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Geothermal Energy in the European Union

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

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Abstract

The EU's geothermal energy sector, although small, has considerable potential to support the bloc's energy transition. This annual update report highlights the status of both power and direct heat applications, covering technology development, value chains, and markets. Despite being a well-established technology, geothermal energy faces challenges such as high up-front expenses and complex licensing issues. However, innovative projects, such as closed-loop systems, and the integration of geothermal heating and cooling in industry and for agriculture offer promising opportunities for growth. The report also notes the need for increased research and innovation investments, for improved sustainability, and to address skills shortages.

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

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Executive Summary

This annual update report from the Clean Energy Technology Observatory looks at the status of geothermal energy for power and for direct heat application in the EU. It addresses technology development and trends, value chains and markets. Shallow geothermal energy systems and underground thermal storage systems are not covered here, while ground-source pumps are addressed in a companion CETO report on heat pumps.

Geothermal energy technology is well-established, but remains the smallest of the commercial renewables despite offering the highest capacity factor. In the EU it currently provides 0.2% of electric power and approximately 0.7% of heat energy consumption. Nonetheless it offers considerable potential to support the EU's energy transition. It is included in the Net Zero Industry Act, and the EU also activity supports the sector through the Horizon Europe programme and the Innovation Fund. The SET-Plan Implementation Group and the European Technology Innovation Platform for Geothermal Energy provide strategic planning.

Globally, geothermal power grew by less than 1% in 2023 to reach a total installed capacity of 14.8 GW, compared to an annual growth rate of 3% over the last decade. The EU's net capacity was unchanged at 0.9 GWe in 2023, and generated 6.2 TWh. The European Geothermal Energy Council (EGEC) notes that in Europe as a whole 40 projects are being developed, and over 100 are being investigated. If all of these were to be implemented, it would at least double the current capacity.

For geothermal heat production, the EU outlook is more promising. Annual growth has been about 10% over the last decade. 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. There is considerable scope for further development as the EU has around 5000 DHC systems in operation., The EU's goal is to triple geothermal heat by 2030, implying an increase to approximately 114 GWth (81 TWh).

Deep geothermal projects still face the problem of high-risk up-front expenses and often complicated licensing issues. The European Investment Bank and the Innovation Fund have together contributed EUR 136 million to the EAVOR LOOP project to set up a closed loop system in Germany. For heating, there is new urgency for decarbonisation actions and here geothermal can play a significant role, particularly for district heating systems. There is also potential for integration of geothermal heating and cooling for industry and agriculture. 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. Geothermal brines also offer potential for extracting significant quantities of critical raw materials.

Research and innovation investments:

- Public R&I investments: the IEA data from member countries indicates an overall decrease in total spend for this technology over the last decade. The EU is the largest single contributor. A caveat here is that this data is not fully complete as not all members report for all technologies.
- Private R&I investments: the estimates here use patent data as proxy, so with a significant time lag. At global level, a decreasing trend is evident up to 2020. For 2019 (the last year with complete data), China and Korea were leaders, followed by the EU and then Japan. A similar trend is seen in the EU itself. Leadings countries were Germany, France and Austria and Hungary (joint 3rd).

Venture capital (VC) trends: at global level, the period 2019-2022 has seen strong growth in in VC investments in geothermal, with US, China and Canada leading the way. The EU has seen much less VC investment in the same period.

Patents (data to 2021): total number of patents issued globally has stabilised after a period of sustained growth, while the number of high value patents decreased slightly i.e. those filed in more than one patent office. For the latter, the contributions are quite dispersed, and the rest –of-the-world (RoW) grouping used in this study leads the ranking, with US/China (joint 2nd) and then EU. Within the EU for the period 2018-2021 the leaders were Germany, France and Hungary.

Scientific Publications (data to 2023): globally number of publications continues to increase. The top three are China, RoW and EU, while for highly cited papers, the EU moves into 2nd place. Within the EU, the leaders are Germany, Italy and France

Socio-economic indicators: in the EU the sector's turnover, gross value added and employment all dropped slightly in 2022 compared to 2021. Turnover was down to at EUR 0.77 billion from EUR 0.92 billion in 2021, likewise GVA (EUR 420 million for 2022, down from EUR 470 million in 2021) and jobs (6 200 in 2022, down from 7 300 in 2021).

Value and supply chains: the qualitative data available indicates that the EU has a good industry base in all the major activity areas: site investigation and resource assessment, resource development, drilling and sub-surface engineering, resource utilisation and management, operation and sustainable management. It is estimated that the geothermal sector is currently compliant with the goal of the Net-Zero Industry Act (NZIA) to provide at least 40% of the EU's annual deployment needs for strategic net-zero technologies by 2030. However, a more quantitative approach will be needed to understand the industry supply chains and the associated criticalities going forward.

Sustainability and resilience:

- For critical raw materials, the EU has relatively low exposure, mostly through alloying elements used in construction materials and for titanium used for filters. On the other hand, geothermal is unique in offering the possibility of extracting materials from the geothermal brine, and this is being actively pursued in several EU locations.
- Broader sustainability Issues are pollutants and GHGs that can be emitted from geothermal facilities. To mitigate these appropriate containment of both gases and effluents is necessary. Seismic risks with enhanced geothermal systems may also raise public acceptance concerns.
- Skills are an area of concern for deep geothermal energy, as it requires a well-trained, specialised workforce, although there is scope for transfer of exploration and drilling expertise from the oil and gas sector. Also skills are needed within regulatory and permitting agencies.

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

Strengths	**Weaknesses**
– Large potential resource in the EU – Dispatchability and >80% capacity factor – Supports sector coupling with large-scale underground thermal storage – Extensive EU manufacturing base for below- and above ground equipment – Can supply district and cooling networks – Established R&D sector – Significant local employment	– High CAPEX – Licensing delays – Seismic concerns for enhanced geothermal systems – High-temperature resources at moderate depths only available in some EU locations – Competing demand for drilling expertise and equipment from the oil/gas industry
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 – Better technology and expertise can increase exploitable resources – Use expertise from the oil and gas sector – Emergence of the EU heat market (as opposed to a gas market) – EC policies for accelerated licencing	– Low/subsidised fossil fuel prices – Low social acceptance in some countries – 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 2024

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 and 2023 CETO geothermal heat and power reports [1, 2]. The focus is on deep[1] geothermal energy for electric power generation and for direct heat applications, in particular district heating and cooling systems (DHC). Shallow geothermal energy systems such as ground-source heat pumps are covered in a companion CETO report [3].

Although the smallest of the commercialised renewable technologies, geothermal energy directly supports EU Green Deal policies and specifically the 42.5% target for renewable energy in EU energy consumption by 2030, as set by the 2023 recast of the Renewable Energy Directive. 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 CO_2 emissions[2]. The European trade association for geothermal (European Geothermal Energy Council, EGEC) notes that 25% of European cities and industries are located in regions suitable for geothermal heating and cooling [4]. The Fit-for-55 package requires an increase of the renewables share in heating and cooling by 0.8% per year to 2026 and 1.1% until 2030, while for DHC the required annual increase would be 2.1%.

Geothermal heat and power is included in the Net Zero Industry Act, which aims to strengthen the European manufacturing capacity of net-zero technologies and overcome barriers to scaling up the corresponding manufacturing capacity in Europe. It contributes also to the objectives of the Critical Raw Material Act to ensure EU access to a secure and sustainable supply of such materials.

The European Parliamentary Research Service produced a briefing paper on geothermal energy in October 2023 for the ITRE committee [6]. This underscored both the potential benefits and challenges of geothermal energy for the EU, and the relevant policy initiatives. Subsequently the European Parliament adopted a resolution[3] on geothermal energy in January 2024. The Hungary EU presidency is now exploring an EU initiative on geothermal energy to be presented by the end of 2024.

For technology development, the EU's SET-Plan Geothermal Implementation Working Group (IWG) issued an updated strategic roadmap [8] at the end of 2023. This envisages a significant contribution from geothermal heat and power to the EU's 2050 carbon-neutral goal, including the following.

- Geothermal heat to supply more than 25% of Europe's demand for space heating and cooling, and more than 25% in the agricultural sector (greenhouses) and 5% in industrial sectors in the low to medium temperature range.
- Supply 10% of the power production in SET Plan countries.
- Underground thermal energy storage to supply more than 10% of Europe's demand for space heating mainly for district heating, thus requiring collective systems.
- Co-production of minerals and critical raw materials (CRM) such as lithium for resilient transportation sector and strategic autonomy established in at least 10 European regions.

At international level, the IEA has a Geothermal Technology Collaboration Programme (IEA Geothermal or the Geothermal TCP) to foster cooperation on all aspects of geothermal resources and geothermal energy

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 and c) Global markets and EU positioning. Annex 1 provides a summary of the indicators considered and the main data sources used.

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[1] *Deep geothermal is typically defined as any geothermal source beyond 500 m 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] *IEA, https://www.iea.org/reports/renewables-2019/heat*

[3] *European Parliament resolution of 18 January 2024 on geothermal energy (2023/2111(INI)) (C/2024/5738)*

2 Technology status and development trends

Geothermal energy is a mature technology that can provide low-cost energy supply with the highest capacity factor and lowest land area power density among renewables. Up to now commercial exploitation has relied on hydrothermal systems that exploit natural reservoirs trapped in sedimentary rock layers above hot rock formations, usually near plate boundaries. Favourable locations are therefore limited. Such systems can be subdivided based on the temperature of the reservoir fluids. Low enthalpy resources are below 100 °C at 1 km depth, medium enthalpy resources are between 100-180 °C and high enthalpy resources are above 180 °C at 1 km [6].

Enhanced geothermal systems (EGS[4]) or hot dry rocks (HDR[5]) systems do not require a hot fluid reservoir and instead inject water into rock at significant depths (several km) where temperatures are naturally elevated. As such, the range of potential locations is much higher. However EGS systems are less mature and have higher costs due to deep drilling requirements and need for 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. The EU-funded project "A Geological Service for Europe" (GSEU, 2022-2027) includes a GeoEnergy activity that aims to provide "pan-European inventories, characterisations and knowledge of geothermal energy resources, underground capacities for CO2 sequestration and temporary storage of sustainable energy carriers". Initiatives like the database in the Netherlands[6] and government-led mapping and exploration drilling can help reduce project development risks and costs. Global success rates for production wells can improve with better surveying technology and application of best practices. Geothermal installations are site-dependent, and industry knowledge from each project can contribute to developing advanced standards.

2.1 Technology readiness level

Deep geothermal energy technology is commercially available i.e. TRL 9. In parallel, numerous developments are taking place to improve all aspects of the technology. The 2023 strategic research agenda [5] of the European Technology and Innovation Platform on Geothermal (ETIP-G) provides a comprehensive overview of EU research priorities and their respective TRL levels (both current and expected progress to 2030) in the following thematic areas:

- Resource Assessment
- Resource Development: Drilling And Subsurface Engineering
- Resource Utilization And Management
- Resource Sustainable Management
- Data And Knowledge Sharing

2.2 Installed Capacity and Production

2.2.1 Electricity

The global installed capacity at the end of 2023 was 14.798 GW, with the addition of 0.1 GW from 2022 [9]. The associated geothermal electricity production is estimated at 97.3 TWh. The countries worldwide with net capacities above 1 GW are USA, Indonesia, Philippines, Türkiye and New Zealand.

Eurostat give the EU net capacity for 2022 as 0.9 GW (871 MW); data for 2023 is not yet reported, but there was no significant change in 2023 [4]). About 20-25% of this capacity is as cogeneration plants. Italy alone

[4] 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)

[5] 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

[6] *NLOG Nederlandse Olie en Gasportaal https://www.nlog.nl/geothermie*

accounts for almost 90% of capacity (**Table 2**). Electricity production was 6.2 TWh in 2023, down 3% on 2022 (Figure 1). This represented 0.2% of total EU electricity production.

Geothermal electricity capacity increase since 2010 is 12% overall, despite the lack of growth in 2023. According to the European Geothermal Energy Council (EGEC), the reasons for this include: 1) lack or uncertainty of regulatory support; 2) effects of the COVID pandemic slowdown 3) war in Ukraine; 4) project financing and 5) the electricity market is not growing. They also note that there are 36 plants in development, so growth should resume in the coming years.

Indeed the Member State draft updates of National Energy and Climate Plans (NECPs) target a 33% increase in generation to 8 TWh by 2030. EurObserv'ER [9] expects a more modest increase to 7 TWh by 2030.

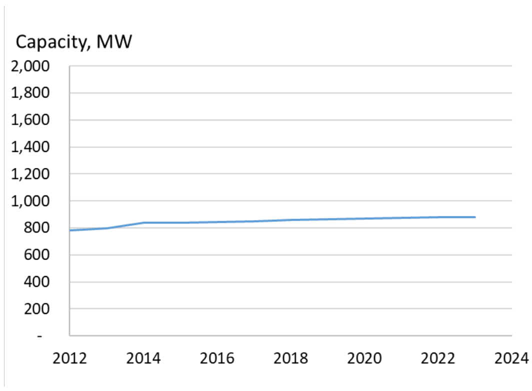
To create high detail energy scenarios for the EU, JRC has developed the POTEnCIA model. In the wider context of the CETO exercise, the model has been used to create the POTEnCIA CETO 2024 Scenario (see Annex 2 for details on the model and scenario). In this scenario, geothermal power capacity increases to 1.5 GW by 2030 and to 8.5 GW by 2050, providing more than 1% of total electricity generation (**Figure 2**).

Table 2. Geothermal electricity generation capacities and production in the EU for 2022 and 2023.

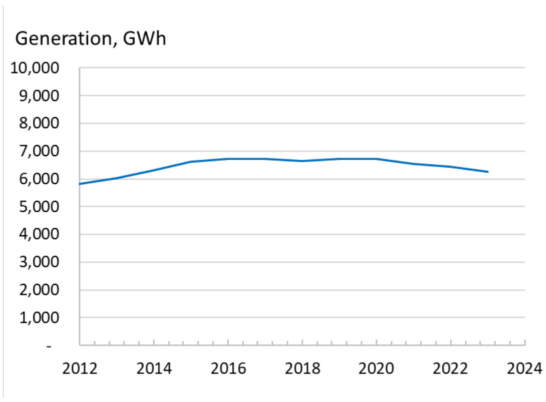
Country	Net Generation Capacity (MW_e)		Electricity Production (GWh)	
	2022	2023 (estimated)	2022	2023
Austria	0.25	0.25	<1	<1
Croatia	10.0	10.0	4	16
France	16.2	16.2	114	114
Germany	50	50	206	206
Hungary	3.0	3.0	73	21
Italy	772	772	5 837	5692
Portugal	29.1	29.1	195	206
EU Total	871	871	6 428	6 238

Sources: JRC representation of Eurostat data for capacity: nrg_inf_epcrw; and production: nrg_ind_pef

Figure 1 EU geothermal electricity net capacity and annual generation



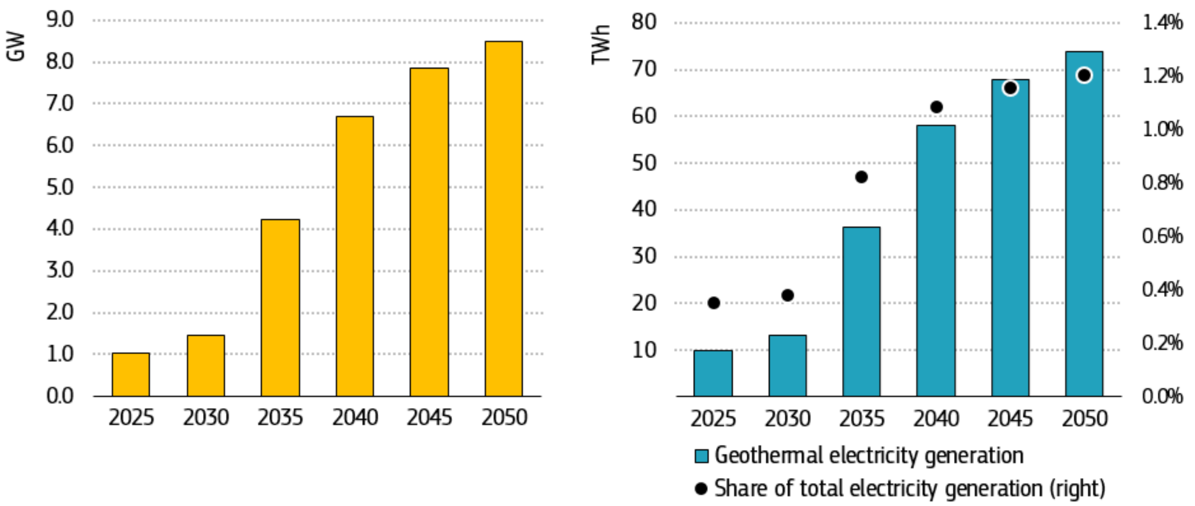
a) total net capacity



b) generation

Sources: JRC elaboration of Eurostat data

Figure 2 EU projected annual installed capacity and electricity generation from geothermal under the POTEnCIA CETO Climate Neutrality Scenario in the EU, 2025 to 2050



Sources: JRC POTENCIA CETO scenario 2024

2.2.2 Heating and Cooling

Globally, REN21 estimates geothermal direct-use[7] heat at 205 TWh, a 32% increase on the 2022 value (155 TWh). This represents a very modest contribution (2%) to the total market for low and medium temperature heat of about 12,000 TWh (of which 58% for buildings and about 42% for industrial process) [13]. Looking to the future, the IRENA World Energy Transitions Outlook 2023 [14] 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.

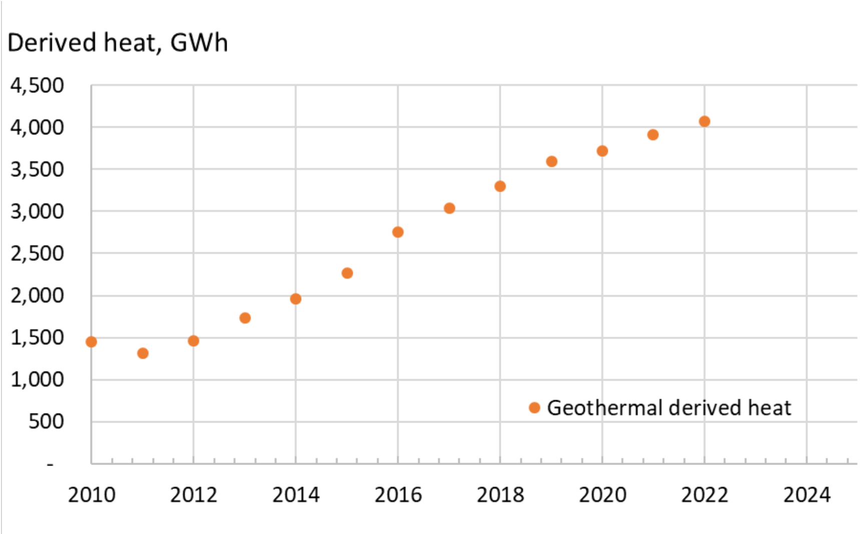
For the EU, Eurostat data shows that the use of geothermal derived heat reached 4.072 TWh in 2022 (2023 data pending), about 0.7% of the EU total (588 856 TWh). There has been steady growth since 2010 of approximately 10 % per year (**Figure 3**). This derived heat value covers a wide range of uses, including heat for residential buildings and commercial premises, so also ground source heat pumps. **Figure 4** shows the breakdown for 2022 by member state.

District heating systems represent an important end-use and are a critical vector for decarbonising heat and cooling. EGEC [4] reports that geothermal plants for district heating and cooling systems in the EU continued to grow in 2023. There are now 298 systems in operation, up 8 since 2022. A further 64 projects are reportedly in development/investigation reflecting the considerable market potential (the EU has approximately 5000 DHC systems). EGEC also notes the emergence of new large scale geothermal projects using shallower reservoirs, 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 [9] 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 for geothermal energy e.g. Croatia, German, France, Hungary, Ireland, Netherlands and Poland.

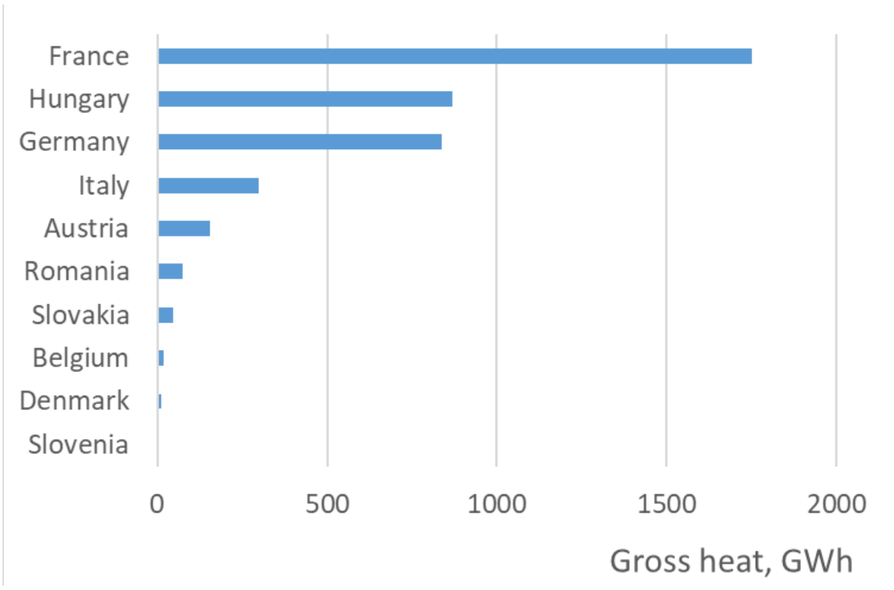
[7] *The REN-21 report notes that this term "refers mostly to energy derived from medium-to-high enthalpy (>100 degrees Celsius (°C)) hydrothermal or hot dry-rock resources, and typically at significant depth. Specifically, it does not include the renewable final energy output of near-surface, ground source (or ground-coupled) heat pumps, sometimes referred to as "geothermal heat pumps".*

Figure 3 EU geothermal heat production 2010 to 2022.



Source: JRC elaboration of Eurostat data (nrg_bal_pef)

Figure 4 Derived heat production for 2022 in the EU member states



Source: JRC graph of Eurostat data (nrg_bal_peh)

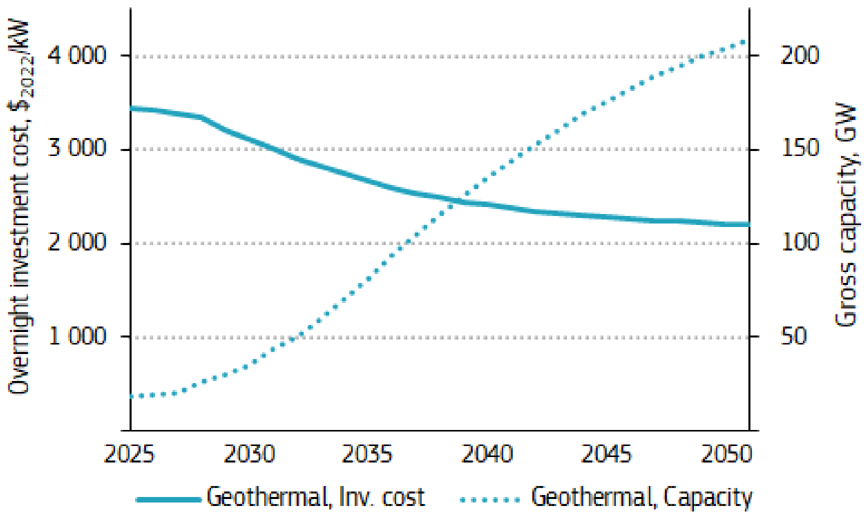
2.3 Technology Costs

According to IRENA [14], in 2023 the global weighted average capital cost (CAPEX) for new geothermal power plants (hydrothermal systems) was USD 4 589 /kW based on a relatively small sample of 7 plants. The range was USD 3413 to 6595 /kW, which ties in with informal reports from the EU of significant variations in costs between locations. The lower range is consistent with the USD 3 478/kW overnight investment cost used in the *Global CETO 2°C scenario 2024* [11]. Average CAPEX has been relatively constant over the last decade. However, for the coming decades, a gradual decrease in overnight investment cost is projected, reaching USD 2 220/kW by 2050 (**Figure 5**). IRENA's global weighted average LCoE for 2023 was 71 USD/MWh, so competitive with other electricity generation technologies, both conventional and fossil. **Figure 6** shows a breakdown of installed costs for a hydrothermal plant. These are dominated exploration and resource assessment, 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.

EGS systems have significantly higher costs. Graham et al [16] estimate 9 000 to 10 000 USD/kW for "near-hydrothermal EGS" and 20 000 to 46 000 USD/kW for "deep (3-6 km) EGS". The corresponding LCOE range is 0.10 to 0.46 USD/kWh, so only competitive at the lower end.

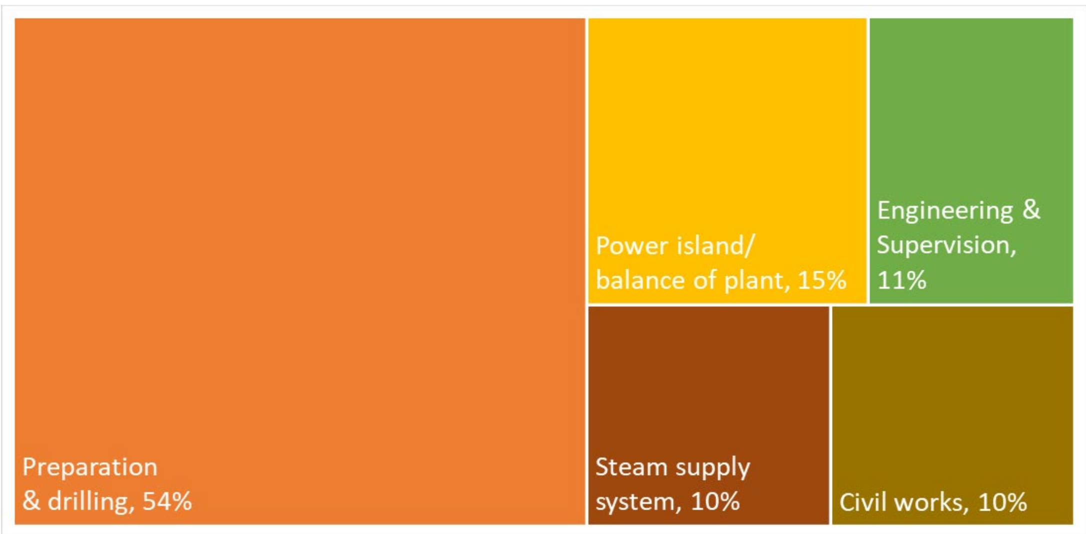
Regarding operational costs, the NREL ATB database [17] gives these in the range of 1.6-2.2% of CAPEX, and plants operate at a capacity factor of approximately 80%. OPEX may need to take account of drilling make-up wells to maintain production pressure in the lifetime of a project (25 years[8]). This 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. Also it would not be a factor for closed-loop EGS systems.

Figure 5 Projected global installed capacity and overnight investment cost for geothermal electricity



Source: CETO 2°C scenario 2024 (POLES JRC model) [9]

Figure 6 Breakdown of CAPEX for a geothermal power plant (hydrothermal reservoir)



Source: JRC reproduction of Graham et al data [16]

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

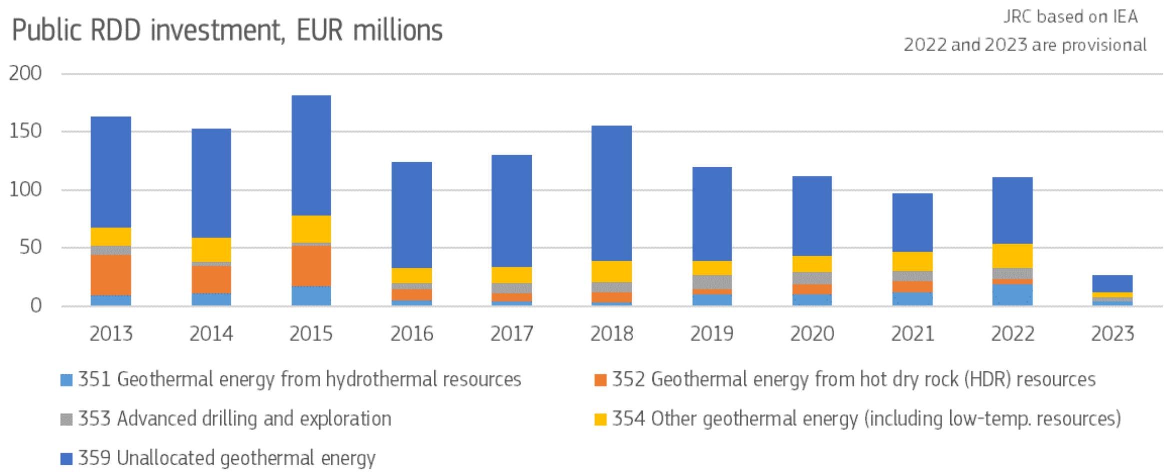
[9] *For more details on the scenario and model see Annex 3.*

2.4 Public RD&I Funding and Investments

The IEA collects annual data on public R&D investments for clean energy technologies from its members [19]. These data are used here to assess the situation for geothermal energy. The data are reported as current values, and no adjustment for inflation has been made.

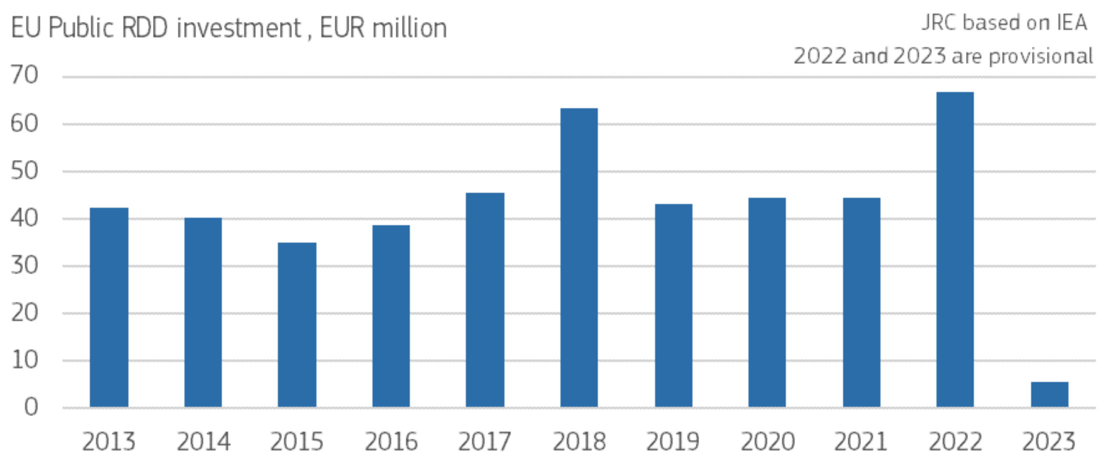
At global level, **Figure 7** shows public investment in the technology has been supported in particular by the EU, USA, Japan and Switzerland, but that overall funding for geothermal decreased over the last decade. In the EU, the reported spending on geothermal research (**Figure 8**) has been relatively constant over the last decade, implying a decrease in real terms. The growth in 2022 is due to significantly increased budgets from Poland and Austria. No data was reported for Italy since 2020, but before that it was a top funder. The EU supported geothermal with EUR 208 million under Horizon 2020 (2014-2020) and this has continued in Horizon Europe (2021-2027), with just over EUR 34 million to the end of 2023. In addition, the Innovation Fund has awarded EUR 95.5 million.

Figure 7 Global geothermal: public RD&D funding over the period 2010 to 2023



Source: JRC based on IEA

Figure 8. EU public RD&D funding for geothermal energy over the period 2010 to 2021.



Source: JRC based on IEA

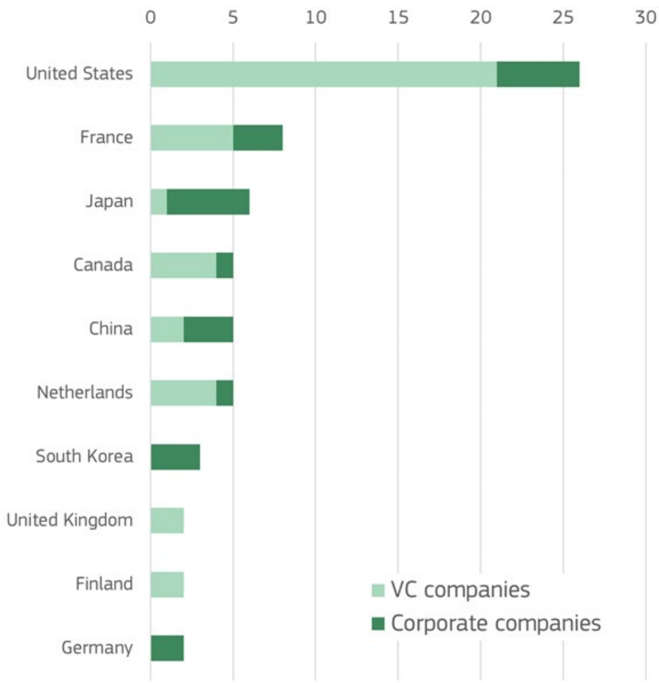
2.5 Private RD&I funding

As shown in Figure 9, 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).

2.5.1 Private R&I investments

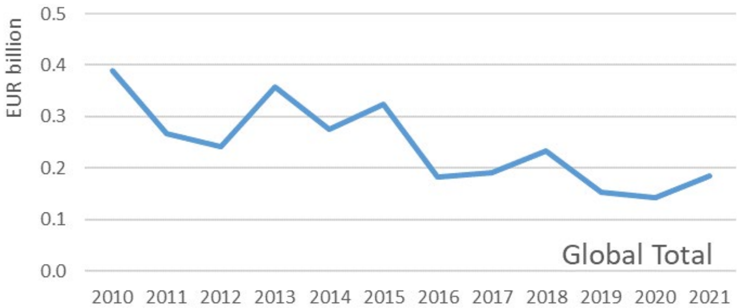
The level of private R&I uses patent data as a proxy [19, 20]. The data to 2021 (patent data have several years lag) are shown in **Figure 10** and indicate some increase in investment after a decade of decline. **Figure 11** shows the trend in cumulative investments over the 2020-2021 period. The EU was typically ranked 3rd or 4th in terms of annual. Investment in this period, although the 2020 data put it lowest (7th place). **Table 3** shows the top 20 organisations for R&D investments, globally (left) and the EU (right).

Figure 9- Number of innovating companies active over the period 2017-2022, by country (Top 10)



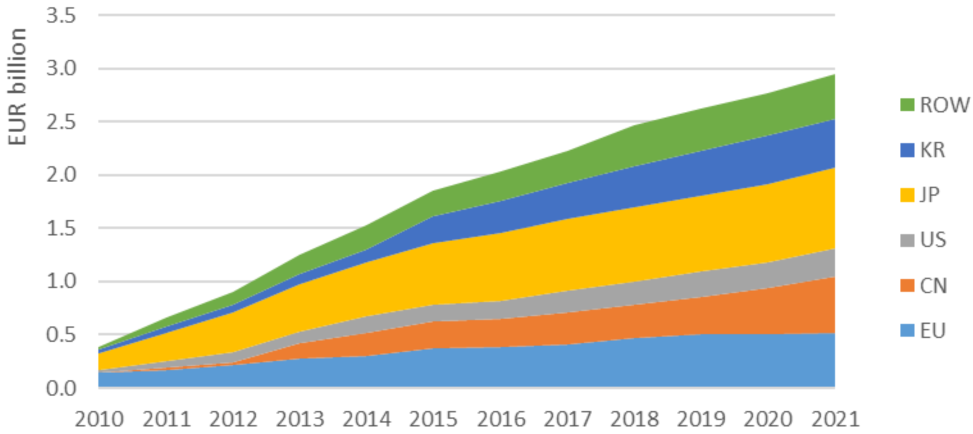
Source: JRC compilation: VC companies include start-ups that were founded or raised venture capital over the period considered. Corporate companies include subsidiaries of top corporate R&I investors with relevant high-value patents over the period considered.

Figure 10. Overall trend in annual R&D investments by private companies, using patenting data as proxy.



Source: JRC analysis

Figure 11. Trends in cumulative R&D investments for the EU and major economies (2020 data is near complete; 2021 data is incomplete).



Source: JRC analysis

Table 3 Top organisations globally for geothermal R&D investments since 2015, based on patenting data.

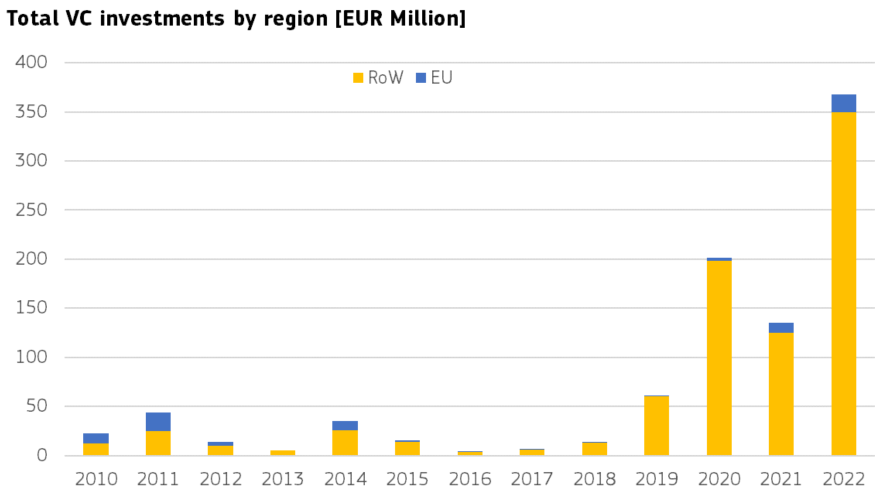
Global leaders, ranked		EU leaders, ranked	
Eavor Technologies Inc	CA	Steinhuser Gmbh Co KG	DE
Japan New Energy Co Ltd	JP	Agrana Beteiligungs Aktiengesellschaft	AT
Dae Sung Groundwater Ltd	KR	Heijmans Nv	NL
Jansen AG	CH	Climasolutions Gmbh	DE
Ecolab Inc	US	Apmh Invest Iv As	DK
Obayashi Corporation	JP	Brennero Innovazioni Tecnologiche Srl	IT
Petrochina Company Limited	CN	Hlscher Wasserbau Gmbh	DE
Est Co Ltd	KR	Quantitative Heat Oy	FI
Steinhuser Gmbh Co KG	DE	Red Srl	IT
Kyodo Tech Co Ltd	JP	Geomax Project Kft	HU
Gg Technology Co Ltd	KR	VITAL WOHNEN Gmbh Co KG	AT
China Petroleum Chemical Corporation	CN	E Tube Sweden Ab	SE
Good Water Energy Ltd	AU	Harjula Solutions Oy	FI
Aguricluster Corp	KR	Trias VM Gmbh	DE
Huaneng Clean Energy Research Institute	CN	Mefa Befestigungs Und Montagesysteme Gmbh	DE
Hans Development Co Ltd	KR	W-Filter Innovacio Kft.	HU
Mitani Sekisan Co Ltd	JP	Geocollect Gmbh	DE
Equinor Energy As	NO	Pfeil Bautrãƒâ¤Ger Gmbh	DE
Corona Corporation	JP	Huisman Well Technology	NL
Kotecengineering Co Ltd	KR	Jenkies Bv	NL

Source: JRC analysis of PATSTAT data

2.5.2 Venture capital investments

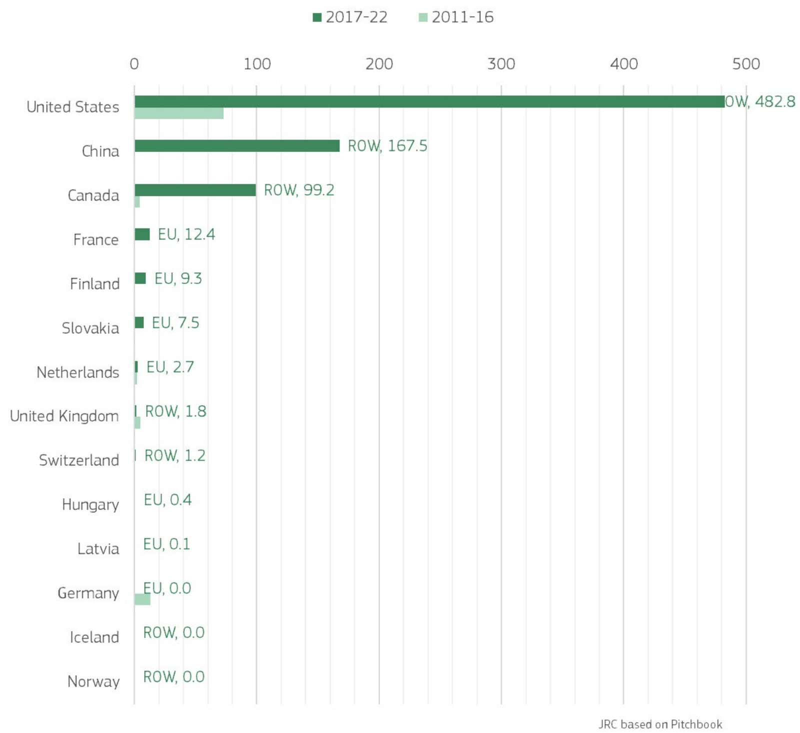
Global venture capital investment has increased sharply since 2019 and amounted to an all-time high of EUR 368 million in 2022, doubling the average investment seen in 2020 and 2021 (**Figure 12**). This confirms a clear acceleration of investment in start-ups and scale-ups active in the development 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 in the leading position. China follows, and while it hosts a much smaller number of companies, it has captured the largest realised deal over the period via the sole company Sinopec Green Energy. 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 12 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 13 Top countries in venture capital investments 2010 to 2022

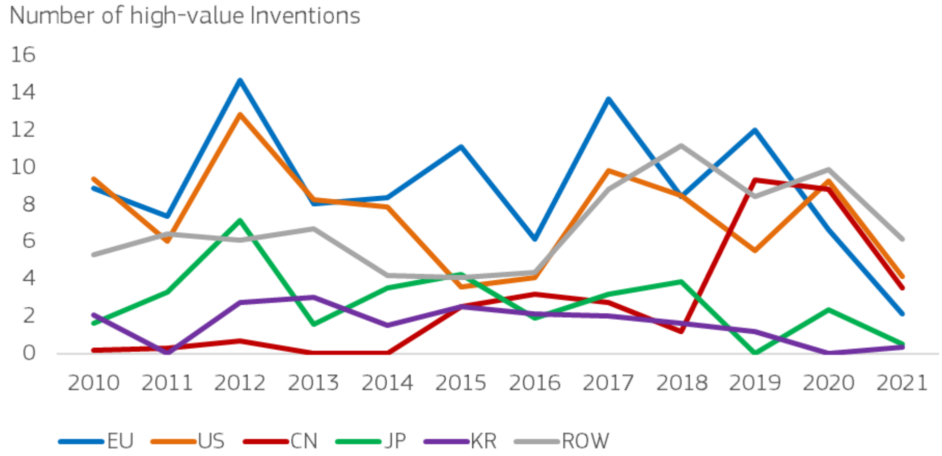


Source: JRC analysis based on Pitchbook data

2.6 Patenting trends

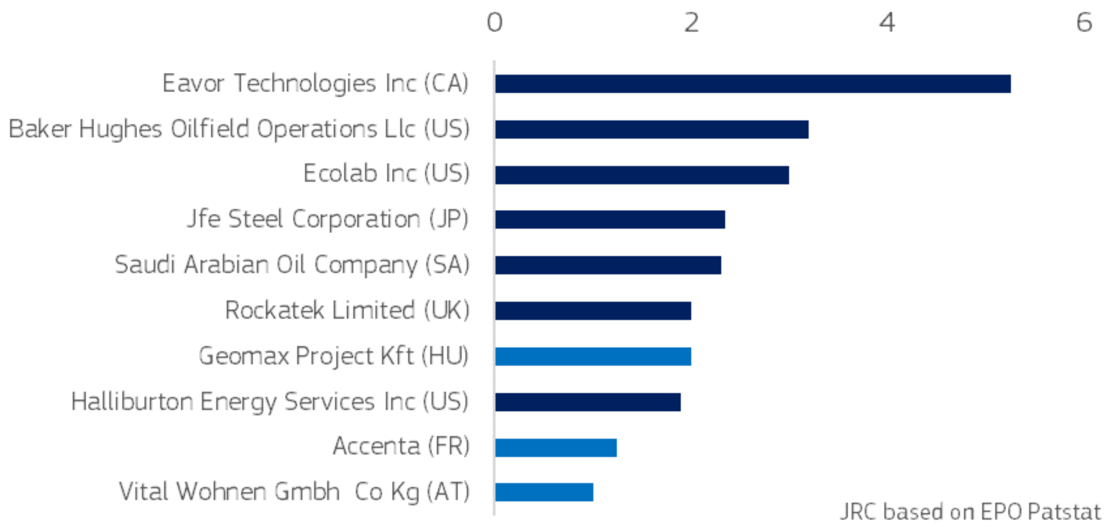
The analysis followed the JRC's methodology [20] applied to the Patstat (European Patent Office) data for the period to 2021. The relevant CPC code is Y02E 10/10 – geothermal energy. Globally, total inventions per year have grown from 150 in 2010 to over 300 in 2021[10], mainly due to a very significant rise in Chinese patents. For high value inventions i.e. patent families that include patent applications to more than one patent office., the EU was leader for most of the decade 2010-2020, but is now overtaken by RoW, US and China (**Figure 14**). **Figure 15** and **Figure 16** show the leading organisations and number of inventions in the same period worldwide and in the EU respectively.

Figure 14. High value invention i.e. with patents filed in more than one patent office, for geothermal from 2009 to 2021



Source: JRC analysis of PATSTAT data

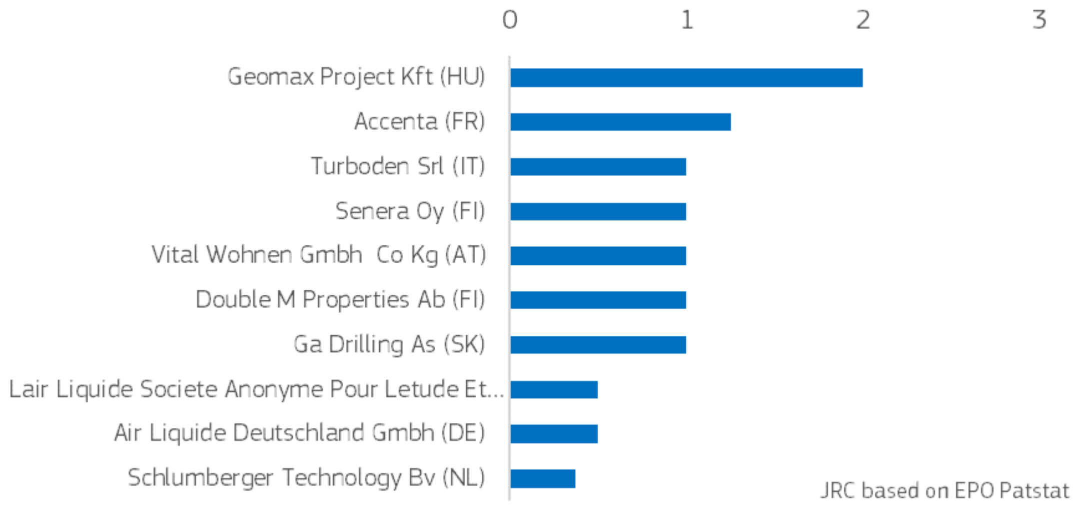
Figure 15 Top 10 entities globally for high-value inventions relating to geothermal energy.



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 16 Top 10 entities in the EU for high-value inventions relating to geothermal energy.

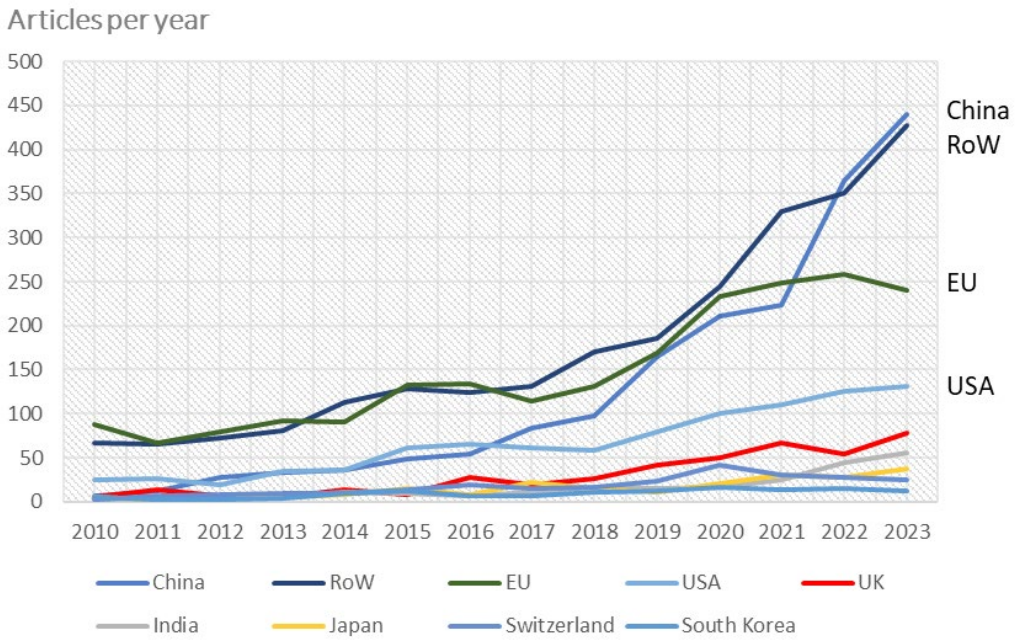


Source: JRC analysis of PATSTAT data

2.7 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 17** shows the time trend for the EU and leading countries and regions. In 2023 China was top with 30% of all articles, while the EU contributed 17%. For impact analysis, **Figure 18** ranks the h-index[12] values for the major country and country groupings based on the whole data set (2010-2023). On this basis, the countries in the RoW grouping have the highest h-value, EU is 2nd and China 3rd. In the EU, Germany leads on publications h-index, followed closely by Italy and France (**Figure 19**).

Figure 17. Trend in scientific publications on geothermal energy for the leadings countries and regions

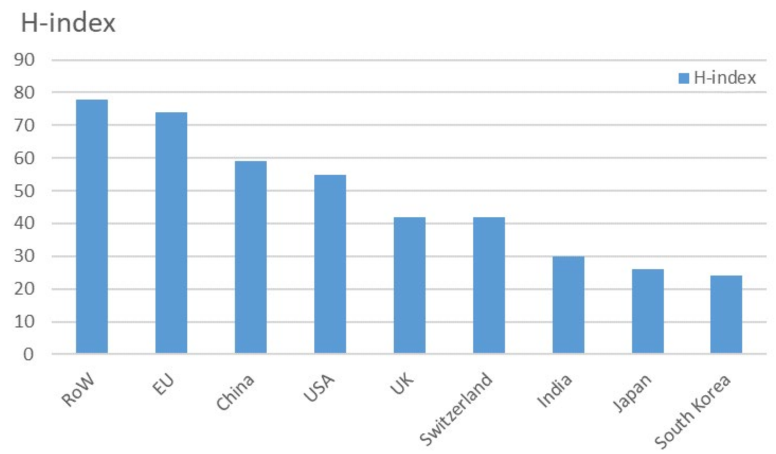


Source: JRC TIM data

[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"

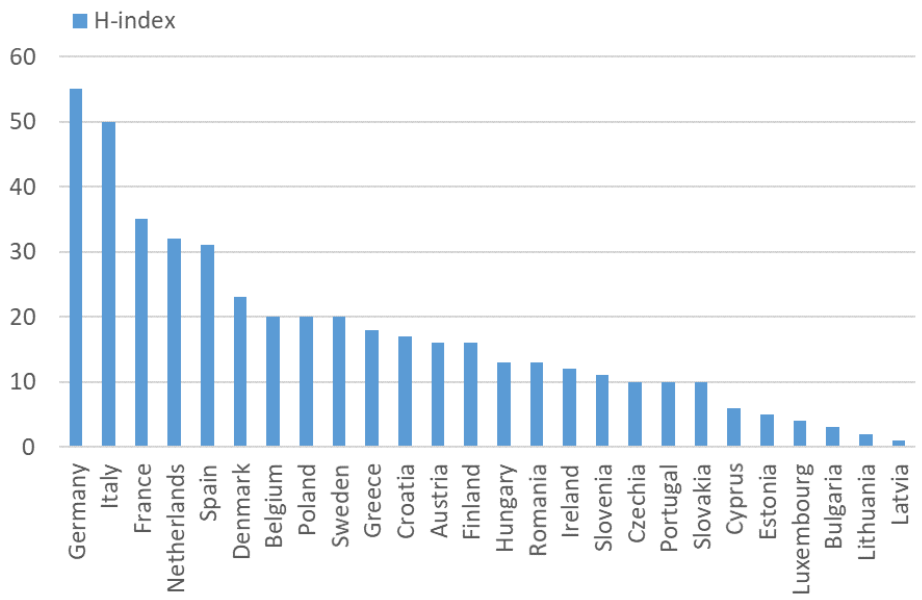
[12] h-index of a country: the largest number h such that at least h articles in that country for that topic were cited at least h times each.

Figure 18. Leading regions and countries for h-value scores for scientific publications on geothermal energy



Source: JRC TIM data

Figure 19 Leading EU countries for scientific articles on geothermal energy (ordered by H-index).



Source: JRC TIM data

2.8 Progress in EU-funded R&D projects

The annual European Commission report [22] to the IEA Technical Cooperation Programme on Geothermal provides an overview of projects with Horizon 200 and Horizon Europe funding to 2023, and following simply gives an overview.

The total amount of EU funding for geothermal energy projects from 2004 to 2023 is EUR 622 million, spread across 140 projects. Horizon 2020 provided the largest R&D funding for geothermal energy, with EUR 268 million allocated to 67 projects.

Projects completed in 2023 include GECO, GEO4CIVHIC, Geo-Drill, REFLECT, and GeoHex, among others. These focused on various aspects of geothermal energy, such as emission gas control, drilling technology, and heat exchange performance.

Ongoing HE projects include GeoSmart, EXCITE, HOCLOOP, and COMPASS, among others. These focus on topics such as geothermal energy storage, drilling technology, and enhanced geothermal systems.

HE projects started in 2023 include PUSH-IT, SMILE, and EarthSafe, and focus on topics such as high-temperature heat storage, coupled processes in geothermal systems, and deep geothermal power.

The reports also mentions:

- The Innovation fund project EAVORLOOP, which received €91.6 million in EU funding, making it the largest individual funding for a geothermal energy project.
- Several projects funded under the LIFE program, including COOLING DOWN, REDI4HEAT, and GEOBOOST. These projects focus on topics such as renewable cooling, geothermal heat pumps, and district heating and cooling.

Overall, the report highlights the EU's commitment to supporting research and innovation in geothermal energy, with a focus on reducing costs, increasing efficiency, and promoting the use of geothermal energy for heating and cooling.

3 Value Chain Analysis

3.1 Turnover

The global geothermal energy market is estimated at USD 66.24 billion (EUR 60 billion) in 2023, with a compound annual growth rate (CAGR) of 6.61% going forward[13].

For the EU, EurObserv'ER puts geothermal energy turnover at EUR 0.77 billion for 2022, down from EUR 0.92 billion in 2021 [9].

3.2 Gross value added

The EurObserv'ER barometer [9] estimates the EU GVA at EUR 420 million for 2022, down from EUR 470 million in 2021 (with marked reductions in Germany, Poland and the Netherlands).

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 2 summarises the information collected.

3.4 Role of EU Companies

The 2023 EGEC market report [4] includes a qualitative assessment of the geothermal energy supply chain in Europe. **Table 4** summarises the roles of European and international suppliers and manufacturers in the main stages of project development and operation. A reasonable positive picture emerges, consistent with the 2023 ENTEC study on the strategic importance of the NZIA technologies [23]. 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.

It is estimated that the geothermal sector is currently compliant with the goal of the Net-Zero Industry Act (NZIA) to provide at least 40% of the EU's annual deployment needs for strategic net-zero technologies by 2030. However a more quantitative approach will be needed to understand the industry supply chains and the associated criticalities going forward.

3.5 Employment

IRENA put the global employment for geothermal (including ground-based heat pumps) at 160 000 jobs for 2023 [25], a decrease from 165 000 jobs in 2021. At this level it represents 1% of the total jobs in renewables (16.2 million).

For the EU, EurObserv'ER puts the combined direct and indirect employment for (deep) geothermal at 6 200 in 2022, a drop from 7 300 in 2021 [10]. This represents 0.4% of their estimate of total EU employment in renewables (1.69 million, direct and indirect).

3.6 Energy intensity and labour productivity

The energy payback time of geothermal is estimated to range from around 2 months to 3.5 years [24]. For geothermal energy, with the main source of energy consumption (beyond the electricity used during operation) comes from well drilling, power plants and pipe construction.

Using EurObserv'ER data, for 2022 the turnover per job was EUR 124 000/job, about average for renewables in the EU. For reference, the highest value was for wind (EUR 158 000/job) and the lowest for biofuels (EUR 82 000/job) [9].

3.7 EU Production Data

At present the EUROSTAT PRODCOM statistics have not been analysed for geothermal systems, since the components do not have unique codes.

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

Table 4 Overview of the role of European and international companies in the EU geothermal sector

Stage	**Typical components & services**	**Europe/EU position**	**International role in European market**
Site investigation and resource assessment	Mapping software and seismic exploration and measurement tools	Good presence in software services and equipment; significant SME involvement	Major US equipment providers
Resource development: drilling and sub-surface engineering	Drilling equipment and services; underground piping and cementing; filters, submersible pumps	Good European market share	Strong North American players; increasing Chinese competition for some aspects
Resource utilisation and management	Surface equipment: piping, heat exchangers, turbines, generators	Significant players for all types of equipment	Many strong international players e.g. for turbines. Increasing competition from international manufacturers of heat exchangers, valves etc.
Operation and sustainable management		Most EU plants are EU-operated	

Source: JRC synthesis of EGEC reporting [24]

4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

The market for geothermal shows modest growth globally, with prospects to expand considerably as countries and regions implement their decarbonisation policies. The theoretical potential far exceeds the current electricity demand in many countries, but only a small portion of the heat in place can be realistically extracted for energy production by current systems working at depths up to 3-4 km. EGS systems, if fully developed, could access depths of up to 10 km.

The industrial position in Europe is seen as reasonably positive, although the EU is underrepresented in the exploration and drilling services. Vonsee et al [26] 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:

- 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.

For heating and cooling the following is specifically noted (based partly on EGEC information):

- 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

4.2 Trade (Import/export) and trade balance

There are no unique COMEXT codes for geothermal equipment, so no trade flow analysis can be presented.

4.3 Resource efficiency and dependence in relation to EU competitiveness

The main raw materials used in geothermal energy systems are listed in Table 5, together with their status in regard to the EU's 2023 list of critical raw materials. The main sensitivities come from construction materials (alloying elements for steel, aluminium, copper), although the share of these used in this sector is dwarfed by that of other technologies and industries.

Geothermal is unique in offering the possibility of extracting materials from the geothermal brine. Minerals such as gold, caesium, rubidium, manganese, zinc, lithium, and high-purity silica can be economically recovered from geothermal brines. EGEC claims that geothermal could provide approximately 20% of the EU demand in lithium by 2050. Commercial extraction of lithium from geothermal brines is being developed in southern Germany, Canada, and the United Kingdom. European R&D projects are also addressing the extraction of raw materials from geothermal brines. CRM-geothermal (2022-2026) will improve an existing atlas of geothermal fluid and critical raw material content and evaluate the potential of different extraction locations in Europe and East Africa.

A recent EC study on long-term security issues for clean technology value chains [26] noted the following concerning geothermal energy:

- Some critical raw material dependencies (as mentioned above).
- Moderate risk of availability of equipment produced outside of Europe
- Moderate risk that the emission of pollutants and GHGs linked to geothermal power plants may pose a challenge to their operations due to environmental regulations and public acceptance concerns.
- Skills are also a moderate risk for deployment as it requires a ”well-trained, specialised workforce”. The study also pointed out that the sector faces shortages of skilled labour, alos within regulatory and permitting agencies.

Table 5 Key raw materials for the geothermal sector

Material Supply	CRM status	Geothermal Use
Aluminium	Yes, indirectly (bauxite)	Plant construction
Carbon (coking coal)	Yes	For steel manufacture, 63% import dependency
Chromium	No	For steel
Copper	Yes	Generator, electrics
Epoxy/Plastics	No	Piping
Iron	No	Well piping, and above ground heat distribution
Molybdenum	No	For steel
Neodynamium	Yes	Permanent magnets in generators
Nickel	No	For steel
Titanium	Yes	For structures

Source: JRC elaboration of ETIP-DG data [24] and Vonsee et al [26].

5 Conclusions

Of the commercially-developed renewable energy technologies, geothermal energy is the smallest sector despite considerable potential in many locations.

Globally, geothermal power grew by less than 1% in 2023 to reach a total installed capacity of 14.8 GW. The EU's net capacity was unchanged at 0.877 GWe in 2023, and generated 6.2 TWh (0.2% of total demand). Although conventional geothermal power systems using hydrothermal reservoirs are cost competitive, only a limited number of locations have been identified so far with access to high temperature fluids using conventional technology. Enhanced geothermal systems using injection methods into deep rock offer promise but costs are non-competitive at present. Several EU-supported projects are exploring EGS, including in particular the EAVOR loop pilot system in Germany with Innovation Fund and EIB support.

For geothermal heat production, the EU outlook is more promising, with a growth rate of 10% over the last decade. 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. The EU's goal is to triple geothermal heat by 2030, implying an increase to approximately 114 GWth (81 TWh).

Investments in research and innovation, both public and private, have shown an overall decreasing trend, both globally and in the EU. More encouragingly, venture capital investment has seen strong growth in the period 2019-2022 with US, China and Canada leading the way. The EU has seen much less VC investment in the same period

In term of scientific output, for patents in 2021 (most recent available data) EU ranked third behind RoW and USA/China (Joint 2nd). Within the EU for the period 2018-2021 the leaders are Germany, France and Hungary. For scientific publications, in 2023 EU-based authors was involved in 17%, less than China (30%) and the group of countries identified as "rest-of-world (also 30%). Within the EU, the leaders are Germany, Italy and France

In the EU the turnover, gross value added and employment all dropped slightly in 2022 compared to 2021. Turnover was down to at EUR 0.77 billion from EUR 0.92 billion in 2021, likewise GVA (EUR 420 million for 2022, down from EUR 470 million in 2021) and jobs (6 200 in 2022, down from 7 300 in 2021).

It is estimated that the geothermal sector is currently compliant with the goal of the Net-Zero Industry Act (NZIA) to provide at least 40% of the EU's annual deployment needs for strategic net-zero technologies by 2030. However, a more quantitative approach will be needed to understand the industry supply chains and the associated criticalities going forward.

For critical raw materials, the EU has relatively low exposure, mostly through alloying elements used in construction materials and for titanium used for filters. On the other hand, geothermal is unique in offering the possibility of extracting materials from the geothermal brine, and this is being actively pursued in several EU locations.

Broader sustainability "Issues are pollutants and GHGs that are emitted from geothermal wells. In addition, contaminants could be emitted into the water. To mitigate emissions appropriate containment of both gases and effluents is necessary. Seismic risks may also pose a challenge to operations due public acceptance concerns.

Skills are an area of concern for geothermal energy, as it requires a well-trained, specialised workforce. Also regulatory and permitting agencies need staff with appropriate skills and expertise.

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List of abbreviations and definitions

ATB	NREL Advanced Technology Baseline
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
COP	Coefficient of Performance
CPC	Cooperative Patent Classification
DHC	District Heating Cooling
EGEC	European Geothermal Energy Council
EGS	Engineered/Enhanced Geothermal System
FiT	feed-in tariff
FOAK	First–of-a-Kind
GSHP	Ground Source Heat Pump
H2020	EU Horizon 2020 Programme
IA	Innovation Action
IRENA	International Renewables Energy Agency
LCoE	levelised cost of electricity
NECP	National Energy and Climate Plan
NREAP	National Renewable Energy Action Plan
NREL	National Renewable Energy Laboratory
OPEX	Operating Expenditure
ORC	Organic Rankine Cycle
PPA	power purchase agreement
PV	photovoltaic
RES	Renewable Energy Source
RoW	Rest of world
SET	Strategic Energy Technology
SME	Small-Medium Enterprise
TES	Thermal Energy Storage
TRL	Technology Readiness Level
UTES	Underground Thermal Energy Storage

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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, literature
	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	CORDIS
Value chain analysis	Turnover	EurObserv'ER
	Gross Value Added	EurObserv'ER
	Environmental and socio-economic sustainability	JRC analysis of various sources
	EU companies and roles	EGEC, literature
	Employment	IRENA, EurObserv'ER
	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	No data
	Resource efficiency and dependencies (in relation EU competiveness)	Literature, EGEC

Source: JRC 2024

Annex 2 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

A2.1 POTEnCIA Model

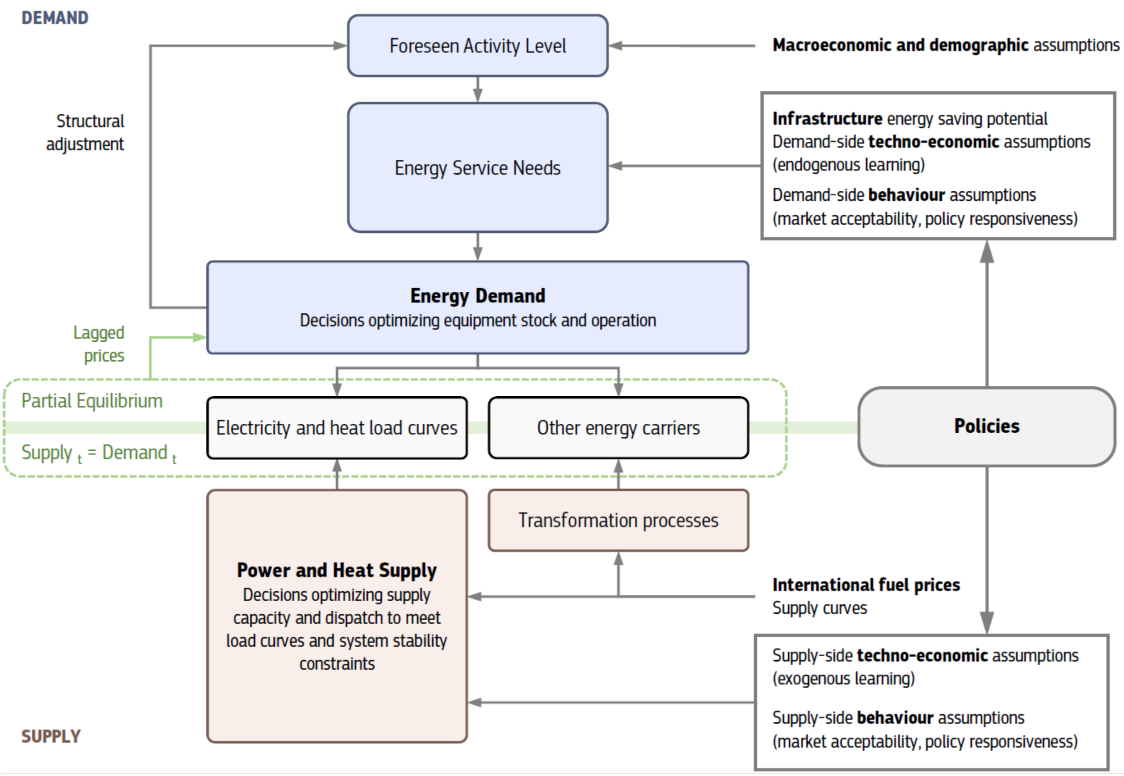
A2.1.1 Model Overview

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 (detailed in Mantzos et al., 2017, 2019) 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.

Figure A2.1 The POTEnCIA model at a glance



Source: JRC adapted from (Mantzos et al., 2019)

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 CO_2 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; Rózsai et al., 2024).

A2.1.2 POTEnCIA CETO 2024 Scenario

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 EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level 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 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the POTEnCIA CETO 2024 Scenario will be available in the forthcoming report (Neuwahl et al., 2024).

A2.2 POLES-JRC model

A2.2.1 Model Overview

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. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

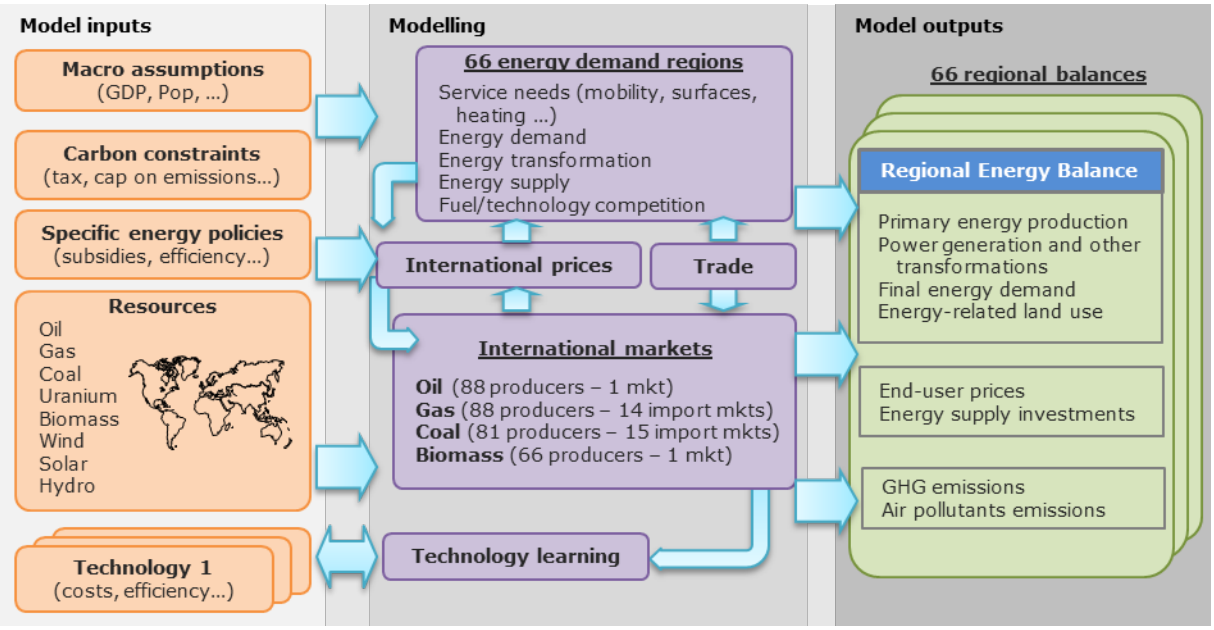
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

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://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

A detailed documentation of the POLES-JRC model is provided in (Després et al., 2018).

Figure A2.2 Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

A2.2.2 POLES-JRC Model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand
Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning
Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characeristics of the power technologies.

Hydrogen

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

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- 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 gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

A2.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The *Global CETO 2°C scenario 2024* and its specific POLES-JRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" (Schmitz et al., 2024).

The *Global CETO 2°C scenario 2024* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects:

- The version of the POLES-JRC model used for the Global CETO 2°C scenario has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.
- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the *Global CETO 2°C scenario 2024* regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

A2.3 Distinctions for the CETO 2024 Scenarios – POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

- The *Global CETO 2°C scenario 2024* (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.
- The *POTEnCIA CETO 2024 scenario* is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050.

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Annex 3 Sustainability Assessment Framework

SUSTAINABILITY ASPECT	METHOD/ APPROACH	INDICATOR(S)	GEOTHERMAL TECHNOLOGY IN THE EU	ADDITIONAL INSIGHTS
SECURITY				
Market trend	Assessment based on energy statistics and literature review for insights or forecasts	Forecasts energy demand	Power: 12% growth from 2012 to 2023. Draft revisions of the NECPs foresee 33% increase to 2030 Heat: 10% annual growth since 2010. 12% growth required to triple geothermal heat by 2030, as proposed in COM(2022)221,	See section 2.2.1 in this report
Trade and trade balance	Analysis of COMEXT data	Imports, Exports, Trade Balance	Not assessed	Geothermal uses a diverse range of components, most of which are not specific to this application and not covered by unambiguous trade codes
Cost of energy	Assessment based on energy statistics and literature review for insights or forecasts.	CAPEX, OPEX, LCoE	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
Critical Raw Materials (CRMs)	Use EC list of CRMs as reference to assess potential supply chain bottlenecks.	CRMs used	Use of steel, copper and titanium for various components and structures, and neodymium in permanent magnets for generators	A range of CRMs can extracted from the geothermal brine (see section 4.3)
Technology-specific permitting requirements	No specific guidance	N/A	Drilling, production and injection are regulated by national mining laws and/or by the water authorities	
Skills and technology development	N/A	N/A	N/A	Future growth scenarios require a skilled work force – see for example the Roadmap Deep Geothermal Energy for Germany[14]
Resilience	Qualitative assessment of e.g. diversity of suppliers and technologies; risk reduction and adaptive capacity	N/A	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	

[14] *Bracke, R. and Huenges (editors, 2022) Roadmap Deep Geothermal Energy for Germany – Recommendations for action for politics, business and science for a successful heat transition. https://doi.org/10.24406/ieg-n-645792*

SUSTAINABILITY ASPECT	METHOD/ APPROACH	INDICATOR(S)	GEOTHERMAL TECHNOLOGY IN THE EU	ADDITIONAL INSIGHTS
Environmental				
Resource efficiency and recycling	Circular economy indicators	Material recovery rates	N/A	Metallic component and structures can be recycled by conventional methods Geothermal brines can provide materials; water (after cleaning) can be used in irrigation[15].
Energy balance	Quantitative indicators	Energy Pay Back Time (EPBT) Energy Return on Energy Invested (EROI)	EPBT 0.2 to 3.5 years[16]	The main source of energy consumption beyond electricity during operation comes from well drilling, power plants and pipes construction. The values here also consider the total fossil fuel use during construction, operation and dismantling,
Climate change	LCA / Product Environmental Footprint (PEF)	Global warming potential (GWP100) kgCO2eq/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 Source: EC Study on 'Geothermal plants' and applications' emissions: overview and analysis'. Final Report, 2020, ISBN 978-92-76-04112-2.	Most emissions are carried by geothermal fluids from the reservoir and there is great variability due to the geological conditions. The review by Jingyi Li et al (footnote 25) reports that flash and dry-steam plants can show high GWP. Organic Rankine Cycle plants show lower GWP: for natural reservoirs 13-126 gCO2eqv/kWh, and for EGS 33 gCO2eqv/kWh
Ozone depletion	LCA / PEF	Ozone Depletion Potential (ODP)		See info the meta-review referenced in footnote 25
Particulate matter/Respiratory inorganics	LCA / PEF	Human health effects associated with exposure to PM2.5		See info the meta-review referenced in footnote 25
Ionising radiation, human health	LCA / PEF	Human exposure to ^{235}U		See info the meta-review referenced in footnote 25
Photochemical ozone formation	LCA / PEF	Tropospheric ozone concentration increase		See info the meta-review referenced in footnote 25
Acidification	LCA / PEF	Accumulated Exceedance (AE)		See info the meta-review referenced in footnote 25

[15] *Jingyi Li et al, Life cycle sustainability assessment and circularity of geothermal power plants, Sustainable Production and Consumption, Volume 35,, 2023,Pages 141-156,ISSN 2352-5509, https://doi.org/10.1016/j.spc.2022.10.027.*

[16] European Environmental Bureau (2021): RESET - Reference Environmental Standards for Energy Techniques – Guidance. Final Version, October 2021

SUSTAINABILITY ASPECT	METHOD/ APPROACH	INDICATOR(S)	GEOTHERMAL TECHNOLOGY IN THE EU	ADDITIONAL INSIGHTS
Eutrophication, terrestrial	LCA / PEF	Accumulated Exceedance (AE)		See info the meta-review referenced in footnote 25
Eutrophication, aquatic freshwater	LCA / PEF	Fraction of nutrients reaching freshwater end compartment (P)		See info the meta-review referenced in footnote 25
Eutrophication, aquatic marine	LCA / PEF	Fraction of nutrients reaching marine end compartment (N)		See info the meta-review referenced in footnote 25
Land use	LCA / PEF	Power density, m2/kWh Soil quality index[17]	0.04 to 0.4 km^2/TWh	Soil health: low impact, but no specific data available
Water use	LCA / PEF	User deprivation potential (deprivation weighted water consumption)	0 to 14 m3/MWh	European Environmental Bureau, 2021
Resource use, minerals and metals	LCA / PEF	Abiotic resource depletion (ADP ultimate reserves)	Not assessed	
Resource use, energy carriers	LCA / PEF	Abiotic resource depletion - fossil fuels (ADP-fossil)	Not assessed	
Biodiversity	Descriptive, based on current EU legislation	N/A	N/A	Geothermal plants can influence ground water ecosystems and may also be close to protected areas and Key Biodiversity Areas. Appropriate actions are needed to manage possible biodiversity impacts effectively.
Social				
Child labour	Assess main suppliers and countries involved in the production of raw materials, intermediate products and components used	Percentage of working children under the legal age or 15 years old (total, male and female) – country level	No information	Requires analysis of raw material supply chains

[17] Aggregating: Biotic production, Erosion resistance, Mechanical filtration and Groundwater replenishment

SUSTAINABILITY ASPECT	METHOD/ APPROACH	INDICATOR(S)	GEOTHERMAL TECHNOLOGY IN THE EU	ADDITIONAL INSIGHTS
Forced labour	Assess main suppliers and countries involved in the production of raw materials, intermediate products and components	Frequency of forced labour (estimated prevalence of population in modern slavery, victims per 1,000 population) - country level	No information	Requires analysis of raw material supply chains
Equal opportunities / discrimination	Reference scale	Gender wage gap (%) Women in the labour force (ratio)	No information	For EU-based activities, subject to EU law
Freedom of association and collective bargaining	Reference scale	Right to strike / Right to association / Right of collective bargaining (point in scale) Trade union density (%)	No information	For EU-based activities, subject to EU law
Working hours	Reference scale	Hours of work per employee and week (hours)	No info	For EU-based activities, subject to EU law
Fair salary	Wages	Sector average wage, per month, Living wage, per month, Minimum wage, per month (Eur/month) country/sector level	No info found	
Health and safety	Accident and fatality rates	Rate of fatal and non-fatal accidents at workplace (# per 100,000 employees), country/sector level	No information found	
Responsible materials sourcing	Descriptive assessment of severe risks in a technology's value chains; see also OECD guidance[18]	N/A	Not assessed	

[18] *OECD (2016), OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas: Third Edition, OECD Publishing, Paris, https://doi.org/10.1787/9789264252479-en.*

SUSTAINABILITY ASPECT	METHOD/ APPROACH	INDICATOR(S)	GEOTHERMAL TECHNOLOGY IN THE EU	ADDITIONAL INSIGHTS
Competition for material resources (incl. water, land, food) and indigenous rights	Descriptive, using e.g. insights from the Environmental justice Atlas	N/A	Not systematically assessed	The EJA list several cases for geothermal on the EU, but it is unclear if the information is up-to-date
Contribution to economic development, including employment	Sector GVA Sector employment	GVA, % of GDP FTE jobs (direct and indirect)	2020: 96 000 worldwide, 40 000 in EU,	slight growth tendency (direct geothermal energy employment, power/heat; source: IRENA Jobs database)
Affordable energy access	No specific guidance	N/A	N/A	Geothermal has a competitive levelised cost energy, and can help keep prices down.
Public acceptance	Descriptive, based on narratives and literature review	N/A	Generally positive image, but in some locations negative perception. Typical concerns: induced seismicity, groundwater pollution, noise pollution, immature technology[19]	
Rural development	No specific guidance indicators can be selected from the FAO Guidelines[20] on defining rural areas and compiling indicators for development policy	Not analysed	Can provide energy (in particular heat) to the agricultural sector near geothermal plants, as well as employment opportunities in rural areas	

Sources: JRC analysis of literature

[19] *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)*

[20] *FAO Guidelines on defining rural areas and compiling indicators for development policy, 2018.*

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