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DEEP GEOTHERMAL HEAT AND POWER IN THE EUROPEAN UNION

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

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Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

CETO is being implemented by the Joint Research Centre for DG Research and Innovation, in coordination with DG Energy.

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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 heat systems. Shallow geothermal energy systems are not covered here, but ground-source pumps are addressed in a companion CETO report.

Globally, deep geothermal energy for electricity generation has seen steady growth in a number of countries, reaching a total installed capacity of around 14.4 GW in 2021. The EU's net capacity was 877 MWe in 2021, but growth is well below the global trend For geothermal heat production in the EU, the outlook is more promising, with EurObserv'ER expecting growth from 870.5 ktoe in 2020 to 1000 ktoe in 2030. In particular the geothermal district heating and cooling (DHC) sector has shown a growth rate in installed capacity of 6%, and there are now 262 systems with a total installed capacity of 2.2 GWth. Growth was led by projects in France, the Netherlands and Poland.

Deep geothermal projects still face the problem of high risk up-front expenses and often complicated licensing issues. 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. 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 focus of geothermal R&I is changing with time, both for EU and national or transnational funding schemes. For example drilling and development of EGS were topics with several funded projects in H2020 and in the first rounds of Geothermica as well as in several nationally funded R&I programmes. That way it was possible to develop technologies from lower TRL to demonstration projects. Looking at these different funding frameworks and national developments, there seems to be a shift towards heating & cooling in urban environments and integration of high temperature storage.

Several successful project developments were able to build on previous projects. For Enhanced Geothermal Systems, the development of the Soultz-sous-Forêts site was a milestone, and all subsequent EGS projects built on the lessons learnt there. Stimulation technologies have been further developed, for example in the DESTRESS project, where the zonal isolation concept for targeted and controlled hydraulic stimulation was tested, which was then further refined in the Geothermica project ZoDrEx and finally applied at the real scale in the FORGE in the USA, funded by the Swiss Federal Office of Energy. Similarly, the adaptive traffic light system applied in the Geothermica projects COSEISMIQ and DEEP was developed in a Swiss project and within the FP7 project GEISER.

In other geothermal R&I priority topics such continuous development was not always possible. For example, geothermal exploration, advances made in IMAGE (FP7) were further developed and applied in GEMex (H2020), leading to breakthroughs in tracer technology for supercritical fluids, in fibre optic monitoring and in integration of multiple geophysical, geological and geochemical datasets. But there has not been a systematic support of exploration and resource assessment projects in the existing R&I framework programmes. Nonetheless. recent progress enabled by ever increasing computing power, allowing the incorporation of more detailed data and structures in geological models, corresponding software developments and technological advances such as fibre-optic sensing for distributed temperatures, distributed acoustic signals and distributed strain measurements at unprecedented resolution requires even new exploration approaches not yet addressed. Drone imaging provides new data sets from inaccessible areas in relatively short time. The wealth of these new data can take advantage of machine learning approaches to process and interpret all the potentially available information. Many of these developments were not mature at the time of the last EU funded exploration project (GEMex).

Overall, it can be seen that several projects are often needed to bring developments to maturity required for market uptake. This suggests a mission-driven approach would be beneficial for the steady and targeted development of the EU's R&I priorities. Such an approach includes the non-technological aspects such as regulatory issues, project economics and stakeholder involvement.

1 Introduction

1.1 Overview

Geothermal energy developments in Europe have seen a somewhat sluggish growth rate, compared to other renewable technologies. This slow growth is not uniform across all fields, requiring a more detailed look to distinguish between the different fields and their distinct challenges and obstacles. For example, ground-source heat pump systems are considered a mature technology, and installations are on a stable growth path. Increased demand in the last two years, however, could not be met due to lack of capacity: components were not delivered in time, skilled workers were not available as much as required, and public administrations and licensing authorities were often overwhelmed (and understaffed) by the increasing demand.

Deep geothermal projects still face the problem of high risk up-front expenses and often complicated licensing issues. 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, when they are developed for heating & cooling, except in regions where the natural heat flow is high enough to make high fluid temperatures at shallow depths accessible, as in the countries with the highest installed capacities for electricity provision: Turkey, Italy and Iceland. Heating projects, even though successful in several places, are usually not in the focus of national or European energy debates, which is reflected by the lower decarbonisation rates for the heating/cooling sector compared to electricity. The incentive to move away from cheap gas or from waste heat generated at large coal-fired power-plants was simply not great enough. In addition, projects trying to develop 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.

In the last few years, however, the situation and the boundary conditions have changed, indicating a possible new era for geothermal development. Large oil & gas companies are beginning to invest in geothermal developments for heating and/or electricity, for example Shell Geothermie BV in the Netherlands, Engie (formerly GDF Suez) in several European countries, Repsol in Spain. This does not only add economically strong developers to the market but also highly skilled and experienced experts on all aspects of subsurface developments. The effect of the Paris Agreement, climate change and the related need to change our energy supply system has reached communities and heat suppliers. National Roadmaps or Masterplans for geothermal developments are published with ambitious targets for 2030 and 2050 (e.g., Netherlands: Masterplan Geothermie, 2018; Germany: Roadmap Deep Geothermal Energy, Bracke & Huenges 2022). Subsurface data are increasingly made available. More and more geothermal training courses, summer schools, and academic courses at the BSc and MSc levels are established in university curricula. And last but not least the shocking awareness that gas prices can soar unexpectedly as cheap natural gas from Russia is not available for the time being has raised awareness of available alternative heat sources.

In addition, new developments and trends make geothermal energy more attractive as a technical solution. Large high-temperature heat pumps are currently being developed to increase temperatures beyond 80°C, which will make lower temperature geothermal sources attractive not only for residential heating but also for district heating networks and industrial processes. At the same time, “medium-deep” geothermal resources are successfully targeted and developed. These resources are deeper than what is normally considered shallow, such that a temperature range of 30-60°C is encountered. These temperatures were formerly considered unattractive for development, but in combination with modern, well-insulated buildings and potentially powerful heat pumps, these resources have become attractive. They are easier (and cheaper) to access, have often better reservoir properties than the deeper reservoirs with resulting high flow rates and are quite abundant everywhere in Europe. The challenge is now to adapt rules and regulations to conditions of this new resource. The safety requirements applicable for deep drilling are probably more than what is necessary for the shallower resources, making their development more costly and complicated than appropriate, but the regulations applying to shallow (usually drinking water) wells are also not applicable.

Other developments are related to heat and cold storage in the subsurface. Various geothermal options have been explored and are now ready to be tested at the large scale and for higher temperatures: Aquifer Thermal Energy Storage (ATES) is well-established at shallow depths and now ready to expand to greater depths and higher temperatures. Progress in the design and layout of large-scale borehole heat exchangers allow efficient thermal storage (heating & cooling) almost everywhere, and hundreds of abandoned mines all over Europe can serve as large volume thermal storage infrastructure. These options can play a key role in the compensation of seasonal fluctuations of the asynchronous heat demand and supply from intermittent sources, including a power-to-heat option for excess electricity supply in the summer.

Another promising development is the extraction of critical raw materials from geothermal brines, as they are co-produced with the energetic use of the fluids. These developments are just at the beginning and require technology development for the efficient extraction, but they already raise enormous interest in the industry.

Also the "old" geothermal technologies are ready for new developments. As district heating networks are being refurbished or newly developed, geothermal energy is always an option as a source for the heat to be distributed. New technological developments such as distributed fibre optic sensing, drone imaging and machine learning make more information and data available and allow us to analyse and use them with advanced software solutions, to address subsurface uncertainty with unprecedented detail, complexity and precision. These technologies, data acquisition and monitoring systems also open completely new opportunities for resource assessment and exploration, reducing the drilling risk and expanding the potential drilling targets. And last but not least, many of the new technologies developed and tested in recent RD&I projects will come to the market. These have the potential to advance our drilling progress, safely develop EGS and control the risk of induced seismicity.

At the same time, new, potentially disruptive technologies and ideas already reached the project pipelines for low TRL developments: for hot and dry rocks the Closed-Loop Geothermal System (e.g., Beckers et al., 2022) promises to serve as a solution without the need of a natural reservoir nor the risks of stimulation measures, by drilling multiple parallel horizontal wells. This technology will be tested at the real scale in the near future. Another emerging option is geothermal power production using stored CO_2 in a combination with CCUS. This approach has long been proposed (e.g., Randolph and Saar, 2011) and is under development for field trials by academic and industry partners.

It is the role of this review to summarise the RD&I developments in the geothermal sector since 2019, to give an overview what technologies are emerging as new solutions and where more support is required.

1.2 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. As such, these are typically organised in three main sections: technology maturity status, development and trends; value chain analysis and global markets and EU positioning. Here the focus is on deep geothermal energy for power and direct heat applications, in particular district heating and cooling systems (DHC). Shallow geothermal energy systems are not covered here, but ground-source pumps are addressed in a companion CETO report (Lyons et al, 2022).

For 2002 the work on deep geothermal energy has focused on technology maturity status, development and trends. For this reason a simplified format is used, covering the following topics:

- Technology Readiness Level
- Installed capacity
- Technology Costs
- R&I funding
- Patenting trends
- Scientific publication trends

— R&I project developments

These are complemented by sections on new trends and on environmental and social sustainability.

The report uses the following information sources:

— The study contract performed for the CETO project by Prof. D. Bruhn,
— Information from EU-funded research projects
— Trade association reports, market research provider reports and others as appropriate
— JRC own review and data compilation
— Existing studies and reviews published by the European Commission (Shortall et al, 2019, Carrara et al, 2020).

The deep geothermal value chain and market situation was reviewed in the staff working document accompanying the Commission's 2020 progress of clean energy competitiveness report (European Commission, 2020. A perspective on the current European market situation is available in the 2021 European Geothermal Energy Council Market Report (EGEC, 2022).

2 Technology State of the Art

Geothermal is a mature, commercially proven technology. It can provide low cost, energy supply with the highest capacity factor of all renewable energy sources in geographies with very good to excellent high-temperature conventional geothermal resources, close to the Earth's surface. The development of unconventional geothermal resources, however, such as EGS or 'hot dry rocks' (HDR), is much less mature. Such projects usually come with significantly higher costs, due to the deep drilling required and the additional stimulation measures needed to bring operations to an economically viable level, rendering the economics of such initiatives currently much less attractive (IRENA, 2021).

Recent international research and developments into more innovative, low-cost drilling techniques and advanced reservoir stimulation methodologies for EGS have delivered some promising results. If and how they will help lower development costs and realise the full potential of enhanced geothermal resources, remains to be seen.

One of the most important challenges faced when developing geothermal energy generation projects lies in the availability of comprehensive geothermal resource mapping. Where it is available, uncertainties developers face during the exploration period are reduced, potentially reducing financial risk and development costs. In most countries in Europe, proprietary subsurface data are not generally made available. A good example of a well-managed and easily accessible information system is the database nlog.nl in the Netherlands, where all available data older than 5 years are listed, including petrophysical and geophysical data. Such comprehensive and accessible availability of information can save high investment costs for geothermal developers for exploration and drilling. For areas with little or insufficient subsurface data, there is a potential role for governments in organising or providing some resource mapping and exploration drilling to get a good overview of the resource base for national planning of energy supply systems, and to reduce project development risks and costs to consumers. Examples of such initiatives are the Geothermal Atlas of Southern Italy (2015) or the ongoing seismic campaign for geothermal energy, the SCAN Project in the Netherlands (https://scanaardwarmte.nl/English/).

Globally, around 78% of production wells drilled are successful, with the average success rate improving in recent decades. This is most likely due to better surveying technology, which is able to more accurately target the best prospects for siting productive wells, although greater experience in each region has also played a part. A key point is that adherence to global best practices significantly reduces exploration risks (IFC, 2013).

In general, geothermal installations are quite individual, as the quality of their resources and resulting management needs are site-dependent. As a result, experience with one project may not yield specific lessons that can be directly applied to new developments. It may, however, provide broader industry knowledge that helps develop more advanced industry standards, from reservoir modelling to O&M practices. Nonetheless, adherence to best international practices for survey and management, with thorough data analysis from the project site, are considered the best risk mitigation tools available to developers (IFC, 2013).

2.1 Technology readiness level

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 (Deep Geothermal IWG, 2020). The updated Deep Geothermal Implementation Plan includes a modification of priorities for research, development and innovation covering a broad range of topics for the geothermal sector across all segments of the deep geothermal value chain.

Table 1. RD&I priorities for the SET-Plan Deep Geothermal Implementation Plan and current TRL.

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

Source: SET-PLAN and authors' elaboration

2.2 Installed Energy Capacity, Generation/Production and Outlook

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. According to theoretical calculations, the energy reserves in the upper 10 km of the Earth's crust are approximately 1.3 x 10^9 EJ (Lu, 2018). In Europe, the economic potential of geothermal power including EGS is estimated at 19 GWe in 2020, 22 GWe in 2030, and 522 GWe in 2050 (Limberger et al., 2014). However only a small portion of the heat in place can be realistically extracted for energy production. Traditional geothermal systems currently extract energy up at depths up to 3-4 km. EGS systems, if fully developed, could access depths of up to 10 km.

IRENA reports the total global installed capacity at around 14.4 GW for the end of 2021, an increased of 44% from 2010 (IRENA, 2022). The IEA Geothermal technical cooperation program's annual report provides details on the status in individual countries (IEA Geothermal, 2022).

For Europe, **Table 2** shows the installed capacities per country for both power generation and heating/cooling (EGEC, 2022). For the EU the gross capacity is just over 1 GWe, however net capacity is 877 MWe. . Growth since 2010 is approximately 12% (EUROSTAT).

Most of the recently installed capacity for electricity in Europe is in Turkey, while installations in Italy and Iceland have not increased. In Germany the trend to install local and small-scale binary power plants continued with the addition of two plants of 1 MW and 5 MW respectively. Electricity production was 6.7 TWh in 2020, and is expected to increase slightly to 7 TWh by 2030 (EurObserv'ER, 2022).

Table 2. Installed total capacity for electricity and for heating & cooling in Europe (Eurostat and EGEC, 2022).

Country	Install. Generation Capacity (MW_e)	Net Generation Capacity (MW_e)	Electricity Production (GWh)	Heating/Cooling Capacity (MW_{th})
Austria	1.3	0.9	0.1	103
Belgium				22
Croatia	16,5	10.0	93.7	22
Cyprus				0,6
Czech Republic				8
Denmark				33
Finland				1
France	17.1	16.2	133.2	470
Germany	47.0	40.0	231.0	356
Greece				17
Hungary	3.0	3.0	16.0	256
Italy	915.5	771.8	6026.1	180
Lithuania				14
Netherlands				369
Poland				137
Portugal	34	29.1	217.2	0
Romania	0.05	0.05	0.0	88
Slovakia				17
Slovenia				11
Spain				8
Sweden				44
EU Total	**1018**	**871**	**6717**	**2156**
Georgia				43
Iceland	754	n/a	n/a	2262
North Macedonia				43
Norway				1
Serbia				56
Switzerland				11
Turkey	1653	n/a	n/a	999
UK				7
Europe Total	**3435.5**	**-**	**-**	**5579**

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

2.2.2 Heating (and cooling)

For geothermal heat production in the EU, overall EurObserv'ER expects growth from 870.5 ktoe in 2020 to 1000 ktoe in 2030. 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

The geothermal district heating and cooling sector continues to grow slowly, with only a 3% growth rate in installed capacity in Europe overall, and 6% in the European Union. In 2021, the total installed geothermal district heating and cooling capacity reached 5.6 GW_{th} in Europe for 364 DHC systems, of which 262 are in the EU with a total installed capacity of 2.2 GW_{th}. While the largest DHC installed capacities are still in Iceland and Turkey, the newly commissioned systems are in nine different countries, with the largest growth happening in France, the Netherlands and Poland. The overall sluggish growth is partly due to the Covid lockdowns and related delays in deliveries, but this effect should be compensated by comparatively more growth in 2022, when delayed plants go into operation.

2.3 Technology Cost – Present and Potential Future Trends

According to the International Renewable Energy Agency, the average installed cost (CAPEX) for new geothermal power plants in 2021 was USD 3 991 /kW, based on a data for eight plants (in total 370 MW) (IRENA, 2022). Operating costs are in the range of 1.6-2.2% of CAPEX, and plants operate at a capacity factor of approximately 80%. The corresponding global weighted average LCoE was 68 USD/MWh. These values have been relatively stable over the last 5 years, and should be taken as broadly representative of a range of technology options regarding the type of resource and system: flash plants, binary ORC plants and EGS plants. The NREL ATB database (NREL, 2022) provides more detailed analysis of technology options and trends.

The 2020 SET-Plan Implementation Plan for Deep Geothermal sets out a series of declarations of intent regarding costs of geothermal power and heat, as well as other critical parameters relating to the economics of exploration and flexible plant operation. The headline targets for production costs (including from currently not exploited unconventional resources, such as superhot, EGS, and/or from hybrid solutions) are below 100 EUR/kWh for electricity and 5 EUR/kWh for heat by 2025.

2.4 Investments

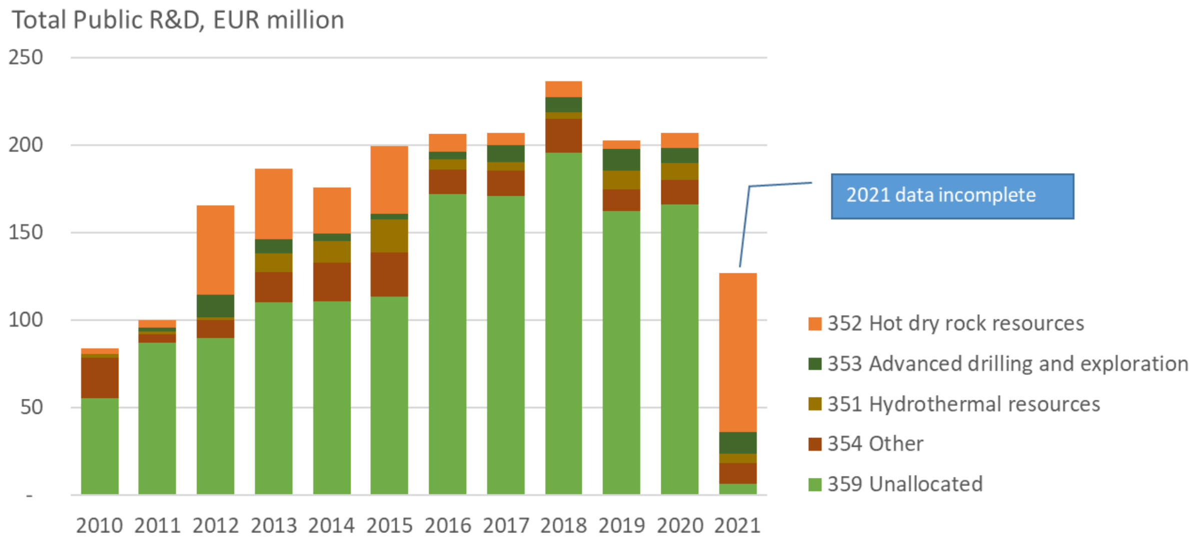
2.4.1 IEA Global Public RD&D data

The IEA collects annual data on public R&D investments for clean energy technologies from its members (IEA, 2021). 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

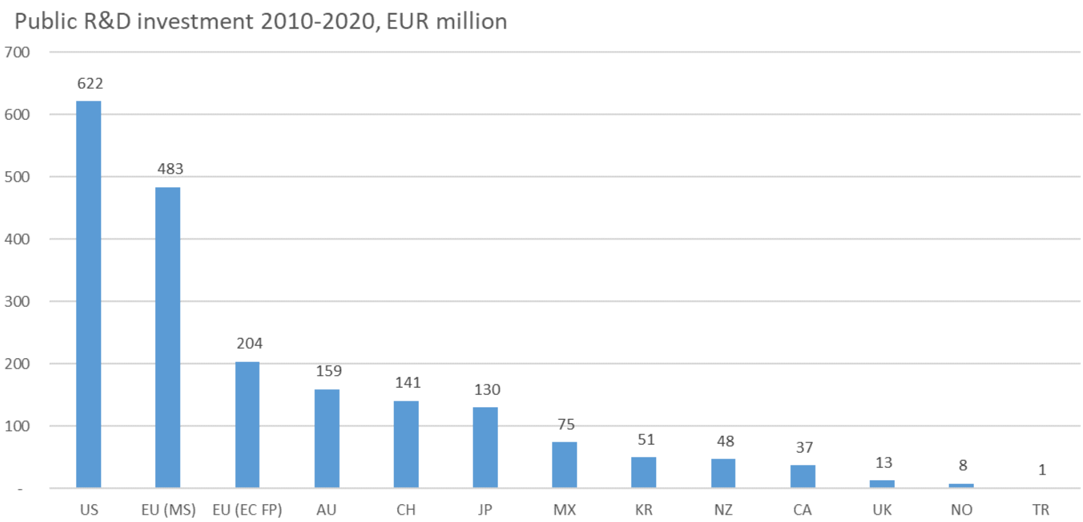
Public investment in EGS technology increased in 2021 compared to previous years (**Figure 1**). The technology is supported in particular in the USA, France, Germany and Switzerland. There is also a significant amount of research funding on theoretical studies on fracture controlled geothermal projects in Norway. Overall spending on geothermal research by an individual country (**Figure 2**) was largest in the USA, but the combined budgets of the EU from the framework programmes and the member states exceeds that of any other country or region in the world. The EU member states with the largest geothermal R&D budgets in 2020 were Germany, Italy, France and the Netherlands (**Figure 3**).

Figure 1. Data reported to the IEA for public RD&D funding over the period 2010 to 2020



Source: JRC based on IEA

Figure 2. Public RD&D funding by the EU and other major economies for geothermal energy over the period 2010 to 2020, from data reported to the IEA.



Source: JRC based on IEA

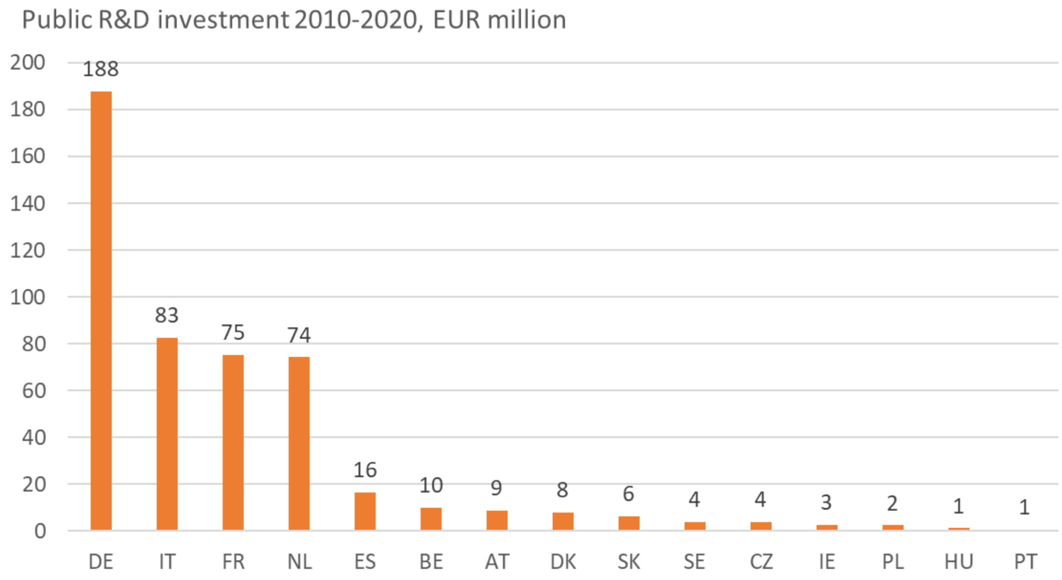
2.4.2 EU Horizon Funding

Under Horizon 2020 (2014-2020) the EU has supported 54 geothermal-related projects with approximately 208 MEUR contribution. **Figure 4** 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.

2.5 Private R&D funding

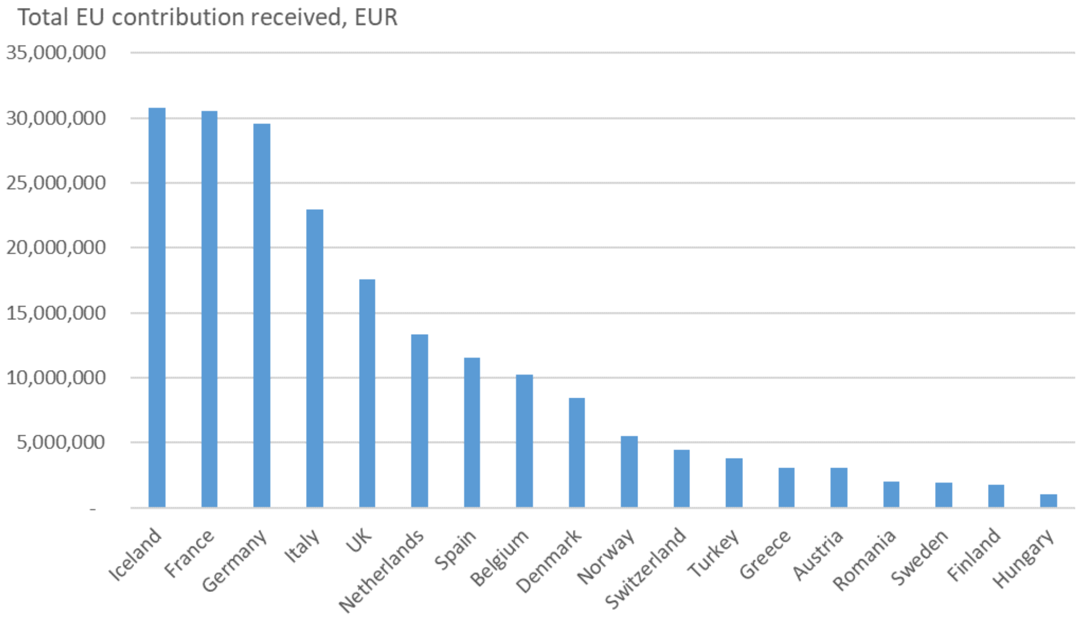
In the absence of technology specific data, estimates of private R&I rely on the use of patenting data as a proxy (Pasimeni et al 2017, Fiorini et al, 2017) and should be interpreted with caution. The resulting data to 2019 (patent data have several years lag) are shown in **Figure 5** and indicate a marked decline in investments over the last decade. **Figure 6** shows the trends at country/regional level. **Table 3** and **Table 4** show the top organisations for R&D investments globally and for the EU, respectively.

Figure 3. Public RD&D funding by EU Member States for geothermal energy over the period 2010 to 2020 according to data reported to the IEA (2020 data for Italy is not available)



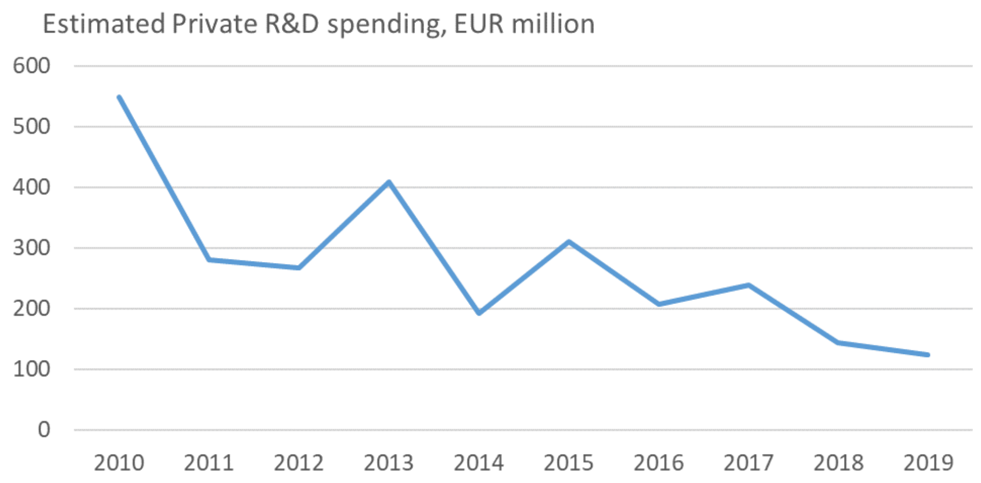
Source: JRC based on IEA

Figure 4. H2020 funding for geothermal projects (countries receiving >EUR 1 million).



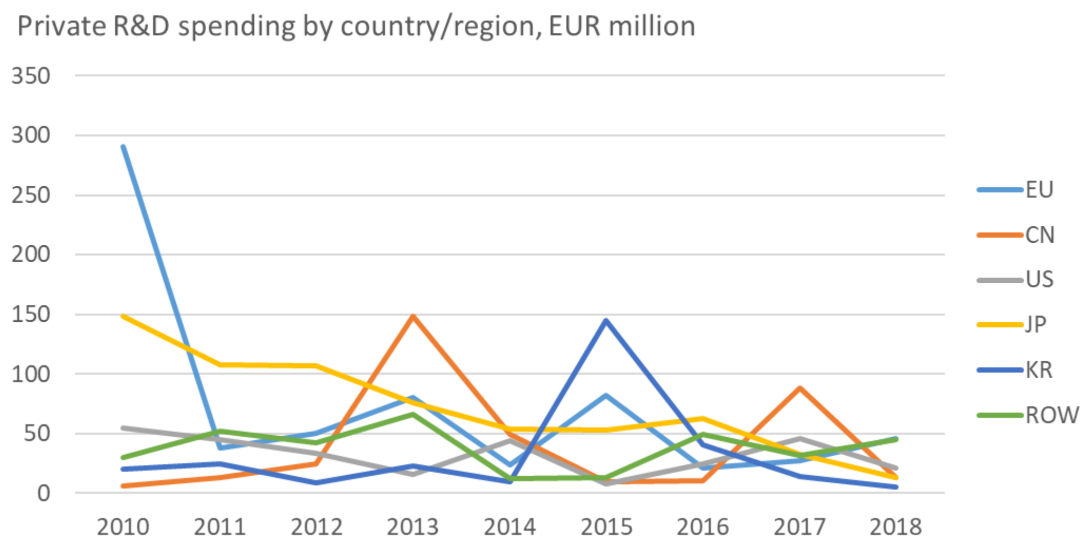
Source: JRC analysis of Cordis data

Figure 5. Overall trend in annual R&D investments by private companies, using patenting data as proxy.



Source: JRC analysis

Figure 6. Trends in annual R&D investments for the EU and major economies.



Source: JRC analysis

Table 3. Top organisations globally for geothermal R&D investments 2015-2019 based on patenting data.

Organisation	Country/ Region[1]
Eavor Technologies Inc	CA
Dae Sung Groundwater Ltd	KR
Ohbayashi Gumi Ltd	JP
Japan New Energy Co Ltd	JP
Jansen Ag	CH
Ecolab Inc	US
Kyodo Tech Co Ltd	JP
Aguricluster Corp	KR
Hans Development Co Ltd	KR
Sekisui Chemical Co Ltd	JP
Est Co Ltd	KR
Kotecengineering Co Ltd	KR
Kupp Co Ltd	KR
Hmfsf Ip Holdings Llc	US
Mitani Sekisan Co Ltd	JP
Korea Hydro Nuclear Power Co Ltd	KR
Shandong Province Binzhou Huonuniao New Energy Technology Co Ltd	CN
Agrana Beteiligungs Aktiengesellschaft[2]	AT
Li Hong Science Technology Co Ltd	TW
Statoil Petroleum As	NO

Source: JRC analysis of PATSTAT data

Table 4. Top EU organisations for R&D investments 2015-2019, using patenting data.

Organisation	Country/ Region
Agrana Beteiligungs Aktiengesellschaft	AT
Steinhuser Gmbh Co KG	DE
Trias VM Gmbh	DE
Bernegger Gmbh	AT
Enoware Gmbh	DE
Holzammer Kunststofftechnik Und Sengenthaler Holz Und Heimwerkerbedarf Gmbh	DE
W-Filter Innovacio Kft.	HU

[1] CA: Canada, KR: Republic of Korea, US; United States of America, TW: Taiwan, JP: Japan, CH: Switzerland, CN: China, NO: Norway
[2] The Agrana Group is a food company based in Vienna that produces sugar, starch, fruit preparation, juice concentrate and ethanol fuel.

Organisation	Country/ Region
Pfeil Bautrãƒâ¤Ger Gmbh	DE
Jenkies Bv	NL
Mefa Befestigungs Und Montagesysteme Gmbh	DE
Quantitative Heat Oy	FI
Harjula Solutions Oy	FI
E Tube Sweden Ab	SE
Exergy Spa	IT
Heijmans Nv	NL
Rototec AB	SE
Hlscher Wasserbau Gmbh	DE
Brennero Innovazioni Tecnologiche Srl	IT
Climasolutions Gmbh	DE
VITAL WOHNEN Gmbh & Co KG	AT

Source: JRC analysis of PATSTAT data

2.6 Venture Capital Investments

Although JRC analyses venture capital (VC) investments for several clean energy technologies using its CINDECS methodology applied to Pitchbook data, up to now deep geothermal is not included.

2.7 Patenting trends

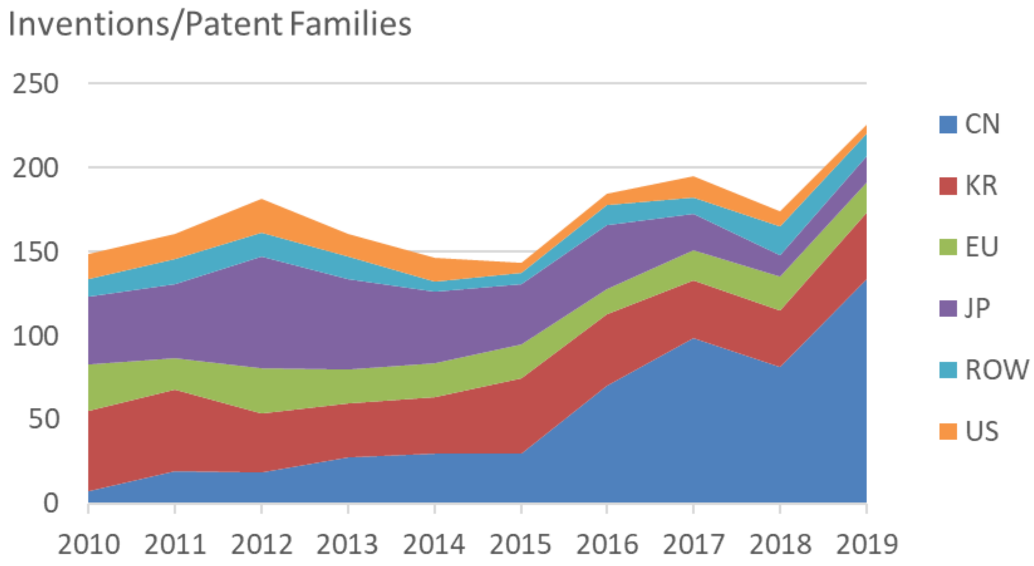
The analysis followed the JRC's methodology (Pasimeni, 2019) applied to the Patstat (European Patent Office) data for the period to 2019. The relevant CPC code is Y02E 10/10 – geothermal energy. The filings are classified as follows:

- 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[3] (**Figure 7**) . 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 8**). Also of note is that in 2019 China moved into 2nd place for high value patents, passing the USA. **Figure 9** shows the listing of top individual countries for high value patents over 2017 to 2019. Germany, Sweden, Italy and France take places 4. 6, 7 and 10 respectively. The leaders are the USA and China. **Table 5** shows the leading organisations for inventions in the same period. The leader, Eavor, is a Canadian company developing a closed-loop deep geothermal system.

[3] Since the analysis for the CPR 2020 SWD, the Chinese patents have been re-categorised, leading to a substantially lower total count (50% less).

Figure 7. Total inventions for geothermal from 2009 to 2019



Source: JRC analysis of PATSTAT data

Figure 8. High value inventions for geothermal from 2009 to 2019

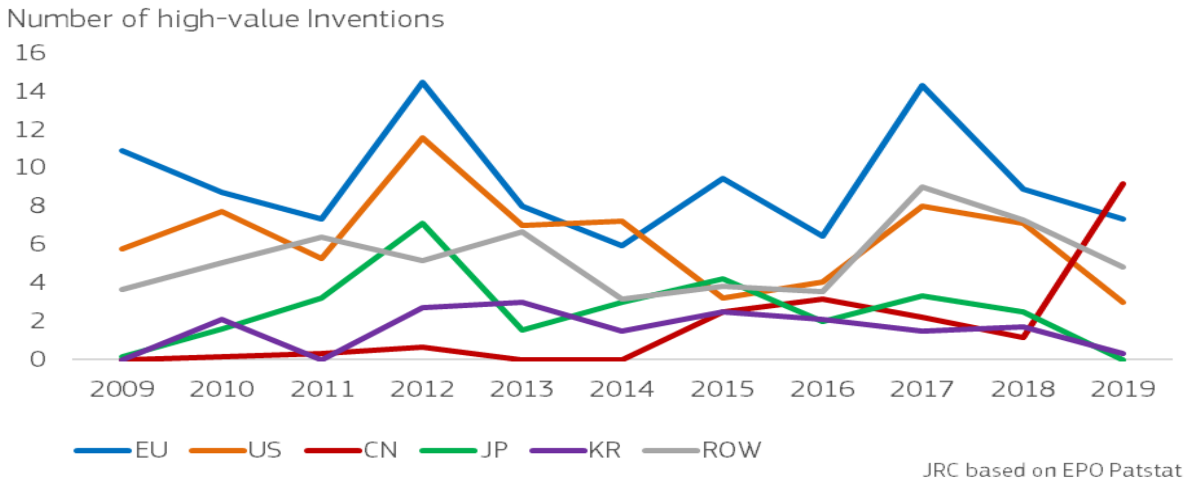


Figure 9. Top 10 countries for high value geothermal energy inventions 2017-2019

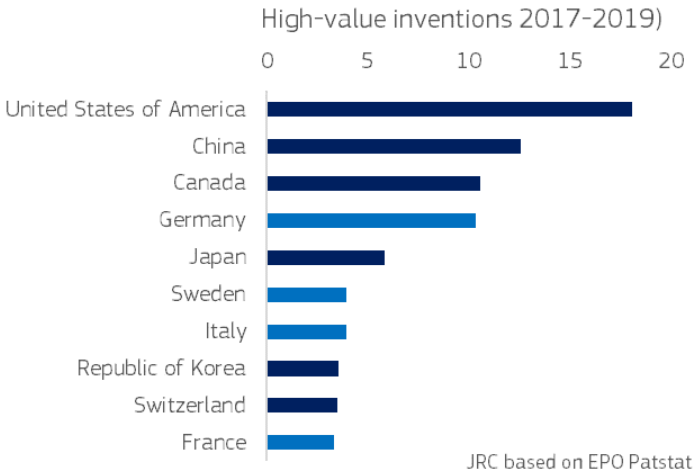


Table 5. Top 10 entities for high-value inventions 2017 -2019

Entity	High Value Inventions
Eavor Technologies Inc (CA)	7
Ecolab Inc (US)	3
E Tube Sweden Ab (SE)	
Jansen Ag (CH)	2
Mitsubishi Heavy Industries Thermal Systems Ltd (JP)	2
Saudi Arabian Oil Company (SA)	2
Steinhuser Gmbh Co Kg (DE)	1
Inotev Inc (CA)	1
Rototec Ab (SE)	1
Ancor Loc Nz Limited (NZ)	1

Source: JRC analysis of PATSTAT data

2.8 Scientific Publications

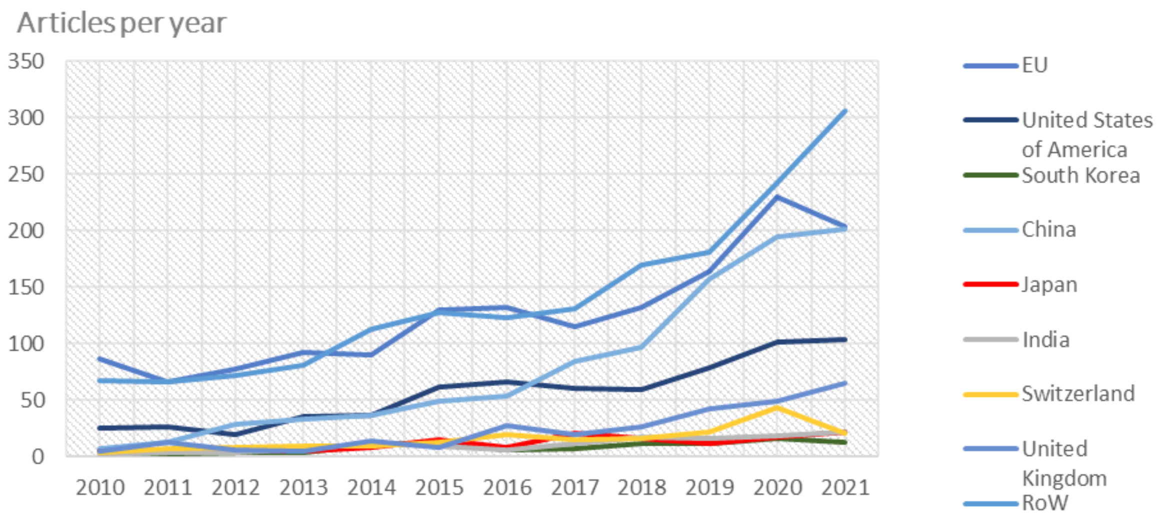
The JRC's Technology Innovation Monitor system (TIM) was used to analyse the scientific articles published over the period 2010 to 2022. The search string was: topic:("geothermal power"~2 OR "geothermal electricity"~3 OR "geothermal heating"~2 OR "geothermal energy" OR "geothermal direct use") AND class:"article" and retrieved 4528 articles. **Figure 10** shows the time trend for the EU and leading countries and regions. The RoW is most prolific, with the EU second. Over the decade China has emerged as a major contributor to the scientific literature, overtaking the USA into third place in 2021.

For impact analysis, TIM provides three parameters:

- Highly cited papers (top 10% cited normalised per year and field)
- Field Weighed citation impact (FWCI) is calculated as the average number of citations the article receive normalised per year and per field.
- 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.

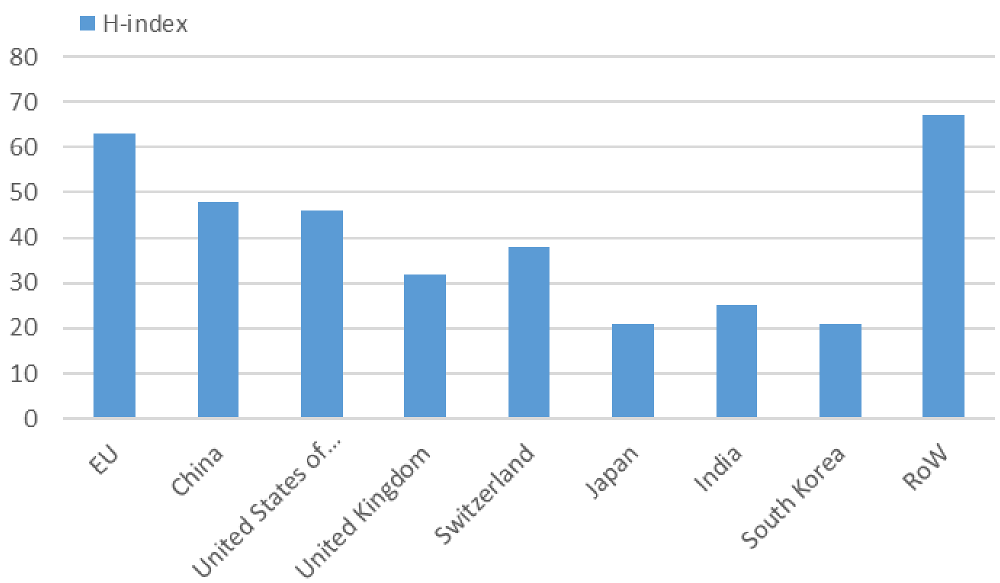
Figure 11 ranks the h-index values for the major country and country groupings based on the whole data set (2010-2022). Table 6 shows the ranking of EU countries, which Germany leads, followed closely by Italy and France.

Figure 10. Trend in scientific publications on geothermal energy for the leadings countries and regions



Source: JRC TIM data

Figure 11. h-value scores for scientific publications on geothermal energy for the leadings countries and regions



Source: JRC TIM data

Table 6. Leading EU countries for scientific articles on geothermal energy (ordered by total articles).

Country	total articles	non highly cited	highly cited articles	FWCI	H-index
Germany	516	454	62	1,047332	42
Italy	319	262	57	1,266889	38
France	140	113	27	1,537373	25
Poland	125	117	8	0,604107	14
Spain	101	89	12	1,010335	22
Netherlands	91	78	13	1,223825	25
Denmark	49	40	9	1,27485	17
Sweden	42	37	5	1,125192	14
Hungary	41	40	1	1,395163	8
Austria	39	36	3	0,897724	12
Belgium	37	33	4	1,051142	12
Romania	36	35	1	0,52752	10
Greece	34	30	4	0,990603	12
Finland	31	25	6	1,322285	10
Croatia	30	25	5	1,163393	13
Portugal	29	24	5	1,210948	9
Czech Republic	28	24	4	0,786789	6
Slovenia	25	23	2	0,626794	9
Slovakia	24	24	0	0,55267	8
Ireland	21	19	2	1,344517	10
Cyprus	8	6	2	1,27465	5
Lithuania	7	6	1	0,555406	2
Estonia	6	6	0	0,581417	4
Bulgaria	4	4	0	0,025153	1
Luxembourg	4	3	1	1,374348	4
Latvia	3	2	1	1,085203	1

Source: JRC TIM data

3 Impact and Trends of EU-supported Research and Innovation

This report summarises trends in geothermal research support at the European level. The primary sources for geothermal RD&D spending are the European framework programmes Horizon 2020 and Horizon Europe and the ERA-Net Geothermica, which is designed to support international cooperation between national funding agencies. In the EU framework programmes, a shift can be observed in research areas that received major attention and support. While drilling and the development of EGS received major research funds in H2020 (e.g., DEEP-EGS, DESCRAMBLE, DESTRESS), new areas of attention in Horizon Europe are heat storage and extraction of critical raw materials (Lithium). These focus areas were already initiated in call1 of the Geothermica Programme 2018 (Projects HEATSTORE and PERFORM). EGS is still an important topic in Geothermica. In the following lists, all projects funded by Geothermica and H2020 are related to the R&D priorities in **Table 1**.

3.1 Geothermica

GEOTHERMICA – ERA-NET Cofund has already supported fifteen high-quality transnational projects on geothermal energy. The total investment in the projects is close to EUR 90 million. About half is funded by GEOTHERMICA and the other half comes from project partners.

The projects cover a broad range of topics such as heat storage, managing induced seismicity, EGS, drilling and completion, production operations, composite casing and integrated applications of geothermal heat. They have participants from the Netherlands, Switzerland, Iceland, Ireland, France, Belgium (Flanders), Denmark, Slovenia, Germany, Spain Portugal (Azores), Norway and the USA.

The GEOTHERMICA funded projects are from two calls: Call1 in 2018 and Call2 in 2020 both demonstrated and validated novel concepts of geothermal energy deployment within the energy system. A third call was published in 2021 as a joint call with the network Joint Programming Platform Smart Energy Systems (JPP SES). The expected start date for projects is September 2022. Key results are highlighted in boxes for selected projects.

3.1.1 Call1 Projects (finished 2021)

1. **CAGE - Composite casing and the Acceleration of Geothermal**

   Objective: Demonstration of several cost-saving and output-improving downhole installation technologies for drilling, completion and airlift technologies

   Relevant R&D priority addressed: 7 - *Advanced drilling/well completion techniques*

2. **ZoDrEx - Zonal Isolation, Drilling and Exploitation for EGS Projects**

   Objective: Demonstration of drilling, completion and production technologies – percussion drilling, zonal isolation, corrosion protection and monitoring
   Relevant R&D priority addressed: 7 - Advanced drilling/well completion techniques

Box 1. ZoDrEX

The **ZoDrEx** project demonstrated the applicability of several drilling and stimulation technologies for EGS in hard crystalline basement rocks in the Bedretto (Switzerland) subsurface laboratory. These technologies were designed and developed in previous projects and demonstrated under realistic conditions. The project showed that percussion drilling of horizontal large diameter strongly deviated boreholes with a length up to 400 m from the Bedretto gallery into granite is feasible. The boreholes were then used to test different zonal isolation designs with novel double packer and multi-packer systems, such that hydraulic stimulation would targeted in well-defined zones only, isolated form the rest of the borehole by the packers. Permeability was increased by a factor of 10 to 100, successfully creating a permeable geothermal reservoir in the granite with minimal seismicity. The test was successfully repeated at the full scale in a follow/up project at the US EGS test facility FORGE in Utah. Another successful stimulation method was tested by drilling narrow sidetracks at varying angles with a microturbine, driven by a water jet through a coiled tubing string. The main body and function of such a turbine is to convert the fluid´s hydraulic energy into rotation and thus mechanical energy. That way several micro/boreholes were created in an attempt to establish a hydraulic connection between borehole and reservoir through the cemented casing.

3. HEATSTORE – High Temperature Underground Thermal Energy Storage

Objective: Lower the cost, reducing the risks and to optimize performance of high temperature (~25 to ~90°C) underground thermal energy storage technologies.

Website: https://www.heatstore.eu

Relevant R&D priorities addressed: 1 - Geothermal heat in urban areas; 2 - Integration of geothermal electricity and heating & cooling in the energy system responding to grid

Box 2. HEATSTORE

The **HEATSTORE** project provided a detailed report on the different Underground Thermal Energy Storage (UTES) technologies for high temperature storage (>25°C). By analysing four different technologies in ongoing and planned projects in six different countries, the project defined the state-of-the-art and provided a roadmap with a clear way forward for the installation of these technologies both at the demonstration sites and in Europe until 2050 (HEATSTORE, 2021). Beyond the specific technological innovation aspects, the roadmap includes Market & Economics, Society & Environment, and Policy & Regulations. The HEATSTORE project has triggered several follow-up projects, at the national (e.g., Germany, Netherlands and Switzerland) and the European level

4. PERFORM

Objective: Improve geothermal plant performance by demonstration of cost-efficient, next-generation technologies and methods (cation-, particle filters, CO_2-injection, thermal stimulation) to enable reduction of obstructive elements and resistance to fluid injection.

Website: http://www.geothermperform.eu

Relevant R&D priority addressed: 5 - Sustainable and efficient production technologies The main body and function of such a turbine is to convert the fluid´s hydraulic energy into rotation and thus, mechanical energy The main body and function of such a turbine is to convert the fluid´s hydraulic energy into rotation and thus, mechanical energy

Box 3. PERFORM

The **PERFORM** project addressed problems such as mineral scaling, particles clogging, corrosion and temperature/stress related effects of geothermal flow and injectivity. For this purpose data about the properties and geology of the reservoirs, the chemistry of the water and precipitates and the construction of the plants were collected and experiments at the plants and in laboratories were performed. The project delivered a database on geothermal fluids and their properties (accessible via the project website). This database is further developed and expanded in the H2020 project REFLECT. In addition, new methods to remove H_2S from geothermal waters were developed and new adsorption materials were identified and tested to remove ions of potential precipitates from the fluids. This technology will be further developed and applied in the follow-up PERFORM 2 project (Geothermica, start Sept. 2022).

5. COSEISMIQ - COntrol SEISmicity and Manage Induced earthQuakes

Objectives: Improve and validate advanced technologies for monitoring and controlling induced seismicity with a data-driven, adaptive decision support tool during industrial applications

Website: http://www.coseismiq.ethz.ch

Relevant R&D priorities addressed: 6 - Development and exploitation of geothermal resources in a wider range of geological settings; 10 - Risk mitigation (financial/project)

Box 4. COSEISMIQ

The **COSEISMIQ** project integrates seismic monitoring and imaging techniques, geomechanical models and risk analysis methods with the ultimate goal of implementing these adaptive, data driven approaches for reservoir optimization and for the control and management of induced seismicity. These methods were developed in several previous projects, including GEISER (FP7) and DESTRESS (H2020). First field tests near the Hengill volcano in Iceland were performed in COSEISMIQ to monitor operations at two major geothermal power stations. This technology is further developed and applied in DEEP project (Geothermica, start 2020) at the US American EGS test facility FORGE in Utah

6. GE-CONNECT

Objective: increase reliability of downhole construction of geothermal wells beyond the state of the art using flexible couplings. The flexible couplings are able to minimize the risk of casing failures. Test integrity of cemented annulus and casing using flexible couplings.

Relevant R&D priorities addressed: 5 - Sustainable and efficient production technologies, 7 - Advanced drilling/well completion techniques

Box 5. GE-CONNECT

The GE-CONNECT project objective was to increase the reliability of the downhole construction of geothermal wells beyond the state of the art, using flexible couplings (patent filed in 2016). Full scale prototypes of the flexible coupling allowing axial casing movements were laboratory tested in GeoWell (H2020). In GeConnect the concept was tested in a real working environment (TRL 5-6) and confirmed the function of thermally expanding casing sliding within cement. Thus the project succeeded in demonstrating this novel technology at relevant temperature and pressure steam conditions. Up to that point the function of Flexible Couplings could only be considered to be a concept, backed by years of modelling and R&D. The project results are therefore an important step towards gaining increased control of casing integrity of moderate- to high-temperature geothermal wells. Additionally, the objective of drilling into superheated/supercritical reservoirs without the currently high risk of casing failures once wells heat up has become more achievable.

7. GEOFOOD

Objective: 1- Design and optimize a demonstration plant in Iceland with direct use of geothermal energy for innovative sustainable circular food production techniques; 2- design and build a research system to optimise energy configuration in The Netherlands at the research facilities of Wageningen University.

Website: https://geofoodproject.eu

Relevant R&D priorities addressed: 4 - Closed loop electric and heating & cooling plants integrated in the circular economy; 5 - Sustainable and efficient production technologies

8. GEO-URBAN

Objective: explore the potential for low enthalpy geothermal in urban environments. Feasibility analysis for the commercial development of deep geothermal resources in two target locations (Dublin, Ireland and Vallès, Spain).

Relevant R&D priority addressed: 1 - *Geothermal heat in urban areas*

3.1.2 Call1 Projects (finished (2021)

1. DEEP - Innovation for De-Risking Enhanced Geothermal Energy Projects

Objective: Innovation for de-risking enhanced geothermal energy projects. DEEP has a strong focus on optimization of monitoring and risk assessment procedures in order to reduce commercial costs to future projects.

Website: http://deepgeothermal.org/home/)

Relevant R&D priorities addressed: 6 - Development and exploitation of geothermal resources in a wider range of geological settings; 10 - Risk mitigation (financial/project)

2. **DEEPEN - DErisking Exploration for geothermal Plays in magmatic ENvironments**

Objective: Develop improved exploration methods and an improved framework for the joint interpretation of exploration data using the Play Fairway Analysis (PFA) methodology. Develop new tools that will help with the subsurface imaging of deep and hot bodies. Demonstrate the PFA methodology at two magmatic systems, at Hengill, Iceland and Newberry Volcano, USA.

Website: www.or.is

Relevant R&D priorities addressed: 8 - Innovative exploration techniques for resource assessment and drilling target definition; 10 - Risk mitigation (financial/project)

3. **TEST-CEM - Sustainable Geothermal Well Cements for Challenging Thermo-Mechanical Condition**

Objective: Sustainable geothermal well cements for challenging thermos-mechanical conditions. The project aims to reduce risks associated with compromised well integrity, common for all geo-wells, and use recently gained insights in the field of materials to evaluate advanced cement systems in a wide temperature range (up to super-critical) and under thermal cycling.

Website: https://www.bnl.gov/test-cem/

Relevant R&D priorities addressed: 5 - Sustainable and efficient production technologies; 10 - Risk mitigation (financial/project)

4. **SPINE - Stress Profiling in EGS**

Objective: Stress profiling in EGS. SPINE is developing new tools for stress profiling in crystalline rock to estimate stimulation efficiency and seismicity related to subsurface heat exchangers' creation.

Website: http://www.geothermica.eu/projects/call-2/spine/

Relevant R&D priority addressed: 6 - Development and exploitation of geothermal resources in a wider range of geological settings

5. **RESULT - Enhancing REservoirs in Urban deveLopment: smart wells and reservoir development**

Objective: Enhancing reservoirs in urban development: smart wells and reservoir development. Demonstrate the potential for increased performance by 30-100% of major (marginal) reservoirs for heating in urban areas in the northern EU.

Relevant R&D priority addressed: 1 - *Geothermal heat in urban areas*

6. **SEE4GEO - Seismoelectric effects for geothermal resource assesment and monitoring**

Objective: Seismoelectric effects for geothermal resource assessment and monitoring. Perform a fully integrated approach to assess the potential of utilization Seismic Electric Effects (SEE) for exploration and development of geothermal systems, by creating a SEE numerical package to be used for improved subsurface tomography, supported and validated by laboratory experiments

Relevant R&D priority addressed: 8 - Innovative exploration techniques for resource assessment and drilling target definition

7. **GRE-GEO - Glass Fibre reinforced Epoxy Casing System for Geothermal Application**

Objective: The GRE-GEO project will develop a new well completion strategy that aims to establish a corrosion-resistant alternative to decrease the development and production costs of geothermal energy while avoiding extra investments.

Website: https://www.gre-geo.org/

Relevant R&D priorities addressed: 3 - Improvement of overall geothermal energy conversion performance for electricity and heating & cooling generation; 7 - Advanced drilling/well completion techniques

3.2 Horizon 2020 Projects

Table 7 list Horizon 2002 geothermal projects that have been completed since 2019. A brief description of the scope and results is given below. Details regarding H2020 projects finished before 2019 are available in the previous Low Carbon Energy Observatory report (Carrara et al, 2020). The list of on-going Horizon 2020 projects is given in **Table 8**.

Table 7. H2020 projects, finished after 2019, sorted by SET-Plan R&I priority

Project	Type	Start-End	EU contribution (€)	R&I Priority
GEOCOND - Advanced materials and processes to improve performance and cost-efficiency of Shallow Geothermal systems and Underground Thermal Storage	RIA	2017 -2021	3 955 740	1, 3
Geo-COAT - Development of novel and cost effective corrosion resistant coatings for high temperature geothermal applications	RIA	2018-2021	4 722 723	5, 7
DESTRESS - Demonstration of soft stimulation treatments of geothermal reservoirs	IA	2015 – 2021	10 713 409	6, 7
DEEP-EGS – Deployment of Deep Enhanced Geothermal Systems for sustainable energy business	IA	2015 -2020	18 982 938	6, 7
GEMex - Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems and Superhot Geothermal Systems	Int. RIA	2016 -2020	9 999 793	6, 7, 8

Source: author analysis of CORDIS data

The GEOCOND project proposed to develop solutions to increase the thermal performance of the different subsystems configuring a shallow geothermal energy system and Underground Thermal Energy Storage by a combination of different material solutions, sophisticated engineering, optimization, testing and on-site validation. A major aspect of the project approach was the improved thermal performance of system components. Components investigated and tested were pipes and the grout, coupling the borehole heat exchangers to the surrounding soil. Pipe materials were selected to improve thermomechanical ageing and to have good thermal conductivity, which improved performance of the overall systems. For this purpose, novel piping materials and a new configuration of pipes was tested. Advanced grouting materials were developed with various additives improving thermal performance and reducing mechanical deterioration due to thermal contraction/expansion. Innovative additives included phase-change materials to maintain optimum grout properties across a wide temperature range. A process was proposed to generate tailor-made performance grouting for various subsurface conditions and installations. On the basis of product developments in the project, a European patent application was filed by the pipe manufacturers for the new geometry and pipe material concept. This configuration combines a specific geometry with high thermal conductivity of the pipe material and can be easily installed, with an extremely low thermal resistance and high energy density.

The Geo-COAT project developed specialised corrosion- and erosion- resistant coatings, based on selected high entropy alloys and ceramic/metal mixtures, to be applied through thermal powder coating techniques. The new high-performance coatings are designed to resist specified threats of the challenging geothermal applications. For this purpose, various geothermal fluids were characterised, different coating techniques were tested and evaluated, the influence of heat treatment on the mechanical and chemical properties of the coating materials was investigated and the impact of the coatings on LCOE, environmental footprint and the sustainability of the geothermal power production was assessed. Compared to state-of-the-art materials, adoption of Geo-Coat technology for pipes, turbine rotors, blades and well casing leads to a reduction of the LCOE by 91% for double flash and by 26% for binary power plants. Similarly, the environmental footprint can be reduced by up to 60%.

The DESTRESS project was one of several Innovation Actions to improve the development of EGS (others are DeepEGS and MEET). Several approaches were proposed and applied to achieve “soft stimulation”, which is enhancement of reservoir productivity without unwanted side-effects such as induced seismicity. For this purpose, thermal, chemical and hydraulic tests were performed to demonstrate their potential. Chemical stimulation was performed at the EGS site Soultz-sous- Forêts. A combined thermal-chemical stimulation was performed at the site in Mezőberény (Hungary) in early 2021. A cooperation with an EGS project in South Korea enabled testing of controlled hydraulic stimulation at the test site near the city of Pohang. The injections followed a site-specific cyclic soft stimulation schedule and were subject to a traffic light system. A total of 52 induced seismic events were detected in real-time during and shortly after the injection. The maximum magnitude of the induced seismicity during the stimulation period was below the target threshold of Mw 2.0, and further knowledge about the stimulated reservoir was gained. The major factors that limited the maximum earthquake magnitude are believed to be: limiting the injected net fluid volume, flow back after the occurrence of the largest induced seismic event, using a cyclic injection scheme, the application of a traffic light system, and including a priori information from previous investigations and operations in the treatment design.

At the Pohang site, the occurrence of a Mw 5.5 earthquake on 15 November 2017 led to an immediate suspension of the project and prevented access to the site. After a year-long study, the international expert commission appointed by the Korean government concluded that the Pohang earthquake was triggered by hydraulic stimulations at the second well, which had not been used for the DESTRESS injections. Nonetheless, the damaging earthquake posed a major challenge to the DESTRESS consortium and led to various research activities published in several scientific articles. However, many questions remain open and are being further investigated, e.g. the relationship between the injection volume and the maximum magnitude or the operation and use of advanced traffic light systems. Due to the suspension of the Pohang project, an alternative site was required to carry out the stimulation treatments.

A second cyclic hydraulic stimulation concept for a target-oriented and safe multi-stage productivity increase was developed for an abandoned well at Geldinganes near Reykjavik (Iceland). This stimulation concept was based on a site assessment with a focus on previous stimulations in the area, existing stress fields and structural geology. Critical for the success of the project was the isolation of new stimulation targets from previously stimulated high-permeability zones. Due to the proximity of the well to the city of Reykjavik, particular emphasis was on seismic risk assessment and mitigation. In total, approximately 20,000 m^3 of water was injected at three different intervals, isolated by packers. Only a few seismic events were registered during the stimulation in the deepest part of the well, with a maximum moment magnitude of Mw -0.1

The advances made in the stimulation and monitoring concepts tested in DESTRESS led to their successful application in other projects, such as the Geothermica projects ZoDrEx and DEEP.

<u>The Deep-EGS project</u> The DEEPEGS project had selected and intended to demonstrate advanced technologies for EGS in three types of geothermal reservoirs in different geological conditions: one high enthalpy site in Iceland beneath the existing hydrothermal field in the Reykjanes volcanic environment with expected temperatures at 5 km depth up to 500-600°C, and two sites in deep basement and carbonate rocks in France. Problems with the latter two sites eventually led to a focus on the site in Vendenheim, Alsace. Stimulation at Vendenheim was postponed to after the end of Deep-EGS and was stopped after a Mw 3.6 seismic event occurred less than 1km from the well in October 2020.

At Reykjanes, the existing geothermal reservoir has almost doubled in volume of proven permeability. A permeable supercritical system with temperatures of up to ~600°C was penetrated below 4km depth. The enormous temperature gradient and the heating up of the well after drilling, which required cooling by the drilling mud, led to the expansion and buckling of the casing. This experience triggered further developments in casing materials (e.g., in the GEMex project) and of flexible couplings, to accommodate thermal expansion and contraction (the Geothermica project GeConnect).

The GEMex project was an international cooperation between the EU and Mexico on geothermal energy research. It was funded by the EC and the Mexican government to finance a joint research programme between European and Mexican partners. Test sites were chosen to investigate a potential supercritical reservoir at Los Humeros, and an advanced EGS site at Acoculco. The sites were chosen to apply and extend approaches developed in previous projects on exploration (IMAGE, FP7), development of supercritical reservoirs (Deep-EGS) and stimulation for EGS (DETSRESS). The broad expertise available in the consortia led to a detailed set of new data, which provided unprecedented detail for the models of the subsurface at Los Humeros. That way the volcanological history of the site could be unravelled and the location of new, deeper and potentially supercritical reservoirs could be identified by a combination of geological, geophysical and geochemical methods. Materials for downhole installations were tested in-situ in one of the deep wells in operation, in cooperation with the local operator.

At Acoculco, the combined methodological efforts around two existing dry wells led to the discovery of critical subsurface structures and an explanation, why the wells are dry, in spite of the presence of hot springs at the surface. The project provided detailed stimulation concepts for the wells to be connected to a permeable structure. Further geophysical measurements identified potentially productive geothermal zones further away from the wells.

Some projects are not explicitly geothermal but include geothermal energy solutions as an option for more generic energy efficiency or research purposes (projects 18-22, **Table 9**; projects 36 and 38, **Table 10**). These projects could not be listed as addressing a specific geothermal R&I Target, which is marked as not applicable in the respective column.

Table 8. Ongoing H2020 projects, sorted by SET-Plan R&I priority

Project	Type	Time-frame	EU contribution (EUR)	R&I Priority
GeoSmart - Technologies for geothermal to enhance competitiveness in smart and flexible operation	IA	2019 – 2024	14.985.759,28	3
REGEN-BY-2 Next REnewable multi-GENeration technology enabled by TWO-phase fluids machines	RIA	2020 - 2024	4.905.748,75	3
GEO4CIVHIC - Most Easy, Efficient and Low Cost Geothermal Systems for Retrofitting Civil and Historical Buildings	IA	2018 - 2023	6.841.960,75	5
GeoFit - Deployment of novel GEOthermal systems, technologies and tools for energy efficient building retroFITting	IA	2018 – 2022	7.896.940,14	5
Geco – Geohermal Emission Control	IA	2018 - 2022	15.599.842,88	5
GeoHex - Advanced material for cost-efficient and enhanced heat exchange performance for geothermal application	RIA	2019 - 2022	4.989.401,25	5

Project	Type	Time-frame	EU contribution (EUR)	R&I Priority
GeoPro - Accurate Geofluid Properties as key to Geothermal Process Optimisation	RIA	2019 – 2022	4.898.982,50	5
REFLECT - Redefining geothermal fluid properties at extreme conditions to optimize future geothermal energy extraction	RIA	2020 – 2022	4.992.761,25	5
MEET - Multidisciplinary and multi-context demonstration of EGS exploration and Exploitation Techniques and potentials	IA	2018 - 2022	9.972.818,88	6
OptiDrill - Optimisation of Geothermal Drilling Operation with Machine Learning	RIA	2021 - 2023	3.985.302,50	7
Geo-Drill - Development of novel and cost-effective drilling technology for Geothermal Systems	RIA	2019 - 2022	4.996.400,00	7
ORCHYD - Making geothermal energy a more viable alternative	RIA	2021 - 2023	3.999.945,00	7
LEAP-RE Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy	RIA	2020 - 2025	14.952.219	n/a
RE-COGNITION - REnewable COGeneration and storage techNologies IntegraTIon for energy autONomous buildings	RIA	2019 - 2022	4.990.000	n/a
ALIGHT - Copenhagen Airport: a Lighthouse for the introduction of sustainable aviation solutions for the future	IA	2020 – 2024	11.957.081	n/a
EXCITE - Electron and X-ray microscopy Community for structural and chemical Imaging Techniques for Earth materials	RIA	2021 – 2024	4 999 635,50	n/a
TEMPO - TEMPerature Optimisation for Low Temperature District Heating across Europe	IA		3 130 868,43	n/a

Source: authors' analysis of CORDIS data

Table 9. ERC Grants and Marie Skłodowska-Curie Actions, sorted by project name

Project	Type	Start-End	EU contribution EUR
ARMISTICE Analysis and Risk Mitigation measures for Induced Seismicity in supercriTICal gEothermal systems	MSCA Individual Fellowship	2021 - 2023	160 932
EASYGO - Efficiency and Safety in Geothermal Operations	ITN EJD	2020 - 2024	3 416 039
GeoREST - predictinG EaRthquakES induced by fluid injecTion	Starting Grant	2019 - 2024	1 438 201

MaPSI Mathematical and Numerical Modelling of Process-Structure Interaction in Fractured Geothermal Systems	Consolidator Grant	2021 - 2026	2 .000 000
MODERATE Magma Outgassing During Eruptions and Geothermal Exploration	Consolidator Grant	2021 - 2026	2 821 036
NERUDA - Numerical and ERT stUdies for Diffusive and Advective high-enthalpy systems	MSCA Individual Fellowship	2018 - 2021	175 420
PRD-Trigger - Precipitation triggered rock dynamics: the missing mesoscopic link	Starting Grant	2020 - 2025	1 491 330
THERM - Transport of Heat in hEteRogeneous Media	MSCA Individual Fellowship	2020 - 2022	196 708

Source: authors' analysis of CORDIS data

Table 10. H2020 CSA projects and ERA Net Cofunds ending after 2019 (sorted by project name)

Project	Type	Start-End	EU contribution (EUR)
CROWDTHERMAL - Community-based development schemes for geothermal energy	CSA	2019 - 2022	2 305 801
ENeRAG - Excellency Network Building for Comprehensive Research and Assessment of Geofluids	CSA	2018 - 2022	999 039
GEOENVI - Tackling the environmental concerns for deploying geothermal energy in Europe	CSA	2018 – 2021	2 495 872
GeoERA - Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe	ERA Net	2017 – 2022	10 000 000
GEORISK - Developing geothermal and renewable energy projects by mitigating their risks.	CSA	2018 - 2021	2 184 118
GeoTWINN - Strengthening research in the Croatian Geological Survey: Geoscience-Twinning to develop state-of-the-art subsurface modelling capability and scientific impact	CSA	2018 - 2022	996 718
GeoUs - Geothermal Energy in Special Underground Structures – Building Czech research excellence in geothermal energy	CSA	2020 - 2022	796 250
SU-DG-IWG Support Unit for the Deep Geothermal Implementation Working Group	CSA	2019 - 2022	1 006 750

Source: authors' analysis of CORDIS data

Looking at the number of geothermal projects finished after 2019 and the still ongoing projects (**Table 8**) it is obvious that some R&D priorities (**Table 1**) received much more EU funding than others. In Geothermica, for comparison, the distribution across the different research topics is somewhat more balanced. In H2020, most funded projects, and also the largest overall budget, were in R&D priority 5 *Sustainable and efficient production technologies* (**Table 11**). This included projects on advanced materials (e.g., GeoHEX) as well as on CO_2 emission reduction and control (GECO) and retrofitting of buildings (GeoFIT). A relatively large amount of funding went to R&D priority 6 *Development and exploitation of geothermal resources in a wider range of geological settings*, while several smaller projects were funded in R&D priority 7 *Advanced drilling and well completion techniques*. The large projects on priority 6 were funded early on in H2020, when the emphasis was on EGS developments for testing and demonstration at the real scale (DEEPEGS and DESTRESS). All EGS projects overlapped thematically with R&D priority 7 on drilling. The GEMex project included both EGS and drilling as well as exploration (R&D priority 8) aspects, but here the focus was on the collaboration with Mexico to test these technologies jointly. R&D priorities 1, 2 and 4 did not receive the attention they would need. These are the topics of integration of geothermal solutions in an energy system or in an urban heating system. R&D priority 9 Increasing awareness of local communities and involvement of stakeholders in sustainable geothermal solutions is usually explicitly required as a task in all projects and is sometimes addressed in CSA projects. R&D priority 10 Risk mitigation (financial/project) is rarely addressed as a specific topic, but also as part of R&D project execution. Risk mitigation at the operational project level was not addressed in latest calls and projects.

Table 11. Distribution of H2020 funds across the different R&I priorities

SET-Plan IWP R&D priority	Total H2020 funding (€)	No. of H2020 projects	No. of of Geothermica projects
1. Geothermal heat in urban areas		0	2
2. Integration of geothermal electricity and heating & cooling in the energy system responding to grid and network demands		0	1
3. Improvement of overall geothermal energy conversion performance for electricity and heating & cooling generation	23 847 248	3	1
4. Closed loop electric and heating & cooling plants integrated in the circular economy		0	1
5. Sustainable and efficient production technologies	49 942 611	7	2
6. Development and exploitation of geothermal resources in a wider range of geological settings	39 669 165	3	2
7. Advanced drilling/well completion techniques	12 981 648	3	3
8. Innovative exploration techniques for resource assessment and drilling target definition	9 999 793	1	2
9. Increasing awareness of local communities and involvement of stakeholders in sustainable geothermal solutions		0	0
10. Risk mitigation (financial/project)		0	1

Source: own elaboration

3.3 International developments

The interest in **superhot/supercritical geothermal resources** continued beyond the Iceland Deep Drilling Projects and H2020 projects Deep-EGS and DESCRAMBLE. Plans to develop such resources were developed already within the HADES (Hotter and Deeper Exploration Science) project in New Zealand (Bignall & Carey, 2011) and in the Japan Beyond Brittle Project (Muraoka et al., 2014). All known geothermal projects in supercritical conditions are summarised by Reinsch et al. (2017). Currently, an Icelandic industry-led consortium is planning to drill a third deep well (IDDP-3) at the Hengill volcano. In addition, an international consortium is trying to set up a research project near the site of the first IDDP well in the Krafla volcano, the Krafla Magma Testbed (www.kmt.is). The IEA Geothermal technical cooperation program's annual report also provides details on the developments in the participating countries (IEA Geothermal, 2022).

Enhanced Geothermal Systems (EGS) continue to see development. In Europe, Switzerland has a rigorous programme to establish the technology, with a dedicated subsurface laboratory at Bedretto, where numerous national and international cooperation projects perform tests at controlled but realistic conditions. A complementary infrastructure called Geolab is planned in Germany by the Helmholtz Assocation, to be run by the research centres KIT (Karlsruhe), GFZ (Potsdam) and UFZ (Leipzig). An EGS demonstration project is currently planned in the city of Litoměřice, Czech Republic, where two deep wells into basement rocks are expected to supply heat for a multiple source district heating network, jointly with thermal storage in deep borehole heat exchangers. In the UK, the United Downs project and the Eden project targeting hot granites in Cornwall successfully drilled deep wells and stimulated them. Commissioning of a power plant for electricity supply from United Downs has been announced for 2022 (https://geothermalengineering.co.uk/united-downs). Both projects received co-funding from national and European sources.

In the USA, the DoE has funded a major national research infrastructure for EGS in Utah: the Frontier Observatory for Research in Geothermal Energy – FORGE (https://utahforge.com). FORGE is a dedicated underground field laboratory for developing, testing, and accelerating breakthroughs in Enhanced Geothermal Systems technologies to advance the uptake of geothermal resources around the world. Near term goals are aimed at perfecting drilling, stimulation, injection-production, and subsurface imaging technologies required to establish and sustain continuous fluid flow and energy transfer from an EGS reservoir. The field laboratory comprises a large volume of hot crystalline granite between two deep directionally drilled wells at around 2500 m depth below the surface. One of these wells is already drilled and completed. On site facilities include water, power, offices, broadband internet, which will be required for drilling, stimulation, and injection-production activities. The facility is managed by a multi-disciplinary team of engineers and scientists led by the University of Utah. Partner institutions include universities, national labs, federal and state funded institutions, and private industry. FORGE was used as a test site in several Geothermica projects (jointly with US American partners).

Beyond FORGE, the DoE funds a sizeable EGS research programme. In China, the first EGS well was drilled in 2018 in Hainan, but further information about its development has not been publicly reported so far.

Geothermal **research sites for district heating & cooling** are currently developed in several countries, often related to university campus projects. In the USA at Cornell University develops the Cornell University Borehole Observatory – CUBO (https://earthsourceheat.cornell.edu). In 2022, a first 3km observatory borehole was drilled to further explore subsurface conditions and heat output. In Germany, Karlsruhe Institute of Technology is currently planning DeepStor, a scientific infrastructure to demonstrate the HT-ATES concept targeting former hydrocarbon reservoirs in deep sedimentary rocks (https://geothermics.agw.kit.edu/english/452.php). At the Technical University of Darmstadt, four 750 m deep borehole heat exchangers will be drilled in the framework of the project SKEWs – Seasonal crystalline borehole thermal energy storage. The wells are drilled with a distance of 5 m to each other to build a medium-deep borehole energy storage. The storage system will undergo a 1.5-year test cycle to simulate a seasonal heat supply via mobile heaters and mobile cooling devices. Currently the first well has been drilled. In the Netherlands, a campus geothermal well doublet will be drilled at TU Delft starting in 2023. The wells will be 2 to 2.5 km deep to provide heat of 75°C for the campus and surrounding buildings. It will be operated as a commercial project but serve as a research infrastructure for monitoring, sampling and testing. The wells are part of the European Plate Observing System – Netherlands (EPOS-NL; www.epos-nl.nl). The installation of the infrastructure within this framework includes a permanent monitoring network of surface and downhole seismic stations, fibre optic cables in both wells, several hundred meters of cores, and multiple well logs, to provide background information on the reservoir and allow observation of subsurface changes. Beyond campus projects, the city of Munich develops their urban geothermal district heating network in cooperation with other local developers in surrounding communities and the research team of the GeothermieAllianz Bayern (GAB), a research alliance of several universities cooperating with the developers. So far, six geothermal wells have been drilled, but several more are planned in different locations. Similarly, the city of Geneva in Switzerland develops a district heating and possibly heat storage system. The research collaboration with the university of Geneva is well-developed and often expands to other (international) universities.

4 New Trends

4.1 Extraction of Critical Raw Materials

Extraction of minerals and metals from geothermal brines has a long tradition. For example, the probably most successful example of mineral recovery has been the extraction of boric acid, sodium perborate, and ammonium carbonate from the brines at Larderello, Italy. While the recovery of boric acid was already started there in 1818, commercial production in high volumes occurred between 1850 and 1975, while electricity generation was already going on (since 1913).

Today, several materials could be economically recovered from geothermal brines, specifically gold, cesium, rubidium, manganese, zinc, lithium, and high-purity silica (e.g., Neupane & Wendt, 2017). High-purity zinc has been recovered economically and commercially from geothermal brines, accounting for almost all zinc produced in the USA 2002-2004. These operations were closed due to financial issues unrelated to mineral recovery.

With the increasing demand for batteries, the focus of mineral extraction from geothermal brines has been on lithium. While relatively high lithium concentrations have been reported for geothermal brines in several parts of Europe (Sanjuan et al., 2022, and references therein) and other parts of the world, the first attempts and investigations on the extraction have been reported for the Salton Sea project in California already in 2011. Beyond the extraction of lithium there, the company Simbol Materials has also developed patented technologies for high-purity silica, manganese, and zinc.

Box 6. Lithium extraction from geothermal brine

Currently, most industrially sourced lithium comes from Chile, Australia, Bolivia, Argentina and China. It is usually sourced using two methods: open-pit mining, or extracting brine from underneath the surface of dried lakebeds, salt flats known as salar. Extracting lithium from brines found below such salt flats has been the dominant method of producing lithium. High grade lithium compounds are processed mostly by solar evaporation of salar brines in Argentina, Chile, and Bolivia. Lithium is present in very high concentrations in these brines (typically more than 500 mg of lithium per liter of brine), and processing costs are low. However, lithium separation from salar brines has several disadvantages: Separation is slow (up to 24 months), weather-dependent, and has an extraction efficiency of only about 50%. After lithium is concentrated by solar evaporation, it still requires multiple purification steps.

Looking at the highest concentrations of lithium found in geothermal fluids in Europe so far (Table 12), there is an obvious connection to volcanic and magmatic rocks in or near the reservoirs, such as the Campi Flegrei in Southern Italy or the granitic rocks found in the basement of the Upper Rhine Valley and Cornwall. Also the high LI concentrations in Rotliegend reservoirs of the North German Basin can be explained by the volcanic rocks underlying the Rotliegend sandstone reservoirs. In purely sedimentary environments such as the Bavarian Molasse Basin, the Paris Basin or the geothermal reservoirs currently exploited the Netherlands, Li concentrations found so far are usually <100mg/L.

The economic recovery of lithium from geothermal brines faces several challenges:

- Lithium concentrations are low (Table 12). Extraction methods must be able to capture lithium efficiently at these concentrations. Currently concentrations of >125 mg/L are considered necessary for efficient extraction.
- Large volumes of brines circulated in geothermal operations need to be processed to extract any meaningful amount of lithium. Any recovery process that requires pre-treatment of the brine or chemical modification of the entire brine flow is likely to require large quantities of consumable reagents, which are relatively expensive. Heating or cooling the brines requires energy (that can be provided by the geothermal plant).
- Brines also contain high concentrations of low-value dissolved solids (rock salt, NaCl; potassium chloride (KCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), and others). Their removal should not be required for the recovery of lithium.

- Other than the loss of lithium the extraction should not affect the fluid chemistry, not to upset chemical equilibrium in the reservoir after re-injection.
- An open question is the chemical recharge of the fluid. It is not clear if the cycling and reinjection of the depleted fluid will lead to a decrease in lithium concentration in the (re-) produced fluids.

Table 12. Geothermal Brine Compositions in Geothermal Areas considered for Lithium extraction

Concentrations in mg/L	Salton Sea[4] USA	Campi Flegrei Italy	NGB[5] Germany	Molasse Basin[6]HC-15 Germany	URG[7] Germany	URG[8] France	Cornwall[9] UK
Lithium (Li)	211	480	212	162	168	190	125
Sodium (Na)	52,000	85,200	31,600	21,800	29,900	28,500	4,300
Potassium (K)	14,000	43,400	2,560	1990	3,820	3,790	180
Magnesium (Mg)	160		233	115	99	138	73
Calcium (Ca2+)	24,000		45,400	790	7,250	7,200	2,470
Strontium (Sr)	500		1290		456	498	40
Barium (Ba)	433						
Boron (B)	350	231	116		41.1	45.9	11
Copper (Cu)	4						
Iron (Fe)	2,300						
Manganese (Mn)	1,200						
Nickel (Ni)	4						
Lead (Pb)	100						
Zinc (Zn)	660						
Chloride (Cl)	145,000	314,000	138,000	33,300	64,900	59,900	11,500

Source: authors' elaboration of (Sanjuan et al., 2022 and references therein)

A major focus of RD&D efforts is on the efficient extraction of lithium (and other metals) from geothermal brines. Several different methods are currently tested, all extracting far more than the 50% achieved by evaporation. Extraction methods include

- **Membranes for Nanofiltration** and reverse osmosis. Several membrane techniques have recently been reviewed and described by Stringfellow & Dobson (2021)
- **Ion exchangers** are proposed as a primary direct lithium extraction method from geothermal brines (e.g., Toba et al., 2021). This method is used commercially in the final treatment of wastewaters for decontamination and softening of the water.

[4] Gagne et al. (2015)
[5] NGB - North German Basin: Gross Schönebeck GrSk4
[6] Highest reported value from the Muschelkalk in the SW-German Molasse Basin. Most geothermal developments in the Molasse Basin are in Bavaria, SE-Germany in the Upper Jurassic limestones, where Li concentrations are much lower
[7] URG – Upper Rhine Graben, Insheim
[8] URG – Upper Rhine Graben, Rittershoffen GRT-1
[9] Cornish Lithium Ltd. reported concentrations of >200 mg/L

- **Sorbents** are solid materials (resins) widely used to remove trace metals and pollutants from water. The materials are cheaper than membrane filtrations and are environmentally friendly since they do not require the use of additional acidic solutions. Sorbents are solid materials that selectively adsorb specific molecules or ions. A series of different sorbent materials for selective lithium extraction was investigated by Stringfellow & Dobson (2021).
- **Electrodialysis** mobilisies ions through a permeable membrane applying an electric field potential on the ion solution. The fluid flows between anode and a cathode of an electrodialysis cell through a series of anion and cation exchange membranes in the space between the two electrodes (Gmar & Chagnes, 2019; Stringfellow & Dobson, 2021). It is used in processes of seawater desalination, treatment of wine and fruit juices, radioactive wastewater treatment and regeneration of ion-exchange resin….

Three main industry projects for the commercial extraction of lithium from geothermal brines have been developed in the last few years. In Southern Germany, Australia-based by Vulcan Energy has started to sign lithium supply agreements with industry customers. Their primary source of lithium will be geothermal wells in the Upper Rhine Gaben (Germany/France). In Canada, E3 Lithium has published the Preliminary Economic Assessment of the project in September 2021. The brines of the project come from the Devonian Leduc Reservoir, in the subsurface of Alberta, with reported lithium concentrations of 74.6 mg/L. In addition, the UK based mineral exploration and development company Cornish Lithium Ltd. announced that its subsidiary company GeoCubed Ltd., successfully commissioned and delivered the Direct Lithium Extraction Pilot Plant at Cornish Lithium's Geothermal Waters Test Facility at the geothermal energy project of United Downs in Cornwall. European R&D projects addressing the extraction of raw materials from geothermal brines include CHPM2030 - Combined Heat, Power and Metal extraction from ultra-deep ore bodies, which finished in 2019. The Geothermica project PERFORM, targeting improved performance by preventing corrosion and scaling, included removal of metal cations from the brine. The extraction of metals is also part of the PERFORM 2 project funded within the 2021 Geothermica call (project begin Sept. 2022). A Horizon Europe project directly addressing the extraction of critical raw materials from geothermal brines is CRM-geothermal that started in May 2022.

4.2 High Temperature Subsurface Heat Storage

UTES has received increased attention recently, in the context of the growing urge to shift our energy supply to fluctuating renewable sources. As heat supply and demand are highly asynchronous, with fluctuations much larger than for the electricity supply, large scale seasonal heat storage is key for utilisation of available heat sources in the energy transition. Borehole heat exchangers (BHE) are one possible way to store and supply heating (and cooling) at low temperature ranges in the subsurface, in combination with heat pumps. While this technology can be applied and scaled up in most places in the world, using the heat capacity of the surrounding soil and rocks, it is not as energy efficient as, for example, ATES, which uses the temperature of groundwater for heating, cooling and heat storage. More than 80% of the world's ATES systems are installed in the Netherlands, where shallow aquifers are commonly used for individual office buildings or small residential areas. Storage temperatures are usually limited to 25°C, such that these systems are also combined with heat pumps. So far only few high temperature ATES systems exist for higher storage temperatures, for example for the German Parliament buildings in Berlin and for an industry park in Middenmeer in the Netherlands. An alternative option with enormous heat storage potential are abandoned (and flooded) mines, as used in the city of Heerlen in the Netherlands, where the old coal mines serve as a source of heat for municipal buildings with enormous storage potential.
Starting with the Geothermica project HEATSTORE in 2019, which united innovative storage projects in six different countries, increased attention has been paid to high temperature UTES by the European R&D sector. This is also manifested by Horizon Europe calls such as *HORIZON-CL5-2022-D3-01-04 - Demonstrate the use of high temperature geothermal reservoirs to provide energy storage for the energy system*, as well as several national initiatives on various UTES technologies in the Czech Republic, Denmark, France, Germany, the Netherlands, Norway, Sweden, Switzerland and the UK.

4.3 Medium-deep/low-enthalpy geothermal resources

With new building standards and a drive for better insulation of existing buildings to lower related CO_2 emissions, lower temperature heating systems make low enthalpy geothermal resources more attractive. This trend leads to the development of shallower resources even in regions without naturally high heat flow. These resources have several advantages, as the reservoir rocks are often less compacted and dense, resulting in higher permeabilities and high reservoir productivity. In addition, reservoirs at shallower depths are less costly to develop as they don't require the large drilling rigs and deep wells. Such projects have been in the focus of regional developers, for example in Denmark, Germany the Netherlands and France. In the Netherlands the technical potential for this geothermal resource is estimated to cover 37% of the total current heat demand (Schepers et al., 2018). In a recent development, two geothermal wells to a depth of approximately 1300m with 56°C and very high flow rates were drilled in the city of Schwerin in Northeast Germany, which are planned to become basis of their new district heating network. Current heat pump technology can easily bring the temperatures to 80°C where required.

The R&I demand for this kind of resource is thus related to the R&I priorities 2 - *Integration of geothermal electricity and heating & cooling in the energy system responding to grid and network demands*, 3 - *Improvement of overall geothermal energy conversion performance for electricity and heating & cooling generation* and 4 - *Closed loop electric and heating & cooling plants integrated in the circular economy*. In many areas, there is also a basic demand for characterisation of the medium/deep resource, as it has often been overlooked and therefore rarely been investigated. Typical drilling targets, also for hydrocarbon extraction, were usually deeper, leading to 'white spots' on the map regarding those shallower depths.

Regulatory issues can also become problematic and need to be addressed. In many European countries, the distinction between 'shallow' geothermal and 'deep' geothermal is made based on a somewhat arbitrarily defined depth. For example, in Germany drilling to less than 100m is regulated by the water protection law, which is issued by the federal states, while deeper boreholes require licensing by the national mining law. In the Netherlands the boundary between the Water and Mining law is at 500 m depth. Some potential aquifers cross this boundary. In Italy and France, the distinction is made based on temperature. The potential confusion and overlap of different regulatory guidelines to follow has economic implications for the development of these medium-deep targets, as drilling to greater depths is subject to costly safety regulations. The development of this promising low-cost resource thus requires adaptation of existing regulations and ideally harmonization at the European level.

Last but not least, heat pump technologies are seeing a dynamic development towards higher temperatures, such that industrial applications above 100°C could also be covered with low-enthalpy geothermal energy. This technical development is not uniquely geothermal, but of great relevance for the integration of different technologies in the future energy mix.

5 Environmental and Socio-Economic Sustainability

Environmental: GHG emissions, energy balance, ecosystem and biodiversity impact, water use, air quality, land use, soil health, hazardous materials, technology-specific LCA standards or best practices

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 (start of operation planned in Q4 2022).

Generally, high enthalpy steam based power production tends to co-produce GHG emissions, while low enthalpy resources exploited with binary cycle power plants will emit much less. These differences are explained and quantified in detail in the study on 'Geothermal plants' and applications' emissions' (European Commission, 2020).

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** (**EPBT[10])** of geothermal would range from around 2 months to 3.5 years (European Environmental Bureau, 2021, and references therein). 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.

There is little research on the **environmental impact** of geothermal plants, although some (research) projects are currently in execution and the H2020 project GEOENVI ended in 2021. 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 (Manzella et al, 2021).

Land use of geothermal power is in the range of 0.04 to 0.4 km^2/TWh (European Environmental Bureau, 2021, and references therein). 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 (2021). 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 range from close to 0 to up to 14 m^3/MWh131, geothermal energy performs well in terms of water consumption (European Environmental Bureau, 2021). For geothermal electricity, flash power plants (i.e., power plants that directly use geothermal fluid to drive a generator and re-

[10] EPBT is the time taken for an energy system to generate the amount of energy equivalent to that it took to produce the system

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 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 (Huenges & Ledru, 2010).

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 (e.g., Tomasetta et al., 2015). 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 (e.g., Fleuchhaus et al., 2020).

Social: health, public acceptance, education opportunities and needs, employment and conditions, contribution to GDP, rural development, industrial transition, affordable energy access, safety and (cyber)security, energy security, food security, responsible material sourcing

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 (Shortall et al., 2015). Among them, CH_4, NH_3, mercury, arsenic and SO_2 emissions are associated with potential 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 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. (2013) 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 (2021).

Employment. In Europe, approximately 40.000 persons are employed in the geothermal sector directly, including ground-source heat pumps (IRENA and ILO, 2021). Employment numbers have slowly increased in the last years, unlike other sectors in the energy market. For the deep geothermal sector, EurObserv'ER data for 2020 shows combined direct and indirect employment of 6 100 (a small drop of 300 from the 2019 value). **Table 13** include 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 (Bracke & Huenges, 2022).

Geothermal installations don't require critical raw materials to the extent of other technologies, and all major investments are local. That way geothermal projects can

- contribute to **rural development**, by providing energy to the agricultural sector;
- support **industrial transition**, by supplying process heat for many sectors
- provide **affordable energy access**, without the volatility of energy market developments
- guarantee **energy security**, independent of fuel imports
- be developed with **responsible material sourcing**, as most investment is done locally and critical materials are not required. Instead, several geothermal projects could serve as sources of raw materials such as lithium, zinc, high-purity silica and potentially others.

Economic: cost of energy, critical raw materials, resource efficiency and recycling, industry viability and expansion potential, trade impacts, market demand, technology lock-in/innovation lock-out, technology-specific permitting requirements, sustainability certification schemes. **Figure 12** shows the IRENA data on the levelised costs of different geothermal plant types over the last decade (IRENA, 2022). A large variation is apparent, and overall no significant cost reduction trend has been established (see also section 2.3 above).

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 and 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. 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. In 2020, the global weighted-average total installed cost of the eight plants in IRENA's database was USD 4 486/kW, higher than the recent low of USD 3 538/kW set in 2015. The total installed costs of the eight projects commissioned in 2020 ranged from a low of USD 2 140/kW to a high of USD 6 248/kW.

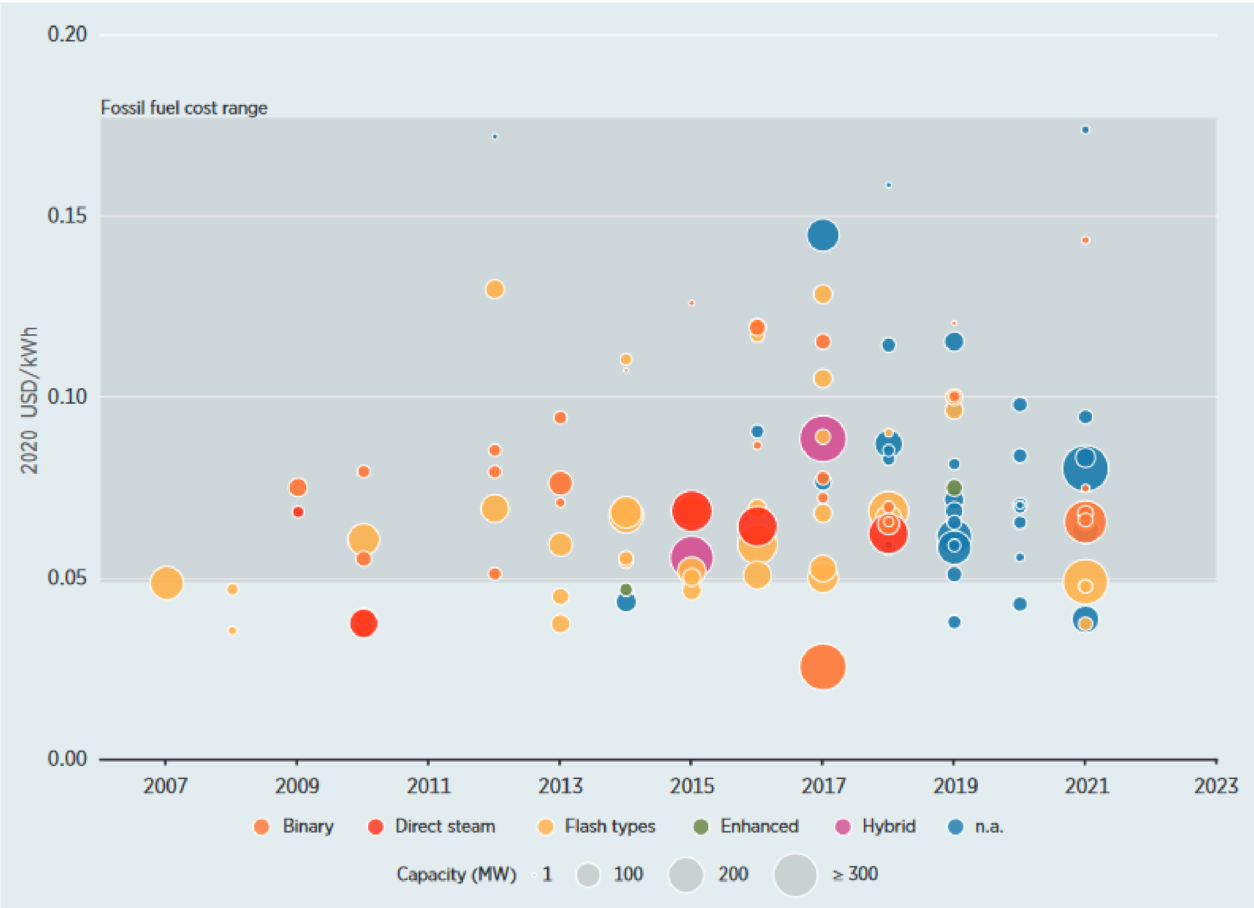
Geothermal plants are typically designed to run as often as possible to provide power round the clock. In 2020, the global weighted-average capacity factor for newly commissioned plants was 83%, while ranging from a low of 75% to a high of 91% for the projects in the IRENA database. These high capacity factors lead to the low LCoE compared to other energy sources. Operational costs are usually low, unless maintenance is required.

In the IRENA database the need for drilling additional wells to maintain production pressure in the lifetime of a project (25 years[11]) was assumed, which brings operation and maintenance costs to USD 115/kW/year. This number is 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.

The overall EU market turnover as reported by EurObserv'ER was EUR 810 million in 2020, with gross value added of EUR 440 million. These values are the same as for 2019 and represents approximately 0.5% of the EU totals for renewables. The Netherlands, Italy, France and Germany accounted for 52% of the turnover (**Table 13**).

Annex 1 provides the overall CETO sustainability matrix with the most relevant information and references.

Figure 12. LCOE of geothermal power projects by technology and project size, 2007-2021



Source: IRENA Renewable Cost Database 2021

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

Table 13. 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
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

6 Conclusions and Outlook

Globally, deep geothermal energy for electricity generation has seen steady growth in a number of countries, reaching a total installed capacity of around 14.4 GW in 2021,. This represents an increase of 44% from 2010 (IRENA, 2022). The EU's net capacity was 877 MWe in 2020, but growth is well below the global trend. In 2021 just 2 small small-scale binary power plants were added, with capacities of 1 MW and 5 MW respectively. Electricity production is projected to increase from 6.7 TWh in 2020 to 7 TWh by 2030 (EurObserv'ER, 2022).

For geothermal heat production in the EU, the outlook is more promising, with EurObserv'ER expecting growth from 870.5 ktoe in 2020 to 1000 ktoe in 2030. In particular rhe geothermal district heating and cooling (DHC) sector has shown a growth rate in installed capacity of 6%, and thre are now 262 systems with a total installed capacity of 2.2 GWth. Growth i was led by projects in France, the Netherlands and Poland. This modest growth may be partly due to delays caused by the Covid pandemic, and may be compensated by stronger growth in 2022, when the affected plants come into operation.

The EU maintains a strong position for R&D investment, high-value patents and scientific publications in this field. The focus of geothermal RD&D is changing with time, both for EU and national or transnational funding schemes. For example drilling and development of EGS were topics with several funded projects in H2020 and in the first rounds of Geothermica as well as in several nationally funded R&I programmes. That way it was possible to develop technologies from lower TRL to demonstration projects. Looking at these different funding frameworks and national developments, there seems to be a shift towards heating & cooling in urban environments and integration of high temperature storage.

Several successful project developments were able to build on previous projects. For Enhanced Geothermal Systems, the development of the Soultz-sous-Forêts site was a milestone, and all subsequent EGS projects built on the lessons learnt there. Stimulation technologies have been further developed, for example in the DESTRESS project, where the zonal isolation concept for targeted and controlled hydraulic stimulation was tested, which was then further refined in the Geothermica project ZoDrEx and finally applied at the real scale in the FORGE in the USA, funded by the Swiss Federal Office of Energy. Similarly, the adaptive traffic light system applied in the Geothermica projects COSEISMIQ and DEEP was developed in a Swiss project and within the FP7 project GEISER.

In other geothermal R&I priority topics such continuous development was not always possible. For example, geothermal exploration, advances made in IMAGE (FP7) were further developed and applied in GEMex (H2020), leading to breakthroughs in tracer technology for supercritical fluids, in fibre optic monitoring and in integration of multiple geophysical, geological and geochemical datasets. But there has not been a systematic support of exploration and resource assessment projects in the existing R&I framework programmes. Nonetheless. recent progress enabled by ever increasing computing power, allowing the incorporation of more detailed data and structures in geological models, corresponding software developments and technological advances such as fibre-optic sensing for distributed temperatures, distributed acoustic signals and distributed strain measurements at unprecedented resolution requires even new exploration approaches not yet addressed. Drone imaging provides new data sets from inaccessible areas in relatively short time. The wealth of these new data can take advantage of machine learning approaches to process and interpret all the potentially available information. Many of these developments were not mature at the time of the last EU funded exploration project (GEMex).

The examples above show that several projects are often needed to bring developments to maturity required for market uptake. This suggests a mission-driven approach would be beneficial for the steady and targeted development of the R&I priorities outlined in this document. Such an approach includes the non-technological aspects such as regulatory issues, project economics and stakeholder involvement. This would enable geothermal technologies to provide their full benefit in an integrated energy supply system.

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List of abbreviations and definitions

ATES	Aquifer Thermal Energy Storage
HT-ATES	High Temperature Aquifer Thermal Energy StorageBTES 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
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
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
NTB	Non-Technical Barriers
OPEX	Operating Expenditure
ORC	Organic Rankine Cycle
PCM	Phase Change Materials
PPA	power purchase agreement
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

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Annexes

Annex 1. Summary Table for Environmental and Socio-economic Sustainability

Parameter/Indicator	Input (guidelines info in italics)
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 km²/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
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).
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

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