R&D investments 2015-2019 based on patenting data.

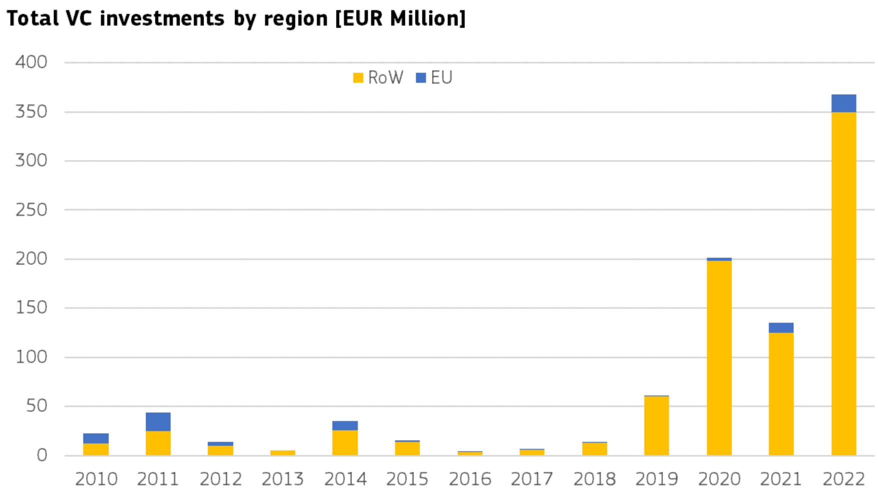
Global			**EU**	
Eavor Technologies Inc	CA		Steinhuser Gmbh Co KG	DE
Japan New Energy Co Ltd	JP		AGRANA BETEILIGUNGS AG	AT
Dae Sung Groundwater Ltd	KR		QUANTITATIVE HEAT OY	FI
Obayashi Corporation	JP		Climasolutions Gmbh	DE
Jansen Ag	CH		APMH Invest IV AS	DK
Ecolab Inc	US		BRENNERO INNOVAZIONI TECNOLOGICHE SRL	IT
China Academy Of Building Research	CN		Hlscher Wasserbau Gmbh	DE
Est Co Ltd	KR		HEIJMANS NV	NL
Chongqing Bingyuanhong Energy Saving Technology Development Co Ltd	CN		W-Filter Innovacio Kft.	HU
Chengdu Deshanneng Science And Technology Co Ltd	CN		ENOWARE GMBH	DE
Kyodo Tech Co Ltd	JP		BERNEGGER GMBH	AT
Aguricluster Corp	KR		JENKIES BV	NL
Hans Development Co Ltd	KR		Pfeil Bautrãƒæ’ã‚Â¤Ger Gmbh	DE
Gg Technology Co Ltd	KR		Trias VM Gmbh	DE
Steinhuser Gmbh Co KG	DE		MEFA BEFESTIGUNGS UND MONTAGESYSTEME GMBH	DE
Mitani Sekisan Co Ltd	JP		GEOCOLLECT GMBH	DE
Kupp Co Ltd	KR		RED SRL	IT
Kotecengineering Co Ltd	KR		E Tube Sweden AB	SE
Korea Hydro Nuclear Power Co Ltd	KR		Harjula Solutions Oy	FI
East Japan Railway Company	JP		VITAL WOHNEN Gmbh Co KG	AT

Source: JRC analysis of PATSTAT data

2.4.2 Venture capital investments

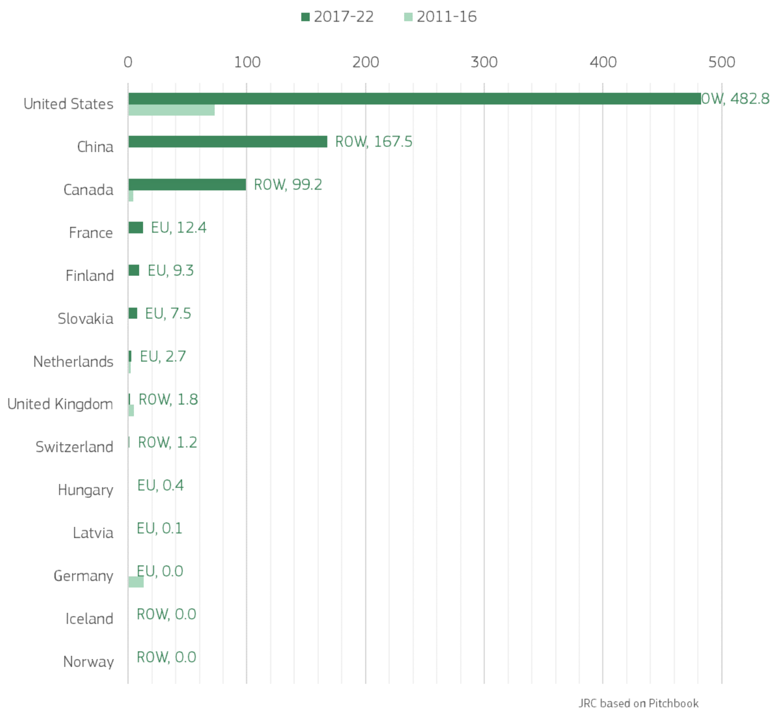
Global Venture Capital investment has increased sharply since 2019 and amount to an all-time high of € 368 million in 2022, doubling the average investment seen in 2020 and 2021 (**Figure 14**). This confirms a clear acceleration of investment in start-ups and scale-ups active in the development of geothermal solutions for power and heat. A limited number of larger deals in companies based in the US (such as Fervo Energy, Dandelion Energy and Quaise Energy) or Canada (Eavor) are driving the growth of both early-stage and later-stage investment and position the US (1st) in a leading position. While it hosts a much smaller number of companies, China (2nd) follows and has captured the largest realised deal over the period via the sole company Sinopec Green Energy. On the contrary, the EU – which hosts 33% of all active venture capital companies – only accounts for 4.1% of the global VC investment realised between 2017 and 2022.

Figure 14 Trends in venture capital investments in the EU and the rest of the world 2010 to 2022



Source: JRC analysis based on Pitchbook data

Figure 15 Top countries in venture capital investments 2010 to 2022



Source: JRC analysis based on Pitchbook data

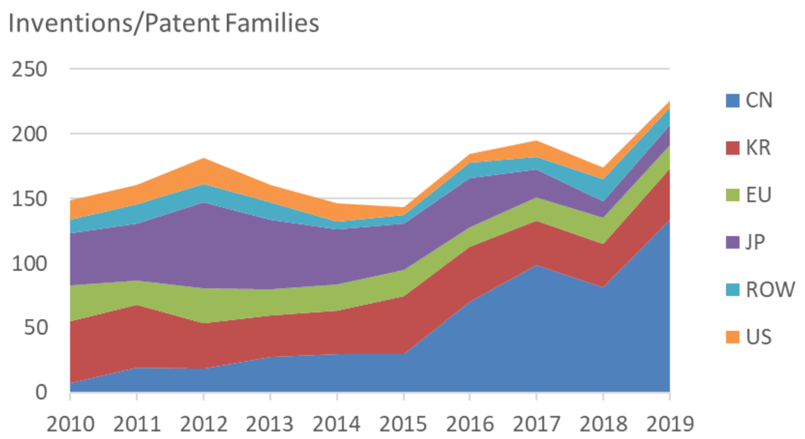
2.5 Patenting trends

The analysis followed the JRC's methodology [16] applied to the Patstat (European Patent Office) data for the period to 2020. The relevant CPC code is Y02E 10/10 – geothermal energy. The filings are classified as follows:

- Patent families (or inventions) measure the inventive activity. Patent families include all documents relevant to a distinct invention (e.g. applications to multiple authorities), thus preventing multiple counting. A fraction of the family is allocated to each applicant and relevant technology.
- High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office.
- Granted patent families represent the share of granted applications in one family. The share is then associated to the fractional counts in the family.

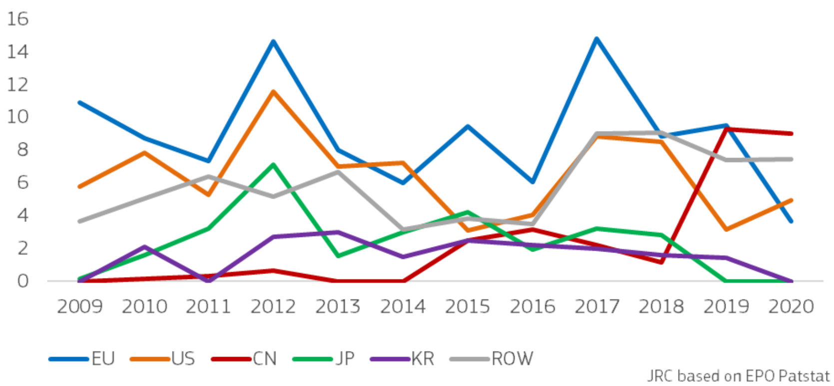
Globally, total inventions per year have grown from 150 in 2010 to over 200 in 2019[10] (**Figure 16**). This is mainly due to a very significant rise in Chinese patents, which has offset a slight decrease from other countries and regions. However for high value inventions the picture changes. The EU was leading inventor for almost all of the decade, but was overtaken by China in 2019 (**Figure 17**). **Figure 18** shows the listing of top individual countries for high value patents over 2018 to 2020. The leaders are China and the USA, with Germany, Italy and France in places 4, 8 and 9 respectively. **Figure 19** shows the leading organisations for inventions in the same period. The first, Eavor, is a Canadian company developing a closed-loop deep geothermal system.

Figure 16. Total inventions for geothermal from 2009 to 2019



Source: JRC analysis of PATSTAT data

Figure 17. High value inventions for geothermal from 2009 to 2020

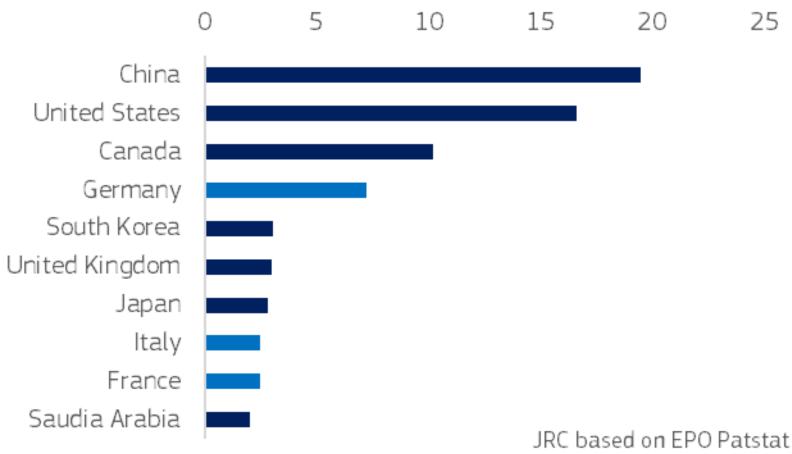


Source: JRC analysis of PATSTAT data

---

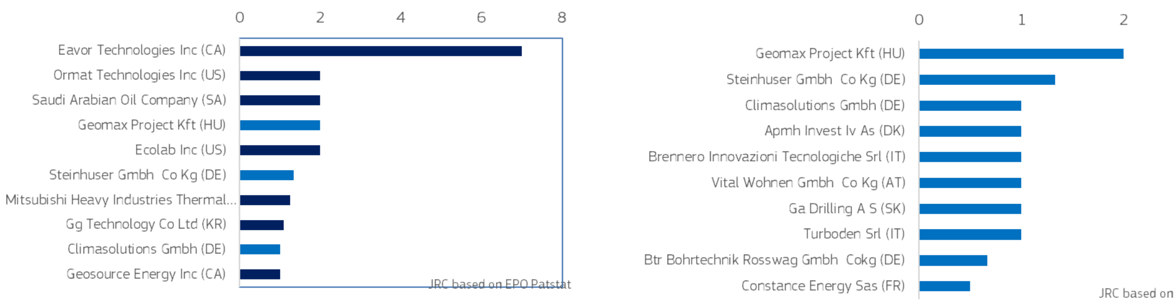
[10] *Since the analysis for the CPR 2020 SWD, the Chinese patents have been re-categorised, giving a much lower total count (50% less).*

Figure 18. Top 10 countries for high value geothermal energy inventions 2018-2020



Source: JRC analysis of PATSTAT data

Figure 19 Top 10 entities for high-value inventions 2018 -2020



(a) Global (b) EU

Source: JRC analysis of PATSTAT data

2.6 Scientific publication trends

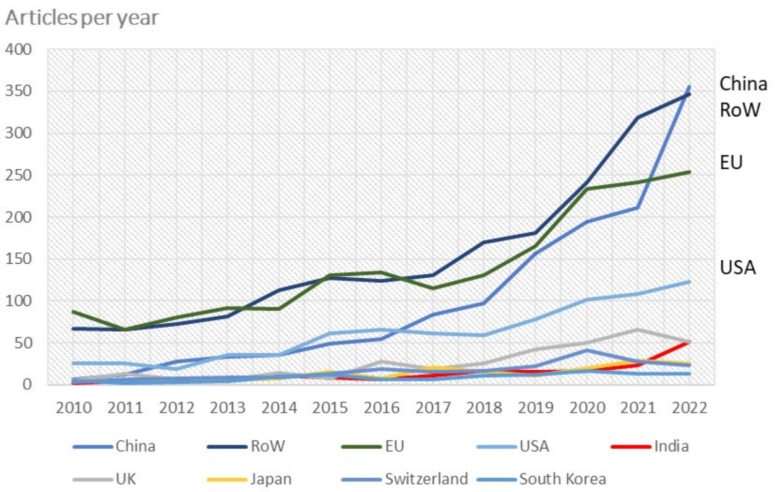
The JRC's Technology Innovation Monitor system (TIM) was used to analyse the scientific articles published over the period 2010 to 2022[11]. **Figure 20** shows the time trend for the EU and leading countries and regions. In 2022 China overtook the "Rest of the World" (RoW) as the most prolific, with the EU in third place.

For impact analysis, **Figure 21** ranks the h-index[12] values for the major country and country groupings based on the whole data set (2010-2022). Table 6 shows the ranking of EU countries, which Germany leads, followed closely by Italy and France.

[11] TIM search string: topic:("geothermal power"~2 OR "geothermal electricity"~3 OR "geothermal heating"~2 OR "geothermal energy" OR "geothermal direct use") AND class:"article"

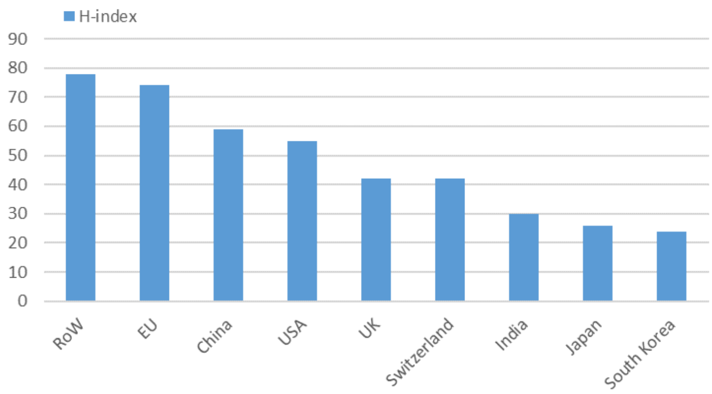
[12] h-index of a country: the largest number h such that at least h articles in that country for that topic were cited at least h times each.

Figure 20. Trend in scientific publications on geothermal energy for the leadings countries and regions



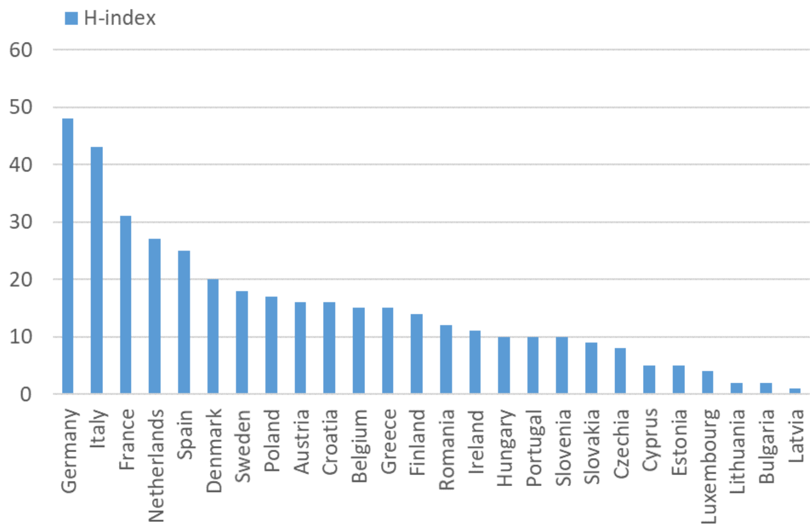
Source: JRC TIM data

Figure 21. Leading regions and countries for h-value scores for scientific publications on geothermal energy



Source: JRC TIM data

Figure 22 Leading EU countries for scientific articles on geothermal energy (ordered by H-index).



Source: JRC TIM data

3 Value Chain Analysis

3.1 Turnover

The global geothermal energy market is estimated at USD 62.65 billion (EUR 57 billion) in 2022, with a compound annual growth rate (CAGR) of 6.3%[13]. For the EU, the EurObsev'ER Barometer on geothermal [10] puts turnover at EUR 0.81 billion for 2020. The corresponding EU country breakdown is given in **Table 5**. The value chain for deep geothermal can be represented by the following elements [17]:

- Exploration & Planning
- Production of Materials Components
- Drilling and Installation
- Transport and Distribution
- Operation and Maintenance
- Recycling and disposal

However, no breakdown in terms of turnover or value-added is available. Several sources indicate that under-ground activities (resource assessments, exploration and drilling) require approximately 40% of a project budget.

Table 5. Selected EurObserv'ER data for 2020 on the deep geothermal sector.

Country	**Turnover EUR million**	**GVA EUR million**	**Employment (direct & indirect) FTE**
Netherlands	180	70	1,100
Italy	150	60	1,000
France	120	40	700
Germany	80	30	500
Hungary	30	10	500
Austria	40	20	200
Spain	10	<10	100
Croatia	<10	<10	100
Poland	10	<10	100
Portugal	<10	<10	100
Romania	10	<10	100
Slovenia	10	<10	100
Belgium	<10	<10	<100
Bulgaria	<10	<10	<100

[13] *See https://www.fortunebusinessinsights.com/geothermal-energy-market-106341*

Cyprus	<10	<10	<100
Czechia	<10	<10	<100
Denmark	10	<10	<100
Estonia	<10	<10	<100
Greece	<10	<10	<100
Finland	<10	<10	<100
Ireland	<10	<10	<100
Lithuania	<10	<10	<100
Luxembourg	<10	<10	<100
Latvia	<10	<10	<100
Malta	<10	<10	<100
Sweden	10	<10	<100
Slovakia	<10	<10	<100
Geothermal	**810**	**440**	**6 100**
All Renewables	**162 970**	**70 460**	**1 313 400**
% Geothermal	**0.5%**	**0.6%**	**0.5%**

Source: JRC elaboration of EurObserv'ER data

3.2 Gross value added

The EurObsev'ER 2021 barometer on geothermal estimates the EU GVA at EUR 440 million for 2020. The country breakdown is given in Table 5.

3.3 Environmental and socio-economic sustainability

The CETO reporting framework on sustainability aims to collect state-of-the art information on a set of environmental, social and economic aspect. Annex 3 summarises the information collected. The following additional considerations regarding research in the area of sustainability are taken from the 2022 CETO report.

3.3.1 Environmental Aspects

There is little research on the **environmental impact** of geothermal plants, although some (research) projects are currently in execution. The H2020 project GEOENVI (Tackling the environmental concerns for deploying geothermal energy in Europe, 2018-2021) developed a simplified Life Cycle Assessment methodology to rapidly calculate the environmental impacts and benefits of geothermal projects, both running and planned, as well overall recommendations on addressing environmental regulations [18].

Most of the **GHG emissions** by geothermal operations is CO_2, carried by geothermal fluids from the reservoir rocks. Therefore there is great variability in GHG emissions due to the geological conditions, hence the need to distinguish projects in volcanic and in non-volcanic areas. In volcanic areas, natural GHG emissions can occur, leading to a sometimes high GHG footprint. The variations in emissions depend on the geology and on the power plant technology. In low-enthalpy geothermal systems in sedimentary basins, sometimes CH_4 is co-produced with the thermal water, especially if the same geological structure has been used for hydrocarbon production.

The CH_4 is separated and often used for additional energy production, for example for electricity generation or to further increase the temperature of the geothermal fluid. The CO_2 resulting from the CH_4 combustion is then vented to the atmosphere, sometimes it is used in greenhouses. Injection of the CO_2 into the geothermal reservoir after extraction from the exhaust gases and compression is an option proposed for the Closed Carbon Geothermal Energy - CCGeo project funded under the Innovation Fund by the EU Emissions Trading System in 2021 at Draškovec in Croatia.

Land use of geothermal power is in the range of 0.04 to 0.4 km^2/TWh [19]. As most energy collection is underground, the limited surface of the power plant compared with a high electrical capacity makes a high areal density compared with other energy technologies. Geothermal heating and cooling projects show even better scores.

Over the life cycle, the drilling and test phase will occupy a surface of land with drilling rigs and material of 4 to 8 km^2 but just for a limited period (1 to 2 years). The operation phase lasts for a period of 20 to 40 years, and the land use is limited to the buildings of the plant(s).

Water: Due to absence of data on water pollution, only **water use** is published in the RESET study by the European Environmental Bureau [19]. In general, large-scale geothermal energy uses subterranean brines as a heat transfer fluid, which does not compete with drinking water. Water remains underground in heating systems, only geothermal electricity production requires cooling towers.

The use of water during the operation phase is highly dependent on the cooling technology used, with a high variability between technologies. With a consumption range from of almost zero to up to 14 m^3/MWh, geothermal energy performs relatively well [19]. For geothermal electricity, flash power plants (i.e., power plants that directly use geothermal fluid to drive a generator and re-inject it) do not consume potable water for cooling. Binary power plants (i.e. power plants that use a heat exchanger) can minimize their water use with air cooling.

Most geothermal plants re-inject water into the reservoir after it has been used to keep reservoir pressure and to prevent contamination and land subsidence. The amount of water needed depends on the size of the plant and the technology used. For steam based geothermal power plants, only a part of the produced steam is condensed and re-injected, such that it can become necessary to inject additional water. However, it is often not necessary to use clean water for this purpose. For example, the Geysers Reference Environmental Standards for Energy Techniques for the large geothermal site in California injects non-potable treated wastewater into its geothermal reservoir.

Beyond operation, water consumption during drilling and construction is related to underground operations. Water is mainly used to produce drill mud (bentonite and water) and to cement the casing during well drilling, with a water use ranging from 5 to 30 m^3 of water per meter drilled [20].

For subsurface heat storage, ATES is a technology using the thermal properties of the ground water to store and recover heat from buildings. Even though nothing is added to the water in the aquifer, the temperature increase can affect microbial life. For this reason, ATES is strictly regulated and limited in fresh-water aquifers. With more than 3000 such shallow ATES systems in operation worldwide, the impact on the water is well-investigated. For high temperature storage, saline aquifers at greater depths can be used. This technology, however, is at an early stage of international implementation, such that detailed studies on the impact of water quality are rare.

3.3.2 Social Aspects

Health: Although geothermal energy is generally considered a clean and sustainable energy source, geothermal industrial development may impact both the environment and human health. Among other effects, effusions from geothermal plants may occur if the produced geothermal fluids contain polluting elements and in case they are not completely contained and treated in order to avoid the contact with air, water and soil. In general, the potential emissions into the air include CO_2, H_2S, hydrogen, NH_3 (ammonia) and CH_4 (methane), radon, volatile metals, silicates, carbonates, metal sulphides and sulphates and traces of mercury, arsenic, antimony, selenium and chromium [21]. Among them, CH_4, NH_3, mercury, arsenic and SO_2 emissions are associated with potential negative impacts on human health. In a thorough and detailed LCA of geothermal power plants in all relevant settings performed for the study on geothermal plants' and applications' emissions (European Commission, 2020), the impact of these chemicals on cancer health effects, non-cancer health effects, on photochemical ozone formation - human health, and on respiratory inorganics was analysed. The results of this analysis suggest that, in rare cases, for a small number of geothermal power plants emissions could cause non-cancer health effects and become a source of respiratory inorganics. Respiratory inorganics can be related to

NH_3 emissions, while heavy metals, and to lesser degree NH_3 and CH_4, are the main causes for the non-cancer health effects.

Public acceptance is also largely affected by hazardous emissions to the environment. While in general public acceptance of geothermal energy is great, the “not in my back-yard” (NIMBY) effect related to the introduction of many new developments can also be observed for some new projects. In an evaluation of negative public statements about geothermal energy developments in the media, Reith et al [22] identified the main issues raising concern:

- Induced seismicity, sometimes occurring due to fluid injection, especially in EGS developments and near tectonically active fault structures in the subsurface
- Groundwater contamination due to emissions and well integrity issues
- Noise pollution from drilling and operations (cooling system)
- Especially EGS is often considered an immature technology, with uncontrollable side effects

Several case studies on critical public acceptance problems with respect to geothermal developments are presented and analysed by Karytsas and Polyzou [23]. The strategies of operating companies generally focus in (a) engaging with the local communities, (b) avoiding and reducing unfavourable impacts, and (c) generating added benefits for surrounding communities.

3.4 Role of EU Companies

Production well drilling and facility construction are responsible for the majority of costs of a geothermal project. Globally, only a handful of companies are specialised in geothermal drilling and about 20 more perform drilling in the oil, gas and geothermal sectors. The EU is underrepresented in the exploration and drilling services. Vonsee et al [17] identify bottlenecks in the EU value chain for rig availability and cost (need for independence from the oil and gas sector, where process are linked to those for fossil fuels), and lack of sufficient knowledge. For the above-ground part, the reference technology was the Binary-ORC system, since it is the most used in recent installations in Europe. The key components considered are turbine/generator, heat exchanger, electrical submersible pump and cooling tower. **Table 7** summarises the situation. Electrical submersible pumps (ESP) and cooling towers were identified as potential bottlenecks in the EU value chain.

The 2020 CPR/CETTIR report noted that the geothermal power plant turbine market (2017 data) was dominated by large industrial corporations that are also active in other energy sectors. The four major manufacturers (Toshiba, Fuji electric, Mitsubushi Heavy Industries and Ormat Technologies) account for about 80% of the installed capacity. The top EU company is Ansaldo Energia (Italy) in fifth position.

The four major organic Rankine cycle (ORC) manufacturers in the European market are Ormat (USA), Turboden (Italy), Atlas Copco (Sweden) and Exergy (Italy), all currently most active in Turkey and Portugal. Toshiba is dominant in Turkey as a flash turbine supplier, as is Fuji in Iceland. Chinese turbine manufacturer Kaishan recently entered the European market supplying an ORC turbo-generator to a Hungarian power plant.

The market for facility construction is very competitive. Many geothermal field operators or power plant operators are national (public) companies such as KenGen in Kenya and CFE in Mexico. In addition, some large private operators exist, such as Calpine, Terra-Gen, Ormat (all from USA) and ENEL (Italy).

Regarding the heat sector, district heating and systems are the largest and fastest growing direct use application of geothermal energy in the EU. Direct-use technologies closely resemble geothermal electric systems, except the heat is used for another purpose. Data and information about players active in the direct use supply and value chain is scarce. Most suppliers of geothermal equipment for the underground part of the installations are from the oil & gas industry (e.g. exploration, drilling, pipes, and pumps).

Major providers for pumps, valves, and control systems include Schlumberger, Baker & Hughes, GE, ITT/Goulds, Halliburton, Weatherford International, Flowserve (all US), Canadian Advanced ESP (Canada) and Borets (Russia). Heat exchangers are supplied mainly by Alfa Laval (Sweden), Danfoss (Denmark), Kelvion Holdings (Germany), SPX Corporation (US), Xylem (US), Hamon & Cie, Modine Manufacturing Company (US) and SWEP International (Denmark).

Table 6 Overview of companies in geothermal below-ground domain operating in Europe (2020).

Equipment Manufacturer/ provider; Drilling Service Company			**Driller/Rig Owner**	
Name	**Coverage**		**Name**	**Coverage**
Aker Solutions	Worlwide		Anger	Europe
Amec	Worldwide		Apache	Worldwide
Bentec	Europe		Boldon Drilling	Europe
BHGE	Europe		BAUER	Europe
Cape Industrial Services	Worldwide		Celler Brunnenbau	Worldwide
Drillmec	Europe		COFOR	Europe
Drillstar	Europe		CROSCO	Europe
Fangmann	Europe		DAFORA	Europe
Fugro	Worldwide		Dalrup	Europe
Halliburton	Worldwide		Enel GP	Europe
Huisman	Europe		Herrenknecht	Europe
Herrenknecht	Europe		Iceland Drilling	Europe
Marathon	Worldwide		ITAG	Europe
Noble Drilling	Europe		KCA Deutag	Europe
Odjfell Drilling	Worldwide		Maersk	Worldwide
Schlumberger	Worldwide		Marriott Group	Worldwide
Weatherford	Europe		NOV	Worldwide
Welltec	Europe		SAIPEM	Europe
Scientific Drilling	Worldwide		SMP	Worldwide
			Transmark EDS	Europe

Source: JRC reproduction of EGEC/ETIP-DG data [24]

Table 7 Analysis of the role of EU companies in the geothermal above-ground domain (2019).

Component	Company name	Total production facilities	Production facilities in EU	% production in EU	HQ Location
Turbine	Turbine Ormat	>1	0	0%	Non-EU
	Exergy	2	1	50%	EU
	Atlas Copco-Exergy	5	1	20%	EU
	Turboden Heat exchanger	1	1	100%	EU
Heat Exchanger	Alfa Laval AB	42	22	52%	EU
	Danfoss & Sondex Holdings A/S	69	36	52%	EU
	Kelvion Holdings Gmbh	49	32	65%	EU
	SPX Corporation	28	5 or less	n/a	Non-EU
	Xylem Inc.	n/a	n/a	n/a	Non-EU
	Gunter AG & Co. KG	8	3	38%	EU
	Hamon & Cie international SA	3	1	33%	EU
	Modine manufacturing company	n/a	n/a	n/a	Non-EU
	SWEP international	5	2	40%	EU
Electrical Submersible Pump	Schlumberger	17	4	24%	Non-EU
	Baker Hughes	>20	3	n/a	Non-EU
	GE Oil & Gas	n/a	n/a	n/a	Non-EU
	ITT/Goulds	12	1	8%	Non-EU
	Canadian ESP	1	0	0%	Non-EU
	Flowserve	10	5	50%	Non-EU
	Halliburton	16	n/a	n/a	Non-EU
	Weatherford International	50	n/a	n/a	Non-EU
	Borets company	7	1	14%	Non-EU
Cooling tower	Dow Chemical company	214	n/a	n/a	Non-EU
	GE Power	n/a	n/a	n/a	Non-EU

	Babcock & Wilcox	9	3	33%	Non-EU
	SPX	28	5 or less	n/a	Non-EU
	Ecolab/Nalco	11	3	27%	Non-EU
	ETC Ltd.	n/a	n/a	n/a	Non-EU

Source: JRC reproduction of Vonsee et al [17]

3.5 Employment

Global overall employment for geothermal (including ground-based heat pump) given as 196 000 jobs by IRENA. For the EU deep geothermal sector, EurObserv'ER data 2020 shows combined direct and indirect employment of 6 100 (a small drop of 300 from the 2019 value).

Table 5 includes a breakdown for the EU member states. It is worth noting that as most of the economic value is created locally, also employment in the geothermal sector is required locally. In future scenarios, this implies a demand of skilled work force for an upscaling of geothermal installations in Europe, as pointed out in great detail in the Roadmap Deep Geothermal Energy for Germany [26].

3.6 Energy intensity and labour productivity

3.6.1 Energy intensity

For geothermal energy, the main source of energy consumption beyond electricity during operation comes from well drilling, power plants and pipes construction. When considering the total fossil fuel use during construction, operation and dismantling, the energy payback time of geothermal would range from around 2 months to 3.5 years [19]. This makes geothermal a very efficient technology in terms of Energy Payback Time. These figures, however, do not consider the energy consumed by the products (pipes, etc.) during the extraction of raw materials and manufacturing.

3.6.2 Labour productivity

Using EurObsev'ER the analysis in 2020 estimated the turnover per job at around EUR 115 000, about average for renewables in the EU. For reference, the highest value was for wind (EUR 155 000/job) and the lowest for biofuels (EUR 60 000/job).

3.7 EU Production Data

At present the EUROSTAT PRODCOM statistics have not been analysed for geothermal systems. Potentially relevant codes for above-ground power generation technology include:

- Steam turbines & other vapour turbines (excl. for marine propulsion), of an output <40MW' (code: 840682)
- AC generators of an output > 750 kVA' (code: 850164)
- 'Heat exchange units, nondomestic' (code: 841950)
- Centrifugal pumps' (code: 841370)
- Air conditioning machines, comprising a motor-driven fan and elements for changing the temperature and humidity, including those machines in which the humidity cannot be separately regulated' (code: 41510)

4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

As outlined in section 2.2, the market for deep geothermal shows modest growth globally, with prospects to expand considerably as countries and regions implement their decarbonisation policies. The potential for extraction of lithium from the geothermal brines used to produce electricity can add an important revenue stream.

The industrial position in Europe is seen as reasonably positive, although the EU is underrepresented in the exploration and drilling services. Vonsee et al [17] identify bottlenecks in the EU value chain for rig availability and cost (need for independence from the oil and gas sector, where process are linked to those for fossil fuels), and lack of sufficient knowledge.

The European trade association EGEC sees the following key factors for the competitiveness of the sector:

- Prices of materials, equipment, components and services.
- Oil price, which has a strong bearing on drilling rig availability (high oil price corresponds to less availability) and on OPEX for machinery operation
- Energy costs in general (affecting OPEX across the supply chain)
- Lack of European manufacturers and suppliers for certain materials, components and services

Specifically in relation to heating and cooling the following is noted (based partly on EGEC information):

- High fossil fuel energy prices are a major driver for investment decisions on projects
- Exploration and development of new reservoir remain an important challenge.
- Growth of district cooling geothermal systems – or at least systems with some cooling capacity – can be important for geothermal projects.
- New large scale geothermal projects are being developed, which do not necessarily rely on “deep” reservoirs.
- Geothermal projects are quickly diversifying in their nature (more diverse range of target temperatures, cooling become a greater component of the project development), their uses (with a greater focus on 5th generation district heating, uses of industry), and in their business models.
- Thermal underground storage is an import enabler for exploiting all renewables heat sources.

Concerning manufacturing industry, the EU geothermal sector is currently compliant with the proposed Net-Zero Industry Act (NZIA) requirement to provide at least 40% of the EU’s annual deployment needs for strategic net-zero technologies by 2030.

4.2 Trade (Import/export) and trade balance

The EU is considered to be a net exporter of services and equipment for deep geothermal technology. Vonsee et al [17] analysed the status for above-ground equipment for the period 2012-2017 using proxy trade codes as shown in Table 8.

Table 8 Analysis of EU trade balance for above-ground geothermal power plant equipment.

Component	Relevant Trade Code (but not specific to Binary-ORC Systems)	EU trade balance 2017
Turbine	Steam turbines & other vapour turbines (excl. for marine propulsion), of an output <40MW’ (code: 840682)	+ USD 69 m
Generator	AC generators of an output > 750 kVA’ (code: 850164)	+ USD 699 m
Heat exchanger	‘Heat exchange units, nondomestic’ (code: 841950)	+ USD 1706 m

Electrical submersible pump	Centrifugal pumps' (code: 841370)	+ USD 2100 m
Cooling tower	Air conditioning machines, comprising a motor-driven fan and elements for changing the temperature and humidity, including those machines in which the humidity cannot be separately regulated' (code: 41510)	- USD 1336

Source: JRC elaboration of Vonsee et al [17]

4.3 Resource efficiency and dependence in relation to EU competitiveness

Critical raw materials are not considered a major issue for the geothermal sector. The main raw materials used are listed below in Table 9. Recently concern is more focussed on the impact of dramatic increases in the cost of carbon steel (for well casings) and stainless steels in 2022 on project economic viability.

On the other hand, the technology offers the possibility of extracting minerals from the geothermal brine. This has a long history, with boric acid being one of the first successfully extracted minerals in Italy. Today, minerals such as gold, caesium, rubidium, manganese, zinc, lithium, and high-purity silica can be economically recovered from geothermal brines. The focus has been on lithium due to increasing demand for batteries. However, economically recovering lithium from geothermal brines faces challenges such as low concentrations, large volumes of brines, and high concentrations of low-value dissolved solids. Several methods, including membranes, ion exchangers, sorbents, and electrodialysis, are being tested for efficient extraction of lithium and other metals from geothermal brines. Commercial extraction of lithium from geothermal brines has been developed in Southern Germany, Canada, and the United Kingdom. European R&D projects are also addressing the extraction of raw materials from geothermal brines. EGEC claims that geothermal could provide approximately 20% of the EU demand in lithium by 2050.

Table 9 Key raw materials for the geothermal sector

Material Supply	**EU CRMA status**	**Use**
Iron	Non-critical	Well piping, and above ground heat distribution
Carbon (coking coal)	63% import dependency	For steel manufacture
Chromium	Mixed	For steel
Nickel	Non-critical	For steel
Molybdenum	Non-critical	For steel
Titanium	Non-critical	For structures
Aluminium	Non-critical	Plant construction
Epoxy/Plastics	Non-critical	Piping
Copper	Not reported	Generator, electrics
Neodynamium	Not reported	Permanent magnets in generators

Source: JRC elaboration of ETIP-DG data [24] and Vonsee et al [17].

5 Conclusions

The Clean Energy Technology Observatory report provides and overview of the status of development of deep geothermal technology, used both for electric power production and for heating and cooling applications for district heating systems and for industrial processes.

Deep geothermal energy has seen consistent growth in many countries, with activity mostly focussed on Asia, In the EU, innovative projects continue to develop despite high upfront costs and complex licensing issues. However, availability of subsurface data remains limited, leading to high acquisition costs. Despite setbacks with the development of enhanced geothermal systems, the EU remains a strong contender in R&D investment, scientific publications and patent development in the geothermal field. However, public funding for geothermal energy is far below other technologies. The EU has continued its support for the sector with several projects being funded under Horizon Europe, and the Innovation Fund has awarded grants for one large scale and one small scale geothermal project.

The value chain for geothermal power production in the EU is complex, involving both above-ground and below-ground activities. The EU market is underrepresented in exploration and drilling services while drilling and facility construction are the major cost aspects of a geothermal project. Concerning manufacturing industry, geothermal is included as strategic industry in the proposed Net-Zero Industry Act.

It is acknowledged that deep geothermal energy faces public acceptance issues, in particular in regard to seismic risks.

References

1. Bruhn, D. et al, Clean Energy Technology Observatory: Deep Geothermal Energy in the European Union-2022 Status Report on Technology Development, Trends, Value Chains and Markets, Publications Office of the European Union, Luxembourg, 2022, doi:10.2760/181272, JRC130585
2. Lyons et al, 2023, Heat pumps in the European Union - 2023 Status Report on Technology Development Trends, Value Chains and Markets, Clean Energy Technology Observatory, European Commission Joint Research Centre, Publications Office of the European Union, JRC34991
3. EGEC Geothermal Market Report 2022 (2023): July 2022
4. Energy Transition Expertise Centre (EnTEC), Report: Supply chain risks in the EU's clean energy technologies, 2023, doi 10.2833/413910
5. IRENA and IGA (2023), Global geothermal market and technology assessment, International Renewable Energy Agency, Abu Dhabi; International Geothermal Association, The Hague.
6. Deep Geothermal IWG (2020): SET Plan Implementation Group Deep Geothermal – Implementation Plan. Revision 1
7. IRENA (2023), Renewable power generation costs in 2022, International Renewable Energy Agency, Abu Dhabi.
8. IEA, Net Zero by 2050 - A Roadmap for the Global Energy Sector, 2022
9. IRENA (2023), World Energy Transitions Outlook 2023: 1.5°C Pathway, Volume 1, International Renewable Energy Agency, Abu Dhabi.
10. EurObserv'ER (2022), The State of Renewable Energies in Europe, 2021 edition, https://www.eurobserv-er.org/pdf/20th-annual-overview-barometer/
11. NREL (National Renewable Energy Laboratory). 2023. "2023 Annual Technology Baseline." Golden, CO: National Renewable Energy Laboratory. https://atb.nrel.gov/.
12. ADEME, Coûts des énergies renouvelables et de récupération en France - Edition 2022
13. IEA database
14. IEA (2023), Energy Technology RD&D Budgets: Overview, IEA, Paris https://www.iea.org/reports/energy-technology-rdd-budgets-overview
15. Fiorini, A. Georgakaki, F. Pasimeni, E. Tzimas, "Monitoring R&D in Low-Carbon Energy Technologies", EUR 28446 EN (2017), https://doi.org/10.2760/434051
16. Pasimeni, F., Fiorini, A., and Georgakaki, A. (2019). Assessing private R&D spending in Europe for climate change mitigation technologies via patent data. World Patent Information, 59, 101927. https://doi.org/10.1016/j.wpi.2019.101927
17. Vonsee, B., Crijns-Graus, W., Liu, W., Energy technology dependence - A value chain analysis of geothermal power in the EU, Energy 178 (2019) 419-435
18. Manzella., A., et al, Compilation of Recommendations on environmental regulations, GEOENVIE project Deliverable number: D.4.2, 2021, accessed at https://www.geoenvi.eu/wp-content/uploads/2021/04/D4.2-Recommendations-on-environmental-regulations-GEOENVI_300421.pdf Masterplan Geothermal Energy in the Netherlands (2018). Download available from www.geothermie.nl
19. European Environmental Bureau (2021): RESET - Reference Environmental Standards for Energy Techniques – Guidance. Final Version, October 2021
20. Huenges, E. & Ledru, P. (2010): Geothermal Energy Systems: Exploration, Development, and Utilization (Wiley-VCH)
21. Shortall, R., Davidsdottir, B., and Axelsson, G (2015): Development of a sustainability assessment framework for geothermal energy projects. Energy for Sustainable Development, 27, pp. 28–45. https://doi.org/10.1016/j.esd.2015.02.004

22. Reith, S., Kölbel, T., Schlagermann, P., Pellizzone, A., and Allansdottir, A. (2013): Public acceptance of geothermal electricity production. Deliverable 4.4 of the GEOELEC project (www.geoelec.eu)
23. Karytsas, S. and Polyzou, O. (2021): Chapter 5 - Social acceptance of geothermal power plants. In: Thermodynamic Analysis and Optimization of Geothermal Power Plants (eds: Colpan, C.O., Ezan, M.A., and Kizilkan, O.), Elsevier, Pages 65-79. https://doi.org/10.1016/B978-0-12-821037-6.00004-4
24. Garabetian, T., Dumas, P., EGEC, ETIP-DG Report on Competitiveness of the geothermal industry, 2020
25. IRENA and ILO (2021): Renewable Energy and Jobs – Annual Review 2021. International Renewable Energy Agency, International Labour Organization, Abu Dhabi, Geneva.
26. Beckers, K.F., Rangel-Jurado, N., Chandrasekar, H., Hawkins, A.J., Fulton, P.M.. and Tester, J.W. (2022): Techno-Economic Performance of Closed-Loop Geothermal Systems for Heat Production and Electricity Generation. Geothermics, 100, 102318, https://doi.org/10.1016/j.geothermics.2021.102318.

List of abbreviations and definitions

ARES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CHPM	Combined Heat, Power, and Metal
COP	Coefficient of Performance
CPC	Cooperative Patent Classification
DAC	Direct Air Capture
DHC	District Heating Cooling
DOI	Declaration of Intent
EGEC	European Geothermal Energy Council
EGS	Engineered/Enhanced Geothermal System
FiT	feed-in tariff
FOAK	First–of-a-Kind
GCHP	Ground Coupled Heat Pump
GSHP	Ground Source Heat Pump
H2020	Horizon 2020 Programme
HSA	Hot Sedimentary Aquifer
HT-ATES	High Temperature Aquifer Thermal Energy Storage
IA	Innovation Action
IP	Implementation Plan
IRENA	International Renewables Energy Agency
LCoE	levelised cost of electricity
LT	Low Temperature
MPC	Model Predictive Control
MRL	Manufacturing Readiness Level
MSCA	Marie Skłodowska-Curie Action
NECP	National Energy and Climate Plan
NREAP	National Renewable Energy Action Plan
NREL ATB	[US] National Renewable Energy Laboratory Advanced Technology Baseline
NTB	Non-Technical Barriers
OPEX	Operating Expenditure
ORC	Organic Rankine Cycle
PCM	Phase Change Materials

PPA	power purchase agreement
POTEnCIA	Policy Oriented Tool for Energy and Climate Change Impact Assessment
PV	photovoltaic
RES	Renewable Energy Source
RIA	Research and Innovation Action
RJD	Radial water Jet Drilling
SET	Strategic Energy Technology
SGP-RE	Salinity-Gradient Power generation by Reverse Electrodialysis
SI	Specialisation Index
SME	Small-Medium Enterprise
TES	Thermal Energy Storage
TRL	Technology Readiness Level
UTES	Underground Thermal Energy Storage

List of boxes

List of figures

List of tables

Annexes

Annex 1 Summary Table of Data Sources for the CETO Indicators

Theme	Indicator	Main data source
Technology maturity status, development and trends	Technology readiness level	SET-Plan WG and JRC
	Installed capacity & energy production	EurObserv'ER, Eurostat, EGEC, IRENA
	Technology costs	IRENA, NREL-ATB, ADEME
	Public and private RD&I funding	JRC elaboration of IEA data
	Patenting trends	JRC analysis of Patsat data
	Scientific publication trends	JRC Technology Innovation Monitoring
	Assessment of R&I project developments	N/A
Value chain analysis	Turnover	EurObserv'ER
	Gross Value Added	EurObserv'ER
	Environmental and socio-economic sustainability	Expert and JRC analysis
	EU companies and roles	EGEC, literature
	Employment	IRENA
	Energy intensity and labour productivity	Own estimates
	EU industrial production	No data
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	EurObserv'ER, Eurostat, EGEC, IRENA, IEA, Poles-JRC /POTEnCIA analysis
	EU market share vs third countries share, including EU market leaders and global market leaders	Own estimates
	EU trade (imports, exports) and trade balance	Lack of data
	Resource efficiency and dependencies (in relation EU competiveness)	Literature, EGEC

Annex 2 Sustainability Assessment Framework

Parameter/Indicator	Input
Environmental	
LCA standards, PEFCR or best practice, LCI databases	LCIA study (European Commission, 2020a) GEOENVI project: simplified Life Cycle Assessment methodology
GHG emissions	Representative kg CO2eq/kWh: • For electricity: 0.007 to 0.819 kgCO2e/kWhe, with an average of 0.190 kgCO2e/kWhe • For electricity generated by CHP: 0.005 to 0.898 kgCO2e/kWhth, • For thermal energy generated by CHP: 0.003 to 0.723 kgCO2e/kWhth (European Commission, 2020a)
Energy balance	EPBT 0.2 to 3.5 years (European Environmental Bureau, 2021)
Ecosystem and biodiversity impact	Limited information in the report on Geothermal plants' and applications' emissions (European Commission, 2020a)
Water use	0 to 14 m3/MWh (European Environmental Bureau, 2021)
Air quality	Low to moderate impact (European Commission, 2020a; European Environmental Bureau, 2021, and references therein)
Land use	Representative W/m2 for main current technologies, where relevant 0.04 to 0.4 km^2/TWh (European Environmental Bureau, 2021, and references therein)
Soil health	Low impact, but no specific data available
Hazardous materials	No data available
Economic	
LCC standards or best practices	None identified
Cost of energy	Yes, LCoE. 2020: global weighted-average total installed cost was USD 4 468/kW, global weighted-average LCoE 0.071/kWh Installed costs vary with size of the project and with technology: Binary power plants were more expensive than flash geothermal power plants Source: IRENA (2021), Renewable Power Generation Costs in 2020

Parameter/Indicator	Input
Critical raw materials	No information
Resource efficiency and recycling	No specific information identified
Industry viability and expansion potential	Yes, see markets section
Trade impacts	Yes, see markets section for volume and import/export balance
Market demand	Yes, see markets section
Technology lock-in/innovation lock-out	Since geothermal developments are always local, there are no dominant technology providers at the European scale, but sometimes at the national scale (Italy: Enel Green Power). Power plant technologies are dominated by several companies from Japan for flash and steam turbines, while binary plants are dominated by ORMAT (USA/Israel), but with growing competition by several small companies
Tech-specific permitting requirements	Drilling, production and injection are regulated by national mining laws and/or by the water authorities
Sustainability certification schemes	None identified
Social	
S-LCA standard or best practice	None identified
Health	In enthalpy resources with emissions of non-condensable gases, two components may pose a small to medium risk • H_2S exposure in volcanic regions: potential long-term risk for non-cancer human health effects not well-studied (European Commission, 2020). • NH3
Public acceptance	Generally positive image, but in some locations negative perception as for most new technologies affected by the NIMBY attitude. Geothermal specific aspects are worries about • Induced seismicity • Groundwater pollution • Noise pollution • Immature technology (Reith et al., 2013; Karytsas & Polyzou, 2021, Manzella et al, 2021)
Education opportunities and needs	Future growth scenarios require a skilled work force – see for example the Roadmap Deep Geothermal Energy for Germany (Bracke & Huenges, 2022).

Parameter/Indicator	Input
Employment and conditions	2020: 96 000 worldwide, 40 000 in EU, slight growth tendency (direct geothermal energy employment, power/heat; source: IRENA Jobs database)
Contribution to GDP	
Rural development impact	• Direct heat for the agricultural sector (greenhouses) • Heat pumps as stand-alone heat supply
Industrial transition impact	Process heat for the food industry, agriculture and paper mills
Affordable energy access (SDG7)	Technical solutions for small-scale, affordable geothermal power supply exist even for relatively low source temperatures. These are suitable for communities and small towns. Key is: no fuel import dependency
Safety and (cyber)security	Operations independent of imports of critical components or materials
Energy security	Operations independent of imports of critical components or materials
Food security	No interference with food security
Responsible material sourcing	No critical materials or components affected by EU REGULATION (EU) 2017/821 requirements

Annex 3 Energy system models and scenarios used in CETO

A3.1 POTEnCIA Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

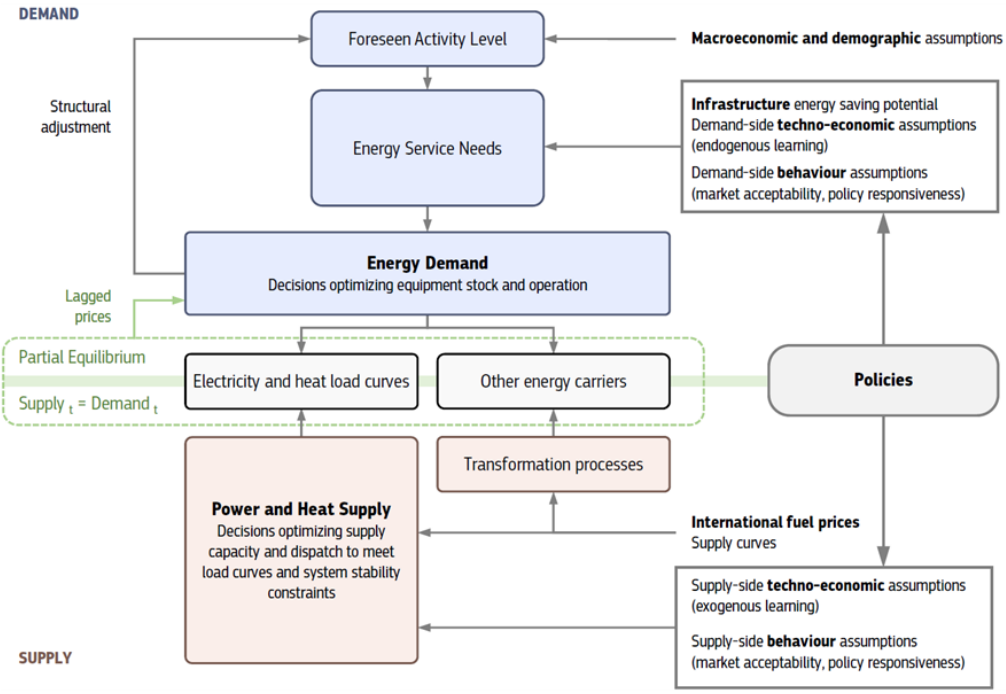
The core modelling approach of POTEnCIA (Figure A3-1; detailed in the POTEnCIA model description and in the POTEnCIA Central Scenario report) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies. This core modelling approach is tailored to each sector, for instance to represent different planning horizons and expectations about future technologies under imperfect foresight. In particular, power dispatch modelling uses a high time resolution with full-year hourly dispatch to suitably depict the increasing need for flexibility from storage and demand response, and the changing role of thermal generation in a power system dominated by variable renewable energy sources. Within this sector modelling framework, investment decisions of the representative agents are simulated with discrete-choice modelling. The model then finds an overall equilibrium across different sectors using price signals for resources such as traditional and renewable energy carriers while accounting for efficiency and environmental costs.

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES). JRC-IDEES has been developed in parallel to POTEnCIA, and an updated release is planned in 2024 to ensure the transparency of POTEnCIA's base-year conditions and to support further research by external stakeholders.

A3.2 POTEnCIA CETO Climate Neutrality Scenario overview

The technology projections provided by the POTEnCIA model are obtained under a Climate Neutrality Scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU27 GHG emissions by 55% by 2030 versus 1990, and reaches the EU27´s climate neutrality by 2050 under general assumptions summarized in Table A3-1. To suitably model technology projections under these overarching GHG targets, the scenario includes a representation of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the deployment of bioenergy and renewable power generation technologies to 2030 is consistent with the EU's Renewable Energy Directive target (42.5% share of renewables in gross final energy consumption by 2030). Similarly, the adoption of alternative powertrains and fuels in transport is also promoted by a representation of updated CO2 emission standards in road transport and by targets of the ReFuelEU Aviation and FuelEU Maritime proposals.

Figure A3-1. The POTEnCIA model at a glance



Source: Adapted from the POTEnCIA Central scenario report

Table A3-1. General assumptions of the POTEnCIA CETO Climate Neutrality Scenario

General scenario assumptions	Modelled scenario and policy assumptions
GDP growth by Member State	GDP projections based on EU Reference Scenario 2020, with updates to 2024 from DG ECFIN Autumn Forecast 2022
Population by Member State	Population projections based on EU Reference Scenario 2020, with updates to 2032 from EUROPOP 2019
International energy markets	Natural gas import projections consistent with REPowerEU targets for supply diversification and demand reduction. International fuel price projections to 2050 aligned with REPowerEU

Source: JRC

A3.3 POLES-JRC Model

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. POLES-JRC is hosted at the JRC and is particularly adapted to assess climate and energy policies.

POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand (Figure A3-2). International markets and prices of energy fuels are simulated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global framework: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2050 and is updated yearly with recent data and model updates.

The POLES-JRC model is used to assess the impact of European and international energy and climate policies on energy markets and GHG emissions, by DG CLIMA in the context of international climate policy negotiations and by DG ENER in the context of the EU Energy Union.

POLES-JRC has also been applied for the analyses of various Impact Assessments in the field of climate change and energy, among them: the "Proposal for a revised energy efficiency Directive" (COM(2016)0761 final) and "The Paris Protocol – A blueprint for tackling global climate change beyond 2020" (COM(2015) 81 final/2).

Moreover, POLES-JRC provided the global context to the EU Long-Term Strategy (COM(2018) 773) and formed the energy/GHG basis for the baseline to the CGE model JRC-GEM-E3.

POLES-JRC forms part of the Integrated Assessment Modelling Consortium (IAMC) and participates in inter-model comparison exercises with scenarios that feed into the IPCC Assessment Reports process.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks – GECO". The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://ec.europa.eu/jrc/en/geco

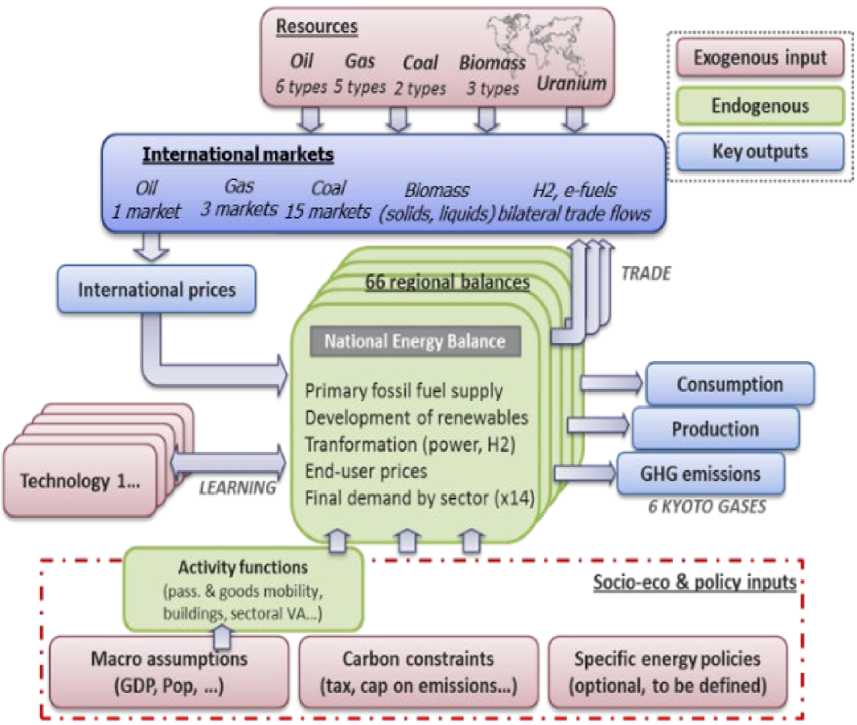
A3.3.1 Power system

POLES-JRC considers 37 power generating technologies, covering existing technologies as well as emerging technologies. Each technology is characterised by its installed capacity, cost parameters (overnight investment cost, variable & fixed operating and maintenance cost), learning rate and other techno-economic parameters (e.g. efficiencies). The cost evolution over time is taken into account by technology learning driven by accumulated capacity.

For renewable technologies maximum resource potentials are taken into account. Similarly, the deployment of carbon capture and storage (CCS) technologies is linked to region-specific geological storage potential. In addition to these technical and economic characteristics, non-cost factors are applied to capture the historical relative attractiveness of each technology, in terms of investments and of operational dispatch.

With regard to the clean energy technologies covered by CETO, the model includes power generation using photovoltaics (utility and residential), concentrated solar power (CSP), on-shore and off-shore wind , ocean energy, biomass gasification and steam turbines fuelled by biomass, geothermal energy as well as hydropower. CCS-equipped combustion power technologies are considered as well. Moreover, electricity storage technologies such as pumped hydropower storage and batteries are also included.

Figure A3-2. *Schematic representation of the POLES-JRC model architecture*



Source: JRC

A3.3.2 Electricity demand

The total electricity demand is computed by adding the electricity demand from each sector (i.e. residential, services, transport, industry and agriculture). The evolution over time of the sectoral electricity demand is driven by the activity of each sector and competition between prices for electricity and other fuels.

POLES-JRC uses a set of representative days with an hourly time-step in order to capture load variations as well as to take into account the intermittency of solar and wind generation. The usage of representative days also allows to capture hourly profiles by sector and end-uses.

With a view to other CETO technologies influencing electricity consumption, the model includes heat pumps in the residential and service sector, batteries for electric vehicles and electrolysers.

A3.3.3 Power system operation and planning

The power system operation assigns the generation by technology to each hour of each representative day. The supplying technologies and storage technologies must meet the overall demand.

The capacity planning considers the existing structure of the power mix (vintage technology), the expected evolution of the demand, and the production cost of technologies.

A3.3.4 Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from the grid or power from solar and wind, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of coal and biomass as well as high temperature electrolysis using nuclear power.

Hydrogen can used as fuel in all sectors. Moreover, hydrogen is used to produce fertilisers as well as to produce fuels used in the transport sector (i.e. gaseous and liquid synfuels and ammonia). POLES-JRC models global hydrogen trade and considers various means of hydrogen transport (pipeline, ship, truck, refuelling station).

A3.3.5 Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM model[14]. This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass potential, production cost and carbon value. Moreover, the emissions from land use and forestry (CO2) as well as agriculture (CH4 and N2O) are derived from GLOBIOM.

Power generating technologies using biomass are biomass gasification (with and without CCS) and biomass fuelled steam turbines.

Hydrogen can be produced from biomass via gasification and pyrolysis. Moreover, the production of 1st and 2nd generation biofuels for gasoline and diesel is considered.

A3.3.6 Carbon Capture Utilization and Storage (CCUS)

POLES-JRC takes into account CCUS technologies for:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS;
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and coal and biomass pyrolysis;
- Direct air capture (DAC) where the CO2 is stored or used to produce synfuels (gaseous or liquid);
- CO2 storage in geological sites.

A3.3.7 Model documentation and publications

A detailed documentation of the POLES-JRC model and publications can be found at:

- https://publications.jrc.ec.europa.eu/repository/handle/JRC113757

---

[14] *Global Biosphere Management Model (GLOBIOM) model description. International Institute for Applied Statistical Analysis, Laxenburg, Austria.* http://www.globiom.org

- https://ec.europa.eu/jrc/en/poles

A3.4 POLES-JRC CETO Global 2°C Scenario

The global scenario data presented in this CETO technology report refers to a 2°C scenario modelled with the POLES-JRC model. The 2°C scenario assumes a global GHG trajectory consistent with a likely chance of meeting the long-term goal of limiting the temperature rise over pre-industrial period to 2°C in 2100.

The 2°C scenario was designed with a global carbon budget over 2023-2100 (cumulated net CO_2 emissions) of approximately 1150 $GtCO_2$, resulting in a 50% probability of not exceeding the 2.0°C temperature limit in 2100. A single global carbon price for all regions is used in this scenario, starting immediately (2023) and strongly increasing. The 2°C scenario is therefore a stylised representation of an economically-efficient pathway to the temperature targets, as the uniform global carbon price ensures that emissions are reduced where abatement costs are lowest. This scenario does not consider financial transfers between countries to implement mitigation measures.

The POLES-JRC model has been updated with the latest technologies costs from recent literature. Most of the historic data used in the 2°C scenario refers to data used in the GECO 2022 scenarios (energy balances, energy prices, capacities).

Annex 4 Horizon Europe projects on deep geothermal technology

Acronym	Title	Call	Type of Action	Cost
COFFEE	Coupled Flow Processes in Fractured Media across Scales: Insights into Hydraulic Fracture Growth and Radiated Seismic Energy	HORIZON-MSCA-2021-PF-01	MSCA	189,687
COMPASS	Sustainable and cost-efficient Concepts enabling green power production frOM suPercriticAl/Superhot geothermal wellS (COMPASS)	HORIZON-CL5-2021-D3-03	HORIZON-RIA	4,184,145
DeepU	Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation	HORIZON-EIC-2021-PATHFINDEROPEN-01	HORIZON-EIC	3,092,881
GENIES	Gas-water-mineral interfaces in confined spaces: unravelling and upscaling coupled hydro-geochemical processes	ERC-2021-STG	ERC	1,450,931
GEOTHERM-FORA	Support stakeholders fora on geothermal systems	HORIZON-CL5-2021-D3-02	HORIZON-CSA	999,546
HOCLOOP	A circular by design environmentally friendly geothermal energy solution based on a horizontal closed loop - HOCLOOP	HORIZON-CL5-2021-D3-03	HORIZON-RIA	4,997,870
MixUP	Transport modelling for local mixing in granular media		HORIZON MSCA	211,754
PUSH-IT	Piloting Underground Storage of Heat In geoThermal reservoirs	HORIZON-CL5-2022-D3-01	HORIZON-IA	19,763,180
SAPHEA	Developing a single access point for the market uptake of geothermal energy use in multivalent heating and cooling networks across Europe	HORIZON-CL5-2021-D3-02	HORIZON-CSA	1,929,883
SecRHC-ETIP2022-2025	Secretariat of the European Technology and Innovation Platform on Renewable Heating and Cooling in 2022-2025	HORIZON-CL5-2021-D3-02	HORIZON-CSA	1,049,388
TWINN2SET	Preparing energy generation for green hydrogen	HORIZON-WIDERA-2021-ACCESS-03-01 - Twinning		1,491,970

Source: JRC extraction of CORDIS and COMPASS data

GETTING IN TOUCH WITH THE EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),

— at the following standard number: +32 22999696,

— via the following form: european-union.europa.eu/contact-eu/write-us_en.

FINDING INFORMATION ABOUT THE EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

Open data from the EU

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

EU Science Hub
joint-research-centre.ec.europa.eu

@EU_ScienceHub

EU Science Hub - Joint Research Centre

EU Science, Research and Innovation

EU Science Hub

@eu_science

Publications Office of the European Union