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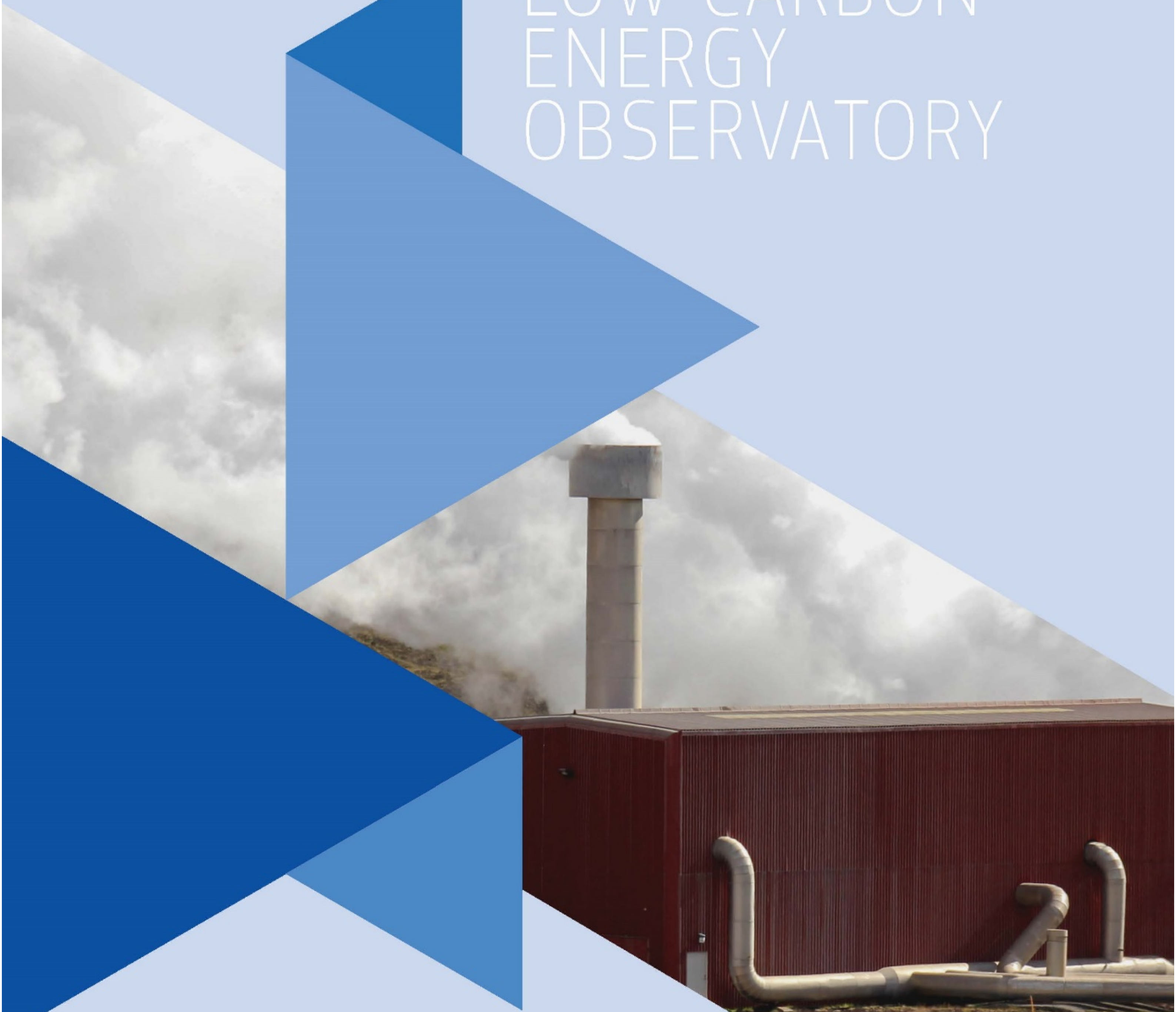
LOW CARBON ENERGY OBSERVATORY



GEOTHERMAL ENERGY

Technology development report

Joint Research Centre

EUR 30508 EN

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Authors

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Foreword on the Low Carbon Energy Observatory

The LCEO is an internal European Commission Administrative Arrangement being executed by the Joint Research Centre for Directorate General Research and Innovation. It aims to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies are covered?

- Wind energy
- Photovoltaics
- Solar thermal electricity
- Solar thermal heating and cooling
- Ocean energy
- Geothermal energy
- Hydropower
- Heat and power from biomass
- Carbon capture, utilisation and storage
- Sustainable advanced biofuels
- Battery storage
- Advanced alternative fuels

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main outputs?

The project produces the following report series:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Future and Emerging Technology Reports (as well as the FET Database).

How to access the reports

Commission staff can access all the internal LCEO reports on the Connected LCEO page. Public reports are available from the Publications Office, the EU Science Hub and the SETIS website.

1. Introduction

The purpose of this report is to provide an assessment of the state of the art of geothermal energy technology up to end 2019, in particular deep geothermal energy, to identify development needs and barriers and to define areas for further R&D in order to meet announced deployment targets and EU policy goals.

1.1. Geothermal energy technologies

Geothermal energy is derived from the thermal energy generated and stored in the Earth's interior. The energy is accessible since groundwater transfers the heat from rocks to the surface either through bore holes or natural cracks and faults (Glassley, 2018).

Deep geothermal energy is a commercially proven and renewable form of energy that can be used for both heat and power generation. Shallow geothermal energy is available everywhere. Shallow geothermal systems make use of the relatively low temperatures offered in the uppermost 100 m or more of the Earth´s crust.

Geothermal technologies can be divided into:

- power generation (hydrothermal and Enhanced Geothermal Systems, EGS);
- direct use (district heating and other use);
- shallow geothermal energy (Ground Source Heat Pumps, GSHP, and Underground/Aquifer Thermal Energy Storage, UTES/ATES).

Previous reports also include in-depth descriptions of the various technologies and their design (JRC 2015a, 2015b, 2019).

1.1.1. Resource potential

A recent study estimates the geothermal resource base specifically for direct heat in deep aquifers (Limberger et al., 2018). Based on the heat and cooling demand of different applications, such as spatial heating, heating of greenhouses and spatial cooling, the geothermal resource base was calculated. It was shown that suitable aquifers underlying 16% of the Earth's land surface could theoretically be suitable for direct use applications, with a 0.4 to 5 x 10^6 EJ that could theoretically be used for direct heat applications (Limberger et al., 2018). The annual recoverable geothermal energy is in the same order as the annual world final energy consumption of 363.5 EJ.

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).

However only a small portion of the heat in place can be realistically extracted for energy production. The heat in place is therefore often translated to economic potential using the levelised cost of energy (LCOE).[1] 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. However, realisation of this future potential will depend on overcoming such technical barriers as the demonstration of innovative, non-mechanical drilling techniques, allowing access to sufficiently high temperatures.

The planned electricity production in the EU Member States is 11 TWh_e according to their National Renewable Energy Action Plan (NREAP) for 2020. However, this target is unlikely to be met, as geothermal generation amounted to 7 TWh_e in 2018, as reported by the International Energy Agency (IEA, 2019). This generation mostly comes from the 0.9 GW_e installed in Italy, see the overview provided by the European Geothermal Energy Council (EGEC, 2019a). Unsurprisingly, the National Energy and Climate Plans (NECPs) reduce this target to 8 TWh_e by 2030 (EGEC, 2019b). In order to put these values in perspective, the current economic potential assuming a LCOE lower than 150 €/MWh_e is 21.2 TWh_e (Miranda-Barbosa et al., 2017), i.e. about twice as the NREAP planned production.

By 2030, predictions show that economic potential could be as much as 34 TWh_e or 1% of the total EU electricity supply.[2] The same authors estimated the economic potential to grow to 2570 TWh_e in 2050 (as

[1] In Europe, the economic potential of geothermal power including EGS is estimated at 19 GW_e in 2020, 22 GW_e in 2030, and 522 GW_e in 2050 (Limberger et al., 2014).

[2] This result is obtained assuming a LCOE of 100 €/MWh (JRC, 2015a).

much as 50% of the electricity produced in the EU) mainly due to economies of scale and innovative drilling concepts (van Wees et al., 2013).

1.1.2. 'Traditional' hydrothermal geothermal systems

Hydrothermal reservoirs of sufficiently high temperatures may be used for power production or combined heat and power production.

The geographical distribution of heat within the Earth's crust is highly variable. Highest heat gradients are observed in areas associated with active tectonic plate boundaries and volcanism. A hot rock formation with natural fractures and or porous structure where water can move due to convection is termed hydrothermal reservoir.

Hydrothermal resources are categorised into low (<100 °C), medium (100 – 180 °C) and high (>180 °C) enthalpy resources. These latter have limited distribution in EU and can only be exploited locally and in some cases regionally. The technologies associated with hydrothermal power and heat production may be considered as mature.

1.1.2.1. Dry steam and flash plants

Dry steam plants, in use since 1904, are used in conjunction with vapour-dominated resources. Flash steam power plants are the oldest and most common type of geothermal power plant. The flash steam technology makes use of liquid-dominated hydrothermal resources with a temperature above 180 °C. In the high-temperature reservoirs, the liquid water component boils, or 'flashes' as pressure drops in one to three stages. During the second and third flashing stage, the risk of scaling increases as the temperature of the fluid is reduced and the concentration of solutes increases. The scaling risk may be decreased by diluting the separated waters with condensates prior to reinjection.

Combined-cycle flash steam plants use the heat from the separated geothermal brine in binary plants (described in the next section) to produce additional power before reinjection. The single-flash and dual-flash power plants reach efficiencies between 30–35% and 35–45%, respectively, when electricity is the sole product. The overall efficiency is greatly increased by adding heat exchangers to produce heat.

1.1.2.2. Binary plants (ORC and Kalina)

Electrical power generation units using binary cycles are able to use low- to medium-temperature resources, which are more prevalent. Binary cycle power plants, employing Organic Rankine Cycle (ORC) or a Kalina cycle, operate at lower water temperatures of about 74-180 °C using the heat from the hot water to boil a working fluid, usually an organic compound with a low boiling point. Air cooled binary plants are also the most appropriate conversion cycles for EGS systems (described in the next section). The majority of the geothermal fluid can be returned to the reservoir following heat extraction and no fluid is lost in cooling towers through evaporation. Heat exchangers play a key role in the design of a binary plant as they ensure the transfer of heat from the geothermal fluid to the working fluid rotating the turbine.

Lower temperature hydrothermal resources are better suited to direct heat applications, described in Section 1.1.4.

1.1.3. Enhanced Geothermal Systems (EGS)

Although currently the vast majority of geothermal energy comes from hydrothermal resources, a large EGS potential is available.

Enhanced Geothermal Systems (also known as Engineered Geothermal Systems) are classified into two sub-categories.

- Hot sedimentary formations where there is no natural convection and heat is distributed by conduction are termed Hot Sedimentary Aquifers (HSA);
- A hot crystalline rock formation with insufficient or little natural permeability or fluid saturation that needs to be stimulated to allow for movement of water is termed petrothermal EGS.

HSAs have more widespread occurrence than hydrothermal reservoirs.

In both HSAs and petrothermal EGSs, fluid is injected into the subsurface where it is heated up on its way to production wells that divert the hot water to power and heat production facilities before it is reinjected to start another cycle.

In petrothermal systems, fluid is injected into the subsurface under carefully controlled conditions, which cause pre-existing fractures to reopen, creating a reservoir with sufficient permeability. Increased permeability allows fluid to circulate throughout the now-fractured rock and to transport heat to the surface where electricity can be generated.

In a HSA system, a reservoir with sufficient permeability already exists. Water can flow through the bulk of the reservoir but there is too much pressure gradient near the wells. Therefore, increasing the well performance and ensuring that the reservoir does not clog up during production are the main challenges for the reservoir engineering. In HSA systems, flow has to be maintained by surface pumps at injection wells, or well pumps in the production wells or both.

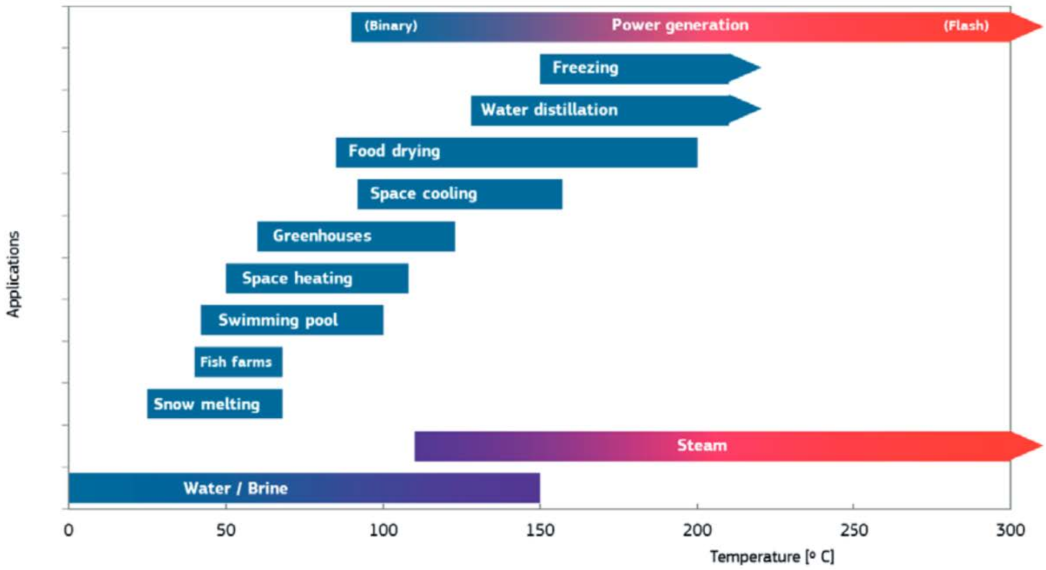
Once a reservoir has been created, the same technologies can be used as in hydrothermal systems, and these technologies are considered as mature.

1.1.4. Direct use

Apart from ground source heat pumps, which take up the largest share of direct use applications, geothermal energy is directly used for the most part in space heating, followed by greenhouse heating, aquaculture, agricultural drying, for industrial uses and for bathing purposes (Lund and Boyd, 2016). However, many other possible applications exist. Such direct-use technologies closely resemble geothermal electric systems, except the heat is used for another purpose (e.g., greenhouses, drying crops).

Geothermal energy has the advantage that it can be exploited through cascade utilisation (varied usage at progressively lower temperatures) which may increase the total efficiency and result in economic benefits. In 1973, Lindal indicated the temperature range of geothermal water and steam suitable for various applications (Gudmundsson et al., 1985). Waste heat from electrical generation plants or heat-only geothermal plants could supply a district heating system, and then supply a cascade of applications requiring successively lower temperatures (Figure 1).

Figure 1. A Lindal diagram of temperature of geothermal water and steam suitable for various applications. Source: JRC elaboration based on (Gudmundsson et al., 1985)



1.1.4.1. Geothermal district heating

Geothermal district heating refers to the use of geothermal energy to provide heat to individual and commercial buildings, or industry, through a distribution network. With new technologies and systems, many regions are developing geothermal technology for heating & cooling. Systems can be small (from 0.5 to 2 MW_{th}), and larger with capacity of 50 MW_{th} (GEODH).[3]

District heating systems (e.g. in the Paris Basin) are based on a sedimentary resource environment, and on the doublet concept of heat extraction, which refers to two wells (2000-3500 m) drilled in deviation from a single drilling pad.

Integration of combined technologies using renewable energy sources is a key feature of smart cities and rural communities. Geothermal can play an important role in smart thermal grids. This helps with the challenge of covering areas of different population density. Geothermal district heating systems can markedly vary in size (whole cities to small villages or areas).

1.1.4.2. Shallow geothermal energy

The normal ground temperature in all countries of the world varies between 2 °C and 20 °C, depending upon the climatic condition of the region or the depth of a borehole. These temperatures provide a basis for heat extraction or heat injection for shallow geothermal systems. Shallow geothermal energy can be exploited in two ways:

- Increase or decrease the temperature of geothermal heat to a desired level using Ground Source Heat Pumps
- Underground Thermal Energy Storage

Ground Source Heat Pumps (GHSPs)

GSHPs come in two general configurations: vertical borehole heat exchangers and horizontal subsurface loops. GSHPs are now the fastest growing application of direct geothermal energy use.

GSHP technology is suitable for residential houses or larger groups of houses, with capacities ranging from under 10 kW_{th} to over 500 kW_{th}. They convert the low temperature geothermal energy to thermal energy at a higher temperature which can be used for space or water heating (Ahmadi et al., 2017).

Usually, a refrigerant is used as the working fluid in a closed cycle (Lucia et al., 2017). An antifreeze solution is circulated inside a closed coil and exchanges heat with the heat source/sink through the ground heat exchanger.

Electric energy is used to drive the compressor and the efficiency of the performance of a heat pump is measured by calculating the ratio of delivered to used energy, which is the coefficient of performance (COP) (JRC, 2014a; Fischer and Madani, 2017).

The COP depends on the temperature difference between heat source and heat sink. The smaller the temperature difference, the more efficient the heat pump will be. GSHP usually have a COP in the range of 3-4 but can reach even up to 6 when well designed (Goldstein et al., 2011; Puttagunta and Shapiro, 2012; JRC, 2013a).

The depths of geothermal heat exchange range from a few metres to more than 200 m, depending on technology used, geological situation, demand profile, and other design considerations. For space cooling, direct cooling from the ground via e.g. cooling ceilings is possible in certain regions with moderate climate, allowing for space cooling with minimum energy input. In warmer regions with higher cooling demand, the heat pump can be used in cooling mode. For well-insulated houses with a forced ventilation system, geothermal energy can contribute to pre-heating or pre-cooling ventilation air while it passes through intake pipes buried in the ground (Aposteanu et al., 2014).

Underground Thermal Energy Storage (UTES)

A key challenge for the heating and cooling sector relates to the seasonal offset between thermal energy demand and supply. UTES is an attractive option to deal with this offset. UTES at 40-90 °C in particular can directly supply heat for low temperature industrial needs such as batch processes or seasonal industries (e.g. sugar refineries), where periods of heat (and/or cold) demand are followed by phases of inactivity.

UTES is preferable for long-term energy storage due to its high storage efficiencies and storage capacities. UTES can be subdivided into open-loop or closed-loop systems. In open-loop systems, also referred to as

[3] When the publication date is unknown, references simply report the project/website name.

Aquifer Thermal Energy Storage (ATES), heat and cold is temporarily stored in the subsurface through injection and withdrawal of groundwater.

The key requirement for ATES is the existence of an aquifer. The vast majority of ATES systems uses unconsolidated aquifers (i.e. aquifers composed of unconsolidated materials, such as silt or clay, sand or gravel) as a storage medium. Deeper systems typically utilise sandstones or highly fractured rocks. The suitability of the subsurface depends on several hydrogeological characteristics such as aquifer thickness, hydraulic conductivity or groundwater flow velocity. ATES is particularly suited to provide heating and cooling for large scale applications such as public and commercial buildings, district heating or industrial purposes (Fleuchaus et al., 2018).

Closed-loop Borehole Thermal Energy Storage (BTES) systems are another common form of UTES. However, unlike ATES, BTES stores thermal energy in the bedrock underground and is hence not limited to locations with aquifers underneath. This kind of system uses borehole heat exchangers to circulate thermal energy in a liquid medium and then discharge it into or out of the bedrock. BTES can be used for both small and large-scale applications.

1.2. Methodology and data sources

In this report, various approaches have been employed to provide an unbiased assessment of the geothermal energy sector. These include primarily in-depth literature reviews, expert judgements, existing KPIs identified by the sector and the collection and analysis of techno-economic information.

1.2.1. Literature review and analysis

Technology needs and barriers have since been identified by the industry, as indicated by the Strategic Energy Technology Plan (SET Plan) temporary working group. The state of the art of each technology was analysed by referring to the key research areas and KPIs set out by the SET Plan group. Indicators on key topics were used to provide an overview of the sector state of the art.

An analysis of EU co-funded projects as well as major national projects (depending on accessibility and data availability) has therefore been carried out. In addition, an overview of national, intra-EU and international funds available is provided to present the main R&D priorities.

1.2.2. Data sources

The main sources of data for this work consist of the EU CORDIS and Compass databases but in cases where project access was restricted, data was collected from project websites or from the peer reviewed literature. Techno-economic information was gathered according to the ETRI methodology, and complemented with updated data (JRC, 2014b; JRC, 2018a).

2. Technology state of the art

2.1. Introduction

Geothermal energy has many sub-technologies at different stages of development that face diverse challenges. In general, the technologies used for traditional hydrothermal geothermal plants and direct uses are mature (Technology Readiness Level, TRL, equal to 9), with some room for further improvement. However, challenges remain for technologies like EGS, which uses many of the same components but has yet to be demonstrated to a sufficient level. This is due to various factors including high upfront costs and high risks associated with drilling to greater depths and in the creation of the enhanced reservoir. Since the EU is not rich in hydrothermal resources, technological advances need to be made to mitigate the high costs and risks for EGSs.

The Implementation Plan of the SET Plan Temporary Working Group is the most up-to date summary of the most important R&I activities for geothermal (SET Plan TWG, 2018). The Implementation Plan reflects the findings of the European Technology and Innovation Platforms for Deep Geothermal and Renewable heating & cooling (Sanner et al., 2011; Dumas et al., 2018). Table 1 shows the starting TRLs for the research and innovative areas and these serve as a benchmark for evaluating progress. Since non-technical barriers play a major role in the uptake of geothermal energy they are also addressed in the SET Plan framework and are included here for completeness.

Table 1. Geothermal R&I areas in the SET Plan Implementation Plan and the associated starting TRL level

R&I category	TRL
Geothermal heat in urban areas	7
Equipment, materials and methods to improve operational availability	4-5
Enhancement of conventional and development of unconventional reservoirs	4
Improvement of performance	5-6
Exploration techniques	5-6
Advanced drilling/well completion techniques	3-5
Integration of geothermal heat and power in the energy system	4-5
Zero emissions power plants	5-6
Awareness of local communities and stakeholder involvement	n/a
Risk mitigation (financial/project)	n/a

Source: adapted from (SET Plan TWG, 2018)

2.2. Indicators

Relevant indicators to monitor the development of geothermal energy technologies are cost, conversion efficiency, GHG emissions and reservoir performance.

2.2.1. Costs

According to a recent report of the International Renewable Energy Agency (IRENA), geothermal in 2018 largely fell within the range of generation costs for fossil-based electricity. For new geothermal projects, the global weighted average LCOE was deemed to be 69 USD/MWh (IRENA, 2019).

A study by Bloomberg Finance shows geothermal LCOE to be relatively stable over the period 2010-2016. Flash turbine technology continues to be the cheapest form, with somewhat declining costs due to favourable exchange rates and cheaper capital costs. As for binary technologies, an increase in competition in the turbine market is expected to produce a downward cost trend. The capital expenditure (CAPEX) has been estimated based on the international literature at € 3 540 €/kW for flash plants, 6 970 €/kW for ORC binary plants and 11 790 €/kW for EGS plants (JRC, 2018a). Operating costs are in the range of 1.6-2.2% of CAPEX.

2.2.1.1. Production costs

SET Plan targets currently relate to reducing production costs, exploration costs and unit cost of drilling. With regard to production costs, SET Plan targets require these to be reduced to below 10 €ct/kWh$_e$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025.

The SET Plan group highlights that solving commonly encountered problems in geothermal applications will serve to reduce costs and make geothermal technologies more feasible. Challenges relate to the high temperatures, high pressures and fluid compositions found in geothermal environments. For both low and high temperature applications, problems such as corrosion and scaling or the gas content of fluids may result in operational issues. Improved materials, methods and equipment such as pumps and heat exchangers will need to be developed in order to improve equipment reliability and to increase the plant utilisation factor.

2.2.1.2. Exploration costs

Exploration costs include exploratory drilling and other exploration techniques. Exploration drilling alone can be up to 11% of CAPEX for geothermal project if accounting for all the activities needed to assess geological risk during the pre-development phase of the project (i.e. preliminary surveys and surface exploration) (Micale et al., 2014; Clauser and Ewert, 2018).

The SET Plan targets require reduction in exploration costs by 25% in 2025, and by 50% in 2050 compared to 2015.

2.2.2. Conversion and utilisation efficiency

A worldwide review of published data on 94 power plants around the world found an average conversion efficiency of 12% for geothermal power plants and a range of 1% for some binary systems to as high as 21% for some dry steam plants (Zarrouk and Moon, 2014). Maximising the efficiency of geothermal heat and power will reduce the cost of geothermal utilisation. The SET Plan working group has identified improving the overall conversion efficiency of geothermal power plants as a priority, with a target of 10% improvement by 2030 and 20% improvement by 2050.

2.2.3. Reservoir performance and sustainable yield

Currently, most geothermal power plants have a lifespan of several decades. Studies show that when a power plant utilises a geothermal resource for several decades, say 30 years, the resource will become depleted and require a recovery period of the same order of magnitude, e.g. up to 300 years (Steingrímsson et al., 2005; Shortall et al., 2015). This type of utilisation has been proposed to be 'sustainable' (Sanyal, 2005; Rybach and Mongillo, 2006; Axelsson, 2010) in that it results in economically feasible power production and a replenishment of the geothermal resource on a timescale acceptable to human societies. Plants with this type of utilisation tend to extract heat around ten times the natural 'renewable' recharge rate, i.e. that rate of replenishment that occurs due to natural heat flow.

However, some power plants extract at a 'commercial' or unsustainable rate of production, characterised by a high reservoir electrical capacity and long economic lifetime. In these cases, the geothermal resource may need longer periods to recover (Sanyal, 2018).

Production at lower rates and/or using production enhancement techniques enables the extraction of more heat and thus prolongs the economic life of a given reservoir (Rybach and Mongillo, 2006). Further studies are required to determine the natural recovery of a broad variety geothermal systems and extraction strategies after economic abandonment (Cook et al., 2017).

SET Plan targets require improvements in reservoir performance resulting in power demand of reservoir pumps to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030.

Concerning heating & cooling applications in buildings, shallow geothermal can be used as season thermal storages, if the source is at suitable temperature: during summer, when cold is needed, heat is deposited in the geothermal pit, whereas during winter heat is extracted. This ensures an overall balance on a yearly basis.

2.2.4. GHG emissions

Currently, several studies present the life-cycle emissions of geothermal plants. The IPCC cited a life cycle assessment median value of below 50 g CO_2e/kWh$_e$ for geothermal power plants, less than 80 g/kWh$_e$ for projected EGS, and between 14 and 202 g/kWh_{th} for district heating systems and GSHPs (Goldstein et al., 2011). More recently, the World Bank estimated a range of 2-20 g CO_2e/kWh_e for plant cycle emissions for geothermal projects, assuming a project lifetime of 30 years (Fridriksson et al., 2016). Another review (Marchand et al., 2015) showed that plant cycle emissions for EGS plants were in the range 22-80 g CO_2/kWh_e compared to 5-100 g CO_2/kWh_e for flash plants and were negligible for binary plants. Direct CO_2 emissions for direct use applications are negligible.

2.2.5. Exploration or financial risk

The exploration risk associated with geothermal projects concerns the risk of not producing an economically feasible flow or temperature of thermal water for production (Ganz, 2015). The current success rate in drilling for geothermal projects is about 50% in green fields and 75% in operated fields (Dumas, 2016). Longer lead times due to the resource identification and exploratory drilling phase, together with a large initial equity commitment usually required prior to debt financing, means that investors demand a higher return for their equity investment.

2.2.6. Social factors

A recent study on a number of European countries showed that the level of acceptance of geothermal energy was mixed. A lack of public knowledge or education on the technologies, and the potential uses of geothermal energy, as well as a lack of government support were cited as contributing factors (GEOCOM, 2013).

Various issues – environmental, financial, participative and perceptive – affect social acceptance of geothermal energy (Reith et al., 2013; Shortall et al., 2015). One of the major negative acceptance factors in Germany for instance is the concern of seismicity and damage through seismicity. Events, such as those seismic events at the trial EGS plant in Basel, can lead to the eventual abandonment of geothermal projects as well as to a lack of support for future projects.

The SET Plan group recommendations are to address environmental and social concerns that pose barriers to geothermal energy, public concerns and perceptions of geothermal installations. Technological solutions that reduce environmental impacts and enhance social benefits are important for public acceptance. Public acceptance of geothermal energy needs increased coordination of regulatory practices. Best practices for managing health, safety and environmental aspects of geothermal projects should be developed.

3. R&D overview

3.1. EU co-funded projects

Figure 2 shows the annual and cumulative EU contribution to co-funded projects focused on geothermal started between 2004 and 2019. This analysis includes the EU Framework Programmes FP6, FP7 and H2020, as well as the Intelligent Energy Europe (IEE)[4] and NER 300 projects[5] (JRC, 2015a). Figure 3 aggregates the EU contribution by funding scheme.

The total amount of funds granted by the EU to geothermal energy in the considered period is € 377 million, shared among 100 projects. It can be observed that more R&D funding has been allocated during H2020 (€ 216 million, 49 projects) than in any other previous funding programme, although with a marked variability across the years.

Figure 2. EU contribution to co-funded projects since 2004: yearly detail and cumulative data. Source: JRC analysis based on CORDIS[6]

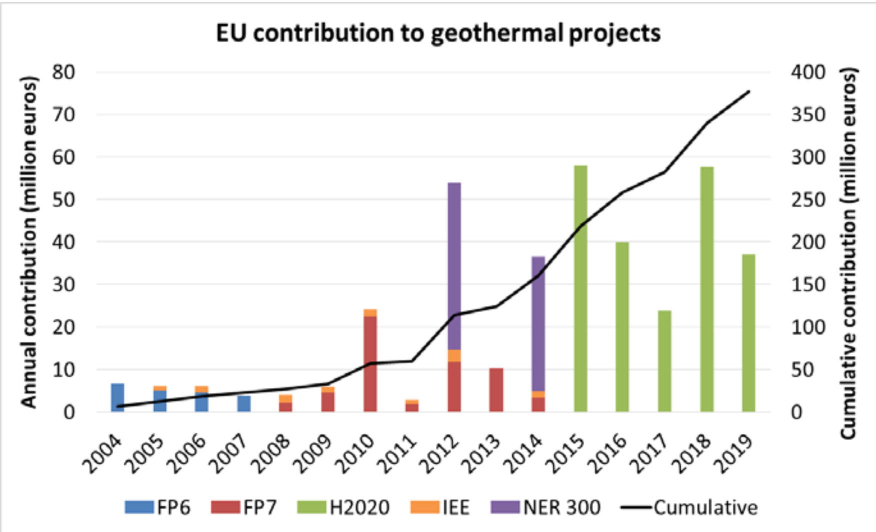
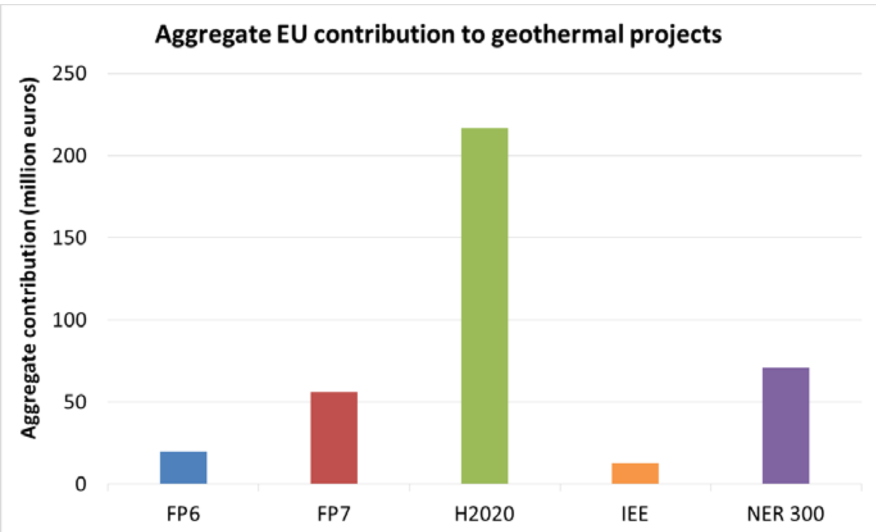


Figure 3. EU contribution to co-funded projects since 2004: aggregate. Source: JRC analysis based on CORDIS

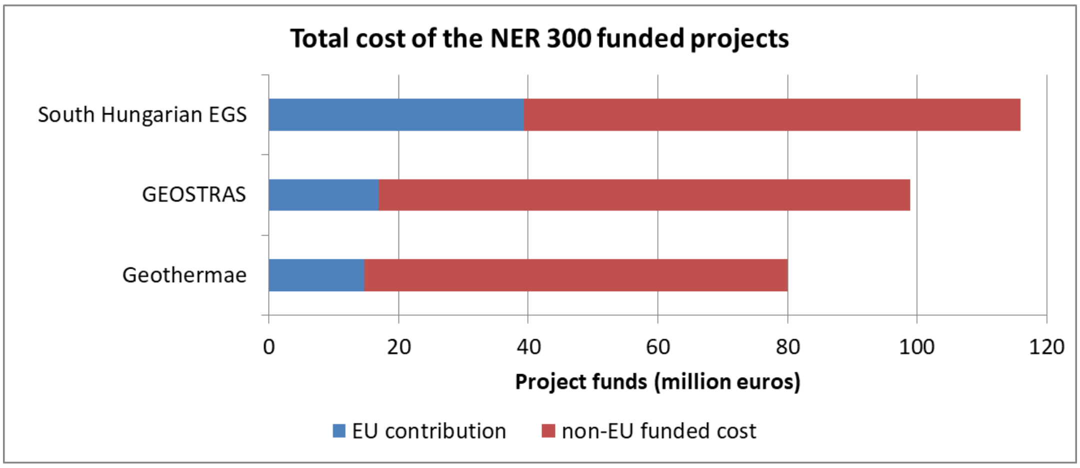


[4] https://ec.europa.eu/easme/en/section/energy/intelligent-energy-europe
[5] https://setis.ec.europa.eu/NER 300
[6] Community Research and Development Information Service of the European Commission, https://cordis.europa.eu

The NER 300 is a funding programme for innovative low-carbon energy demonstration projects. The programme has distributed € 2.1 billion to 38 renewable energy projects and one Carbon Capture and Storage (CCS) project. Three projects were dedicated to geothermal energy: GEOSTRAS (France), Geothermae (Croatia) and South Hungarian EGS Demonstration (Hungary). As the projects entail the construction of actual demonstration plants, they show considerable total costs (€ 99 million, € 80 million and € 116 million, respectively) and proportionally high EU contributions (amounting to about 17%, 18% and 34% of the total costs, respectively). These amounts are markedly higher than in the other funding schemes for R&D at lower TRL levels, as to be expected.

Figure 4 summarises the total cost for the three geothermal NER 300 projects, highlighting the EU contribution.

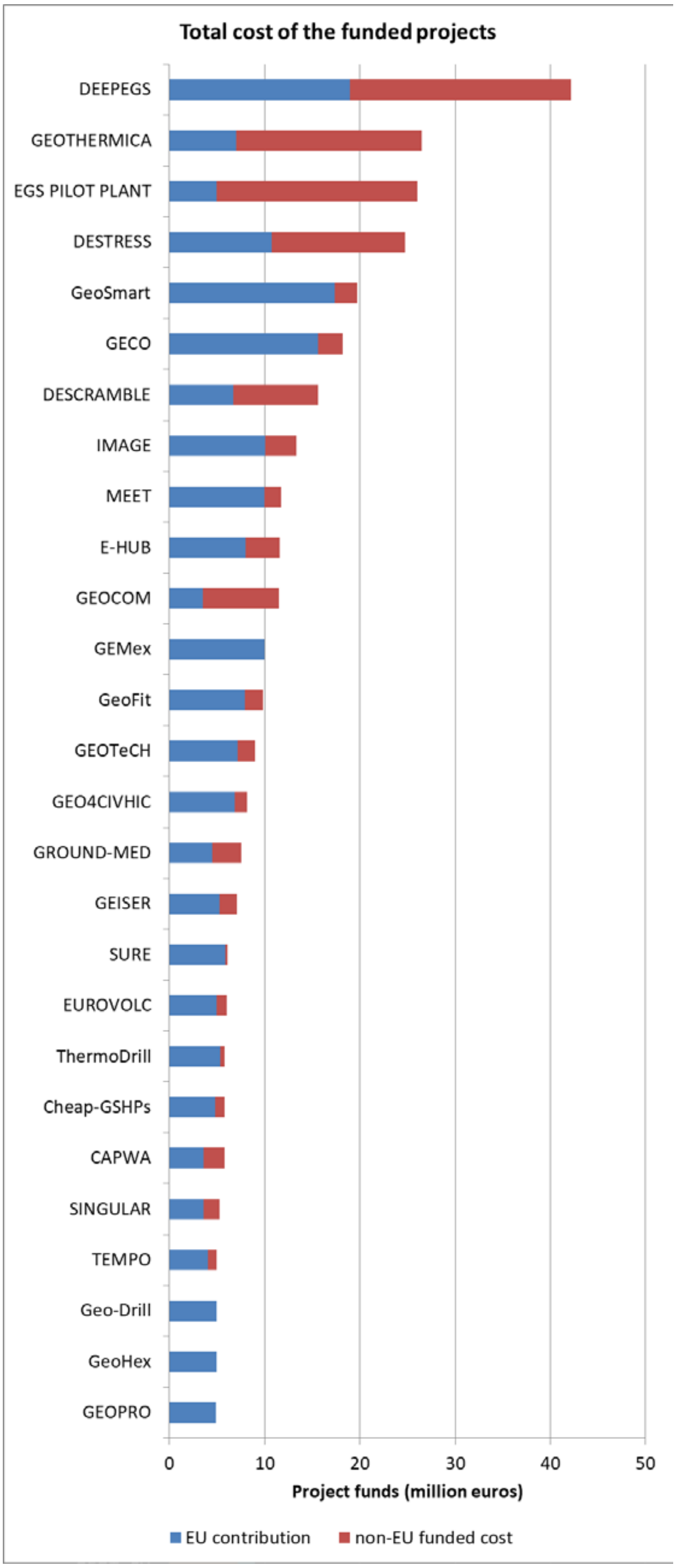
Figure 4. Total cost and EU contribution of geothermal-related NER 300 projects. Source: JRC analysis based on NER 300



Excluding NER 300, the project with the highest total costs is DEEPEGS (H2020, € 42.2 million), followed by EGS PILOT PLANT (FP6, € 26.0 million) and DESTRESS (H2020, € 24.7 million). GeoSmart (H2020, € 19.7 million) and GECO (H2020, € 18.2 million) have slightly lower total costs, but these two projects are characterised by the highest EU contribution after DEEPEGS, with € 17.4 million and € 15.6 million, respectively (the EU contribution to DEEPEGS amounts to € 19.0 million).

Figure 5 shows the total costs and the EU contribution for the thirty EU-funded largest projects (excluding the three NER 300 projects). In general, the larger projects under H2020 are related to drilling, EGS, network creation and district heating systems. Specifically, projects related to EGS have been the highest funded. GEOTHERMICA is a funding programme and is used to fund smaller projects.

Figure 5. Total cost of EU funded geothermal-related projects (thirty most funded). Source: JRC analysis based on CORDIS

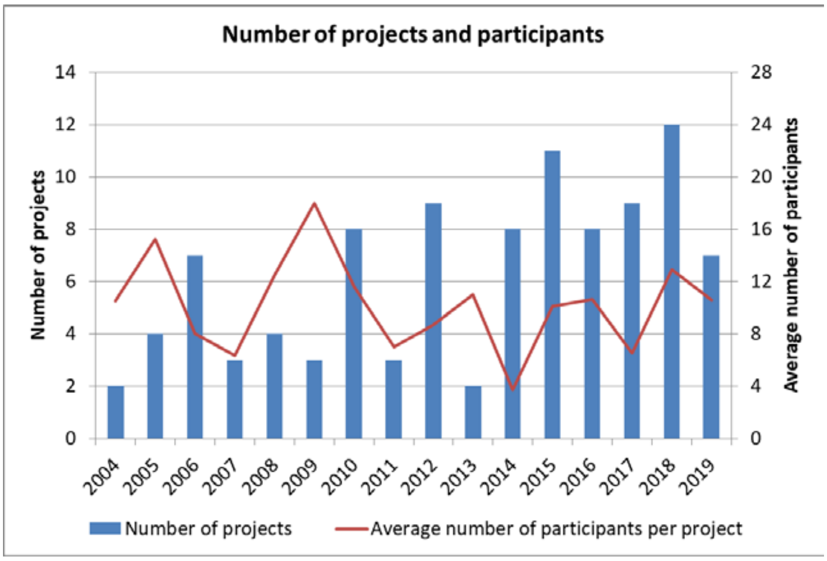


Finally, Figure 6 reports the number of projects funded per year and the average number of participants per project.

The average number of funded projects per year in the considered period is around six. However, it has already been noted that funding to geothermal increased with H2020: unsurprisingly, the average number of funded projects after 2014 is about nine.

The number of participants in each project can vary considerably: projects can be developed by single research centres (or even single researchers, in case of individual fellowships) as well as by consortia composed by tens of participants. The average number of participants per project is 10. The projects with the largest number of participants were GeoFit (26) and GEMex (24).

Figure 6. Number of EU funded geothermal-related projects per year and average number of participants. Source: JRC analysis based on CORDIS



3.2. Flagship areas of the SET Plan

The SET Plan working group for deep geothermal energy have identified a number of R&I activities as 'flagship':

- geothermal heat in urban areas;
- enhancement of conventional reservoirs and development of unconventional reservoirs;
- integration of geothermal heat and power into the energy system and grid flexibility;
- zero emissions power plants.

H2020 projects in SET Plan R&I categories are examined in Chapter 4. Relevant projects which do not fall under H2020 are instead described in the following.

3.2.1. Geothermal heat in urban areas

3.2.1.1. Geothermae

A Croatian company, with co-funding from the NER 300 framework, is developing an innovative geothermal plant north of Zagreb. The project will deliver electricity and district heating to the nearby city of Prelog. The heat will also be used for agricultural and recreational purposes. The project is drilling to depths of 1 800 to 2 300 metres using a binary-cycle geothermal power plant technology.[7]

[7] http://aatg.energy/pilot-project/

The geothermal power plant extracts geothermal brine containing methane gas from a hot sedimentary aquifer (HSA). The plant captures heat from both water and dissolved methane gas to power an ORC turbine (geothermal electricity output 3.1 MW_e. The CO_2 from the aquifer gas combustion is kept in the internal system, cleaned and injected into the same geothermal aquifer, contributing to stability, sustainability and enhanced productivity of the geo-thermal brine. This makes the technology nearly 100% emission-free. The technology is produced and developed in Europe and the intellectual property is owned by European firms. The expected installed capacity will reach 18.6 MW_{el} and 60-70 MW_{th} and the power plant will enter into operation in 2021.

3.2.1.2. GEOCOM

The Geothermal Communities (GEOCOM) FP7 project was launched in 2010 with a vision to increase the visibility of direct heat applications of geothermal energy throughout Europe.

The main objective of the € 11 million project was to implement pilot-scale demonstration of the geothermal energy utilisation on the three selected demo-sites: Morahalom (Hungary), Galanta (Slovakia) and Montieri (Italy). The demonstration activities were complemented by applied research tasks on (1) the technological background of the geothermal resources including system optimisation and system integration, and (2) on the socio-economic aspects of the current and future investments.

A district heating system was installed in Morahalom (population of about 5 800 inhabitants) in the south of Hungary on the border with Serbia. The doublet configuration of one abstraction well and one injection well (1 270 m and 900 m respectively) allows the sustainable resource management of the 63 °C thermal water produced on site from the Upper Pannonian sandstone reservoir with flow rates in the range of 25-30 m^3/hour in summer and 60 m^3/hour in winter. The annual thermal water production on this system is around 190 000 m^3. The full loop runs a total of 3 054 km between the two wells serving with heat and domestic hot water a total number of 12 municipal-owned public buildings mainly in the downtown area. By having the geothermal cascade system in place the proportion of renewable energy within the energy mix of public institutions has grown from 0% up to more than 80% - offsetting the use of 542 029 m^3 natural gas annually, while providing 18 700 GJ of heat per year. As a direct result annual heating-related emissions have also been reduced significantly (by 1 590 t of CO_2, 585 kg of NO_x and 1 113 kg of CO). The GEOCOM project aimed to improve the cascade system with a set of new elements to ensure total utilisation of geothermal energy and to demonstrate cutting edge energy efficiency/retrofitting measures that are currently lacking from geothermal projects in Eastern-Central Europe. A first evaluation revealed that energy demand for heating and domestic hot water was reduced by about 23% on average. CO_2 emissions were reduced by about 70% (Marino and Pagani, 2015).

The city of Galanta (population of about 16 500 inhabitants) is situated in the south-western part of the Slovak Republic. A district heating system of the two production wells – drilled in the 80s and tapping into the reservoir of Upper Pannonian sandstone (similar to the one at Morahalom) at 2 101 m and 2 102 m depths respectively - provide the necessary quantity (regulated 20-25 l/s each) of the 78 °C geothermal fluid for a whole district of the city, where it is utilised as a heating agent and also for domestic hot water purposes.

Prior to the project, there was a discharge of about 0.5 million m^3 of used, still warm and highly mineralised thermal water into the surface waters with unfavourable impacts on the environment. Local activities which could increase the overall efficiency of the existing setup by connecting additional estates (increasing the total heated floor area) to the geothermal loop and by improving the energy efficiency parameters of those buildings which are already benefiting from the service. Within the frame of the project the thermal capacity of the geothermal system was increased by 1 239 kW_{th}. This investment has triggered the erection of three new municipal housing units (101 new apartments) and a few more facilities within the range of the district heating system which are today connected to the loop.

The medieval village of Montieri (population of about 1 250 inhabitants) is located in the Larderello Geothermal District in Tuscany, Italy. The GEOCOM activities involved the whole community delivering three distinct actions: 1) building a brand new and highly efficient district heating system to utilise high enthalpy geothermal steam from the Montieri-4 well, 2) retrofitting a number of selected public buildings, and 3) deploying 8.5 kW_e solar PV as part of the system integration scheme.

3.2.2. Enhancement of conventional reservoirs and development of unconventional reservoirs

A review of all EGS projects in the EU (past and present) is available in (JRC, 2015a). Certain projects of interest to this category are detailed here below.

3.2.2.1. Soultz EGS Demonstration Site

The EGS project at Soultz-sous-Forêts in France involves partners from several EU Member States. Building on the EU-funded projects HOT DRY ROCK ENERGY, HRDD and EGS PILOT PLANT, this project involves a petrothermal EGS system, feeding 1.5 MW_e to the grid. The project involved drilling as deep as 5 000 m and involves two different reservoirs. The deeper reservoir (5 000 m) has lower permeability granite and the higher (3 000 m) fractured granite.

3.2.2.2. GEOSTRAS

GEOSTRAS is a NER 300 project, building on knowledge gained during the Soultz EGS demonstration project. This EGS project aims to produce electric and thermal energy from a high temperature geothermal resource (over 150 °C), by developing a deep underground exchanger in Alsace, a region with low natural permeability. The project will use a deep limestone geothermal system to capture geothermal fluids present in naturally fractured reservoirs. The geothermal plant will produce electricity (241 GWh_e), heat (810 GWh_{th}) and/or cold. This geothermal exchanger is highly innovative, since it increases the chance of success via two different ways of production: direct flow through long drain or conductive/convective geothermal heating on a forced flow inside the well. The expected entry into operation is in June 2021, even if delays with the drilling phase and the construction works are reported, and several permits are not ensured yet.

3.2.2.3. South Hungarian EGS Demonstration

The key objective of this NER 300 project is to provide an alternative to the use of fossil fuels for energy production in the targeted area, Békés county, near the town of Mezőkovácsháza, whilst strengthening the local community and social development by providing opportunities in the field of employment, knowledge transfer and potential for industry. The objective of the project is to develop a reservoir in a high compressional stress field in crystalline rocks and build an ORC geothermal power plant (8.9 MW_e of net electric power) utilising a total production flow rate of 280 kg/s with inlet temperature of 170 °C and 90 °C of outlet temperature. The EGS resource is developed by drilling approximately ten wells at 3 000 - 3 500 m depth intervals. For multi-zone stimulation AltaRock's TZIM Technology is used (Ádám and Cladouhos, 2016).

The project was to supposed to end in December 2018, even if no information has been provided by the consortium since 2017.

3.2.3. Integration of geothermal heat and power in the energy system and grid flexibility

3.2.3.1. Minewater 2.0

The region of Parkstad Limburg (the Netherlands), once reliant on coal mining, is now a hub for new energy research, where educational and research institutions, entrepreneurs and government collaborate to gain valuable experience through practical experiments in new technologies and production facilities such as the Heerlen Minewater project. The project aims to promote local employment, involve local educational and research institutions and to achieve a high social involvement and sustainability awareness of the inhabitants.

Now one of the world's largest geothermal district heating systems using mine water, the Minewater project began as a pilot system, completed in 2008, and was upgraded to a full-scale hybrid sustainable energy structure called Minewater 2.0 (Verhoeven et al., 2014). The project is a part of the Heerlen Sustainable Energy Structure Plan and includes energy exchange rather than energy supply, making use of cluster grids to exchange energy between buildings and the existing mine water grid to exchange energy between cluster grids. Energy is stored and regenerated in the mine waters, rather than depleting it through the addition of a poly-generation system using bio-CHP (Combined Heat and Power), solar energy and waste heat from data centres and industry. Cooling towers are used for peak cold demand. The hydraulic and thermal capacity of the mine was increased by improving the well pumps and pressure system and by reusing the existing mine water return pipe to supply and dispose of mine water. The supply of hot and cold mine water is fully automated and demand-driven by using a pressurised buffer system at extraction wells and special injection valves at injections wells. Mine water installations at the various buildings, clusters and wells are controlled via internet-connected process control units that communicate to a central monitoring system (Verhoeven et al., 2014). In 2015, the objective was to service 500 000 m^2 by the end of 2016 with an eventual total of 800 000 m^2 resulting in a CO_2 emission reduction of 65% on heating and cooling for these connections.

3.2.4. Zero emissions power plants

3.2.4.1. CO_2-DISSOLVED

The objective of the CO_2-DISSOLVED project is to assess the technical-economic feasibility of a novel CCS concept integrating aqueous dissolution of CO_2 and injection via a doublet system, an innovative post-combustion CO_2 capture technology and geothermal energy recovery. Compared to the use of a supercritical CO_2 phase, this approach offers substantial benefits in terms of storage safety, due to lower brine displacement and no pressure build-up risks, lower CO_2 escape risks and the potential for more rapid mineralisation.

This project adds the potential for energy and/or revenue generation through geothermal heat recovery. This adds value to injection operations, demonstrating that an actual synergy between CO_2 storage and geothermal activities may exist (BRGM).

3.2.4.2. CARBFIX and CARBFIX2

A partnership between Icelandic company Reykjavik Energy and Swiss company Climeworks has led to the realisation of the globally first so-called 'carbon negative' geothermal power plant.

CarbFix, an FP7-funded project, and its successor, Carbfix2 (H2020-funded) are collaborative research projects led by Reykjavik Energy, that aims at developing safe, simple and economical methods and technology for permanent CO_2 mineral storage in basalts. The CarbFix project started in 2007 by Reykjavík Energy, CNRS, the University of Iceland, and Columbia University.

CarbFix2 is described in Section 4.8.2.

3.3. Member state and international projects

Information about research projects funded through national funds from Member States or non-EU countries was difficult to obtain. Wherever possible, significant projects will be presented in the following, however, project reports were not available in most of the cases. In addition, few information is available in English. For some countries, the authors were able to at least present the current R&D priorities when no project information could be found. The Temporary Working Group of the SET Plan on deep geothermal systems will provide an overview of relevant national R&I projects that address the targets of the Implementation Plan.[8]

Research priorities in each country very much depend on the available re-sources (e.g. deep vs shallow). It seems common that R&I is now not only focused on technological innovations but also includes knowledge sharing and knowledge transfer activities as well as education/training programs.

3.3.1. France

France is supporting research and innovation projects in geothermal energy through the "programme des investissements d'avenir" (Ministère de la Transition écologique et solidaire, 2019). The main objectives are to improve the competitiveness of the geothermal sector and to increase the potential of exploitable geothermal resources.

For electricity generation, the research is focused on both EGS and conventional:

- knowledge of resources and exploitation;
- components and techniques: designing equipment and improving performance.

For heat production, the focus areas are:

[8] https://setis.ec.europa.eu/implementing-integrated-set-plan/no-1-renewables-ongoing-work

- improved performance of production technologies;
- life-extension of projects;
- development of new geothermal sensors, development of adapted geometries and innovative devices ;
- innovative reconversion of existing structures with deep heat exchangers;
- proposal of methods, components and tools to improve the environmental integration of proposed geothermal technologies;
- establishment of evaluation policies and control of possible pollution.

3.3.2. Germany

Geothermal Energy R&D projects in Germany encompass the whole value chain from planning and exploration to operation and energy utilisation. The main funding areas in 2018 were (IEA Geothermal, 2019):

- data collection (GeotIS);
- corrosion and scaling (for operating power plants);
- advanced drilling technologies (laser, electro-impulse, plasma);
- machinery (workover-rig, submersible pump, valves);
- district heating (Munich, urban areas).

The priority goal of all projects is to lower costs to make geothermal energy economically viable. Some major research projects that are currently ongoing in Germany are presented in the following.

3.3.2.1. GeotIS

The GeotIS project (Figure 7) has prepared geological, geophysical and hydraulic data relevant for planning of geothermal direct use facilities in Germany. GeotIS can be accessed online[9]. GeotIS has been funded through a number of subsequent calls. The current project, GeoFaces will further elaborate the structural 3D-models and expand to formation not covered before. In addition, it will also set up an interactive E-Learning portal.

3.3.2.2. Geothermal heat for Munich

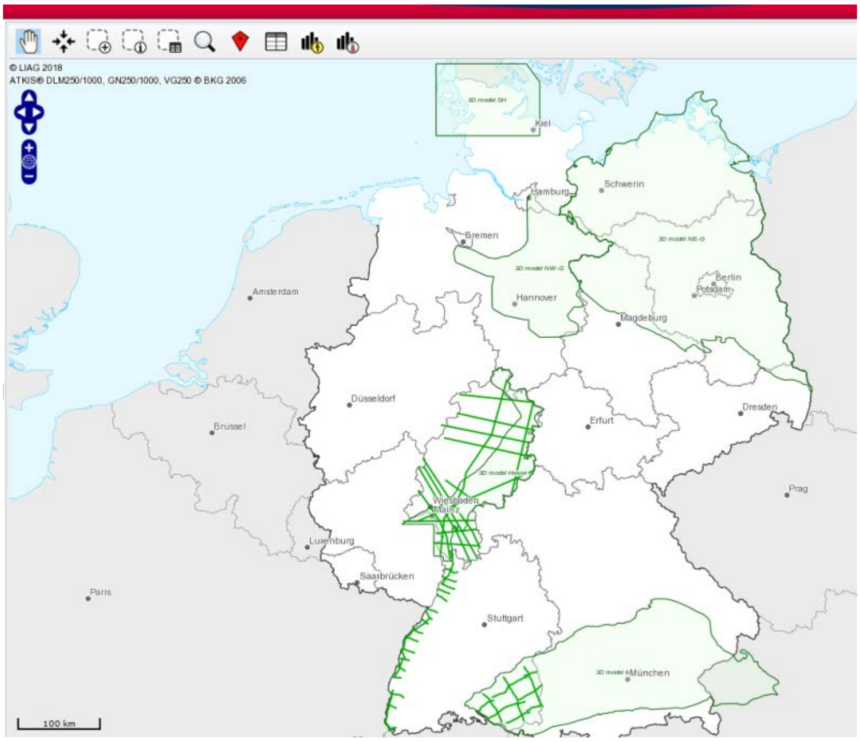
SWM (Stadtwerke München, Munich City Utilities) plans to supply the whole district heating network in Munch from renewable source. GRAME, a large joint project from SWM and the Leibniz-Institut für Angewandte Geophysik, aims at develop a sustainable and optimal reservoir exploitation in the Molasse basin of Bavaria. Current geothermal heat projects usually foresee two sites with one doublet at maximum per exploitation field. The projects wants to optimise exploitation through:

- development of techniques for improved seismic measurements;
- inclusion of S-waves to support interpretation of facies end S-wave speed;
- thermo-hydraulic modelling to depict long-term spatial interference of production and injection arrays;
- retrodeformation to predict transmissibility based on deformation analyses.

Another big part of the joint project is the development of a 50 MW_e power plant and exploration of 400 MW_{th} for district heating in Munich.

[9] https://www.geotis.de/geotisapp/geotis.php

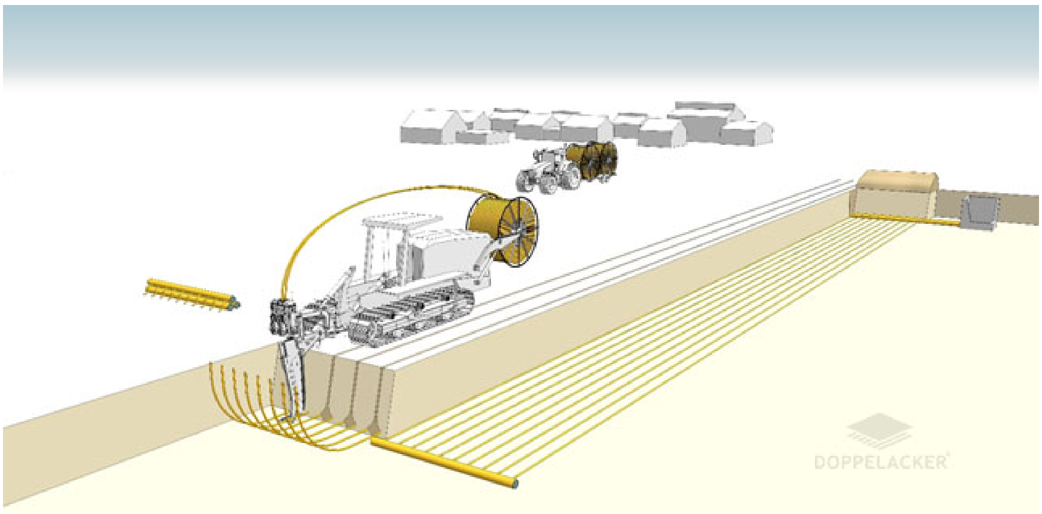
Figure 7. Map of Germany from the GeotIS project. Source: GeotIS



3.3.2.3. KollWeb 4.0

This project (Figure 8) develops a machine to install heat collectors in shallow depths. In addition, a guideline for the installation and operation of collectors and cooling networks will be developed (DOPPELACKER).

Figure 8. Ground collector installation machine. Source: DOPPELACKER



3.3.3. Iceland

The geothermal industry in Iceland is very well developed and private companies are leading in exploration and research.

3.3.3.1. Iceland Deep Drilling Project (IDDP)

The IDDP was founded in 2000 by a consortium of three Icelandic energy companies.[10] The IDDP wants to find out if it is economically feasible to extract energy and chemicals out of hydrothermal systems at supercritical conditions. The project has been awarded ISK 342 million (about € 2.6 million) of funding and also received some support through H2020.

3.3.3.2. Deep Roots of Geothermal Systems

The project (2013-2017) was a collaboration set up by GEORG, the Geothermal Research Group in Iceland.[11] It had strong links with the international research community. The project aimed at:

- studying geology and structure of extinct and exposed volcanic geothermal systems;
- advancing methods for the modelling of the physical processes occurring in the roots of volcanic geothermal systems;
- design of the components of deep geothermal wells, drilled into volcanic systems (to withstand high temperatures, pressures and flow-rates).

3.3.4. Japan

Geothermal research in Japan is funded through the Geothermal Resource Development Department (JOGMEC) and the New Energy and industrial technology Development Organization (NEDO). Priorities of JOGMEG include:

- geothermal reservoir evaluation and management;
- improvement of exploration accuracy;
- drilling technology.

In the past years, JOGMEC developed a method to perform airborne geophysical surveys by helicopter and several areas were mapped in 2017.[12] Subsequently JOGMEC began heat flow drilling to ascertain the underground temperature profile and geological structure to a depth of around 1 000 m. The location of the sites was decided on the basis of the results of the airborne survey. By the end of 2018 heat flow drilling had been completed at four sites (IEA Geothermal, 2019).

Another interesting project of JOGMEC developed and tested new polycrystalline diamond compact (PDC) drilling bits.

NEDO launched a geothermal research programme in 2017 covering:

- hybrid generation systems;
- scaling in brine;
- designing support tools;
- resource assessment.

In particular, NEDO started an R&D project called ‘Development of subduction-origin supercritical geothermal resources’ aiming at utilising super critical fluid at a temperature of 500 °C and at a depth of 5 km.

[10] https://iddp.is/
[11] http://georg.cluster.is/deep-roots-of-geothermal-systems/
[12] Most geothermal resources in Japan are located in national parks, hence the need for airborne methods (IEA Geothermal, 2019).

3.3.5. Mexico

At the end of 2018, 32 geothermal research projects carried out by the Mexican Center for Innovation in Geothermal Energy (CeMIE-Geo), a consortium of academic and industrial partners, were close to termination (IEA Geothermal, 2019). The following four strategic areas are addressed:

- evaluation of national geothermal resources;
- development and innovation of exploration techniques;
- technological developments for exploitation;
- direct use of geothermal heat.

The main focus is on technological developments (10 projects), followed by exploration techniques (9 projects).[13]

In addition two major activities that are currently carried out involve the organisation of training programs and short courses and the establishment of a network of advanced and specialised laboratories (e.g. geothermal fluids, isotope analysis, volcanology).

3.3.6. New Zealand

From July 2018, the available funds for geothermal research in New Zealand dropped from NZD 3.4 million per year (about € 1.9 million) to NZD 2.5 million per year (about € 1.4 million). Research priorities are:

- shallow resources and direct use;
- understanding structure and dynamics of the Taupo Volcanic Zone (TVZ);
- understanding source and models of the TVZ;
- reservoir chemistry.

A major geothermal research programme led by GNS (A New Zealand Crown research institute) addresses the uncertainties of underground resource assessment and mitigation of risks and will receive NZD 1.3 million per year (about € 0.7 million) until 2022.

The Geothermal Institute and GNS Science are also developing next-generation approaches to the numerical modelling of geothermal systems. Interestingly, the project is supported by NeSI (New Zealand eScience Infrastructure) to develop new computer modelling software and enable the coupling of models from different scientific areas (NeSI). The new software will be made available open-source to be used by the sector worldwide.

3.3.7. Switzerland

Several funding bodies such as the Swiss National Science Foundation or the Federal Office for Energy support geothermal research. The main federal institutes (e.g. ETH Zurich, EPF Lausanne) also carry out research in the area.

The current research priorities as fixed by the Swiss Federal Office of Energy (Bundesamt für Energie, BFE) are as follows (BFE, 2018):

- direct use and power production (resource characterisation, deep drilling techniques, induced seismicity);
- shallow geothermal (new utilisation concepts, competition with other use and nature protection, regulatory aspects, Life Cycle Assessment).

Aramis, the research database currently lists about twenty projects in geothermal with a total project cost of about CHF 7.9 million (about € 7.5 million).[14]

[13] http://cemiegeo.org/
[14] https://www.aramis.admin.ch/?Sprache=en-US.

3.3.7.1. Echtzeit Expertensystem zur Analyse und Kontrolle des Risikos von Indizierten Erdbeben

January 2016 - January 2019, CHF 0.8 million

This project aims at utilising micro seismicity in a controlled way to create a deep heat exchanger (Aramis, 2018a), with the ultimate objective of enabling the worldwide potential of deep geothermal. In addition, the product will help the involved partners to portray themselves as global market leaders in seismic risk assessment.

3.3.7.2. GEOSIM

August 2012 – March 2020, CHF 0.6 million

There is a need to estimate seismic risks due to induced earthquakes from geothermal projects. GEOSIM develops the scientific basis for algorithms and software tools that will allow determining the seismic risk in real-time during (Aramis, 2018b).

3.3.7.3. Geothermische Ressourcenanalyse im Bereich KGZ Davos

November 2009 – June 2018, CHF 0.5 million

Successful drilling of a 400 m borehole for the Davos congress centre was carried out in the past (Aramis, 2018c). The project determined the hydraulic and geothermal conditions of the reservoir in the Arosa dolomites through test logs. The results will be used to define the future dimensioning of use and to support the permitting decision.

3.3.7.4. Other projects

Other highlights from recent research include the completion of hydraulic stimulation and fracking tests at the Grimsel test site (SCCER-SoE, 2018), see Figure 9.

Figure 9. Underground Grimsel lab. Source: Grimsel

The DG-WOW (Deep Geothermal Well Optimisation Workflow) project has developed a workflow and a set of supporting software tools to define the optimal borehole direction to maximise the probability of intersection with potential feed zones and to maximise borehole stability.

3.3.8. United States

The main funding body for geothermal research in the US is the Geothermal Technologies Office (GTO) of DOE (Department of Energy). GTO funds geothermal R&D to help stimulate the growth of the geothermal industry and encourage quick adoption of geothermal technologies by the public and private sectors.

Research is funded in four areas (US DoE, 2018):

- EGS;
- hydrothermal resources;
- low temperature and coproduced resources;
- systems analysis.

In June 2018, after three years of planning, site characterisation, and competition, DOE announced the selection of the University of Utah's proposed site out of Milford, Utah, as the location of the Frontier Observatory for Research in Geothermal Energy (FORGE). This is the first dedicated field site of its kind for testing targeted EGS R&D. The intent is to use this collaborative site for transformative science that will create a commercial pathway for large-scale, economically viable EGS (IEA Geothermal, 2019).

In 2018 GTO also continued with a second year of funding for the multi-lab, multi-year EGS Collab effort. The EGS Collab is envisioned as an intermediate-scale field site where the geothermal reservoir modelling and research community is validating against controlled, small-scale, in-situ experiments focused on rock fracture behaviour and permeability enhancement (IEA Geothermal, 2019).

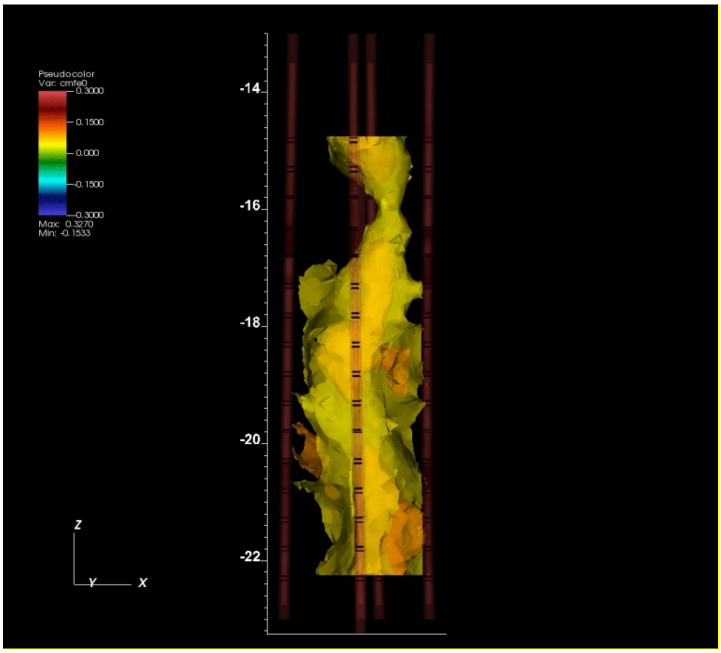
The website of the GTO provides ample information about the ongoing research.[15] Two relevant projects are described below.

3.3.8.1. Subsurface Science, Technology, Engineering, and R&D Crosscut (SubTER)

With E4D-RT (Figure 10), a fracture network was imaged in real-time using supercomputers.[16] The understanding gained in the project will help to improve current models for the prediction of fracture networks (US DoE, 2017).

The tool provides faster, more accurate interpretations of data from simulation models and improves the cost competitiveness of EGS development.

Figure 10. Example of image from E4D-RT. Source: E4D-RT



[15] https://www.energy.gov/eere/geothermal/geothermal-energy-us-department-energy

[16] E4D is a 3D modelling and inversion code designed for subsurface imaging and monitoring using static and time-lapse 3D electrical resistivity (ERdata)

3.3.8.2. High Temperature Downhole Motor

Sandia National Laboratory developed a downhole motor for geothermal drilling (Figure 11). The motor can produce wells with multilateral completions which improves geothermal resource recovery and well construction economics. A prototype will be completed (Sandia, 2017).

Figure 11. High Temperature Downhole Motor. Source: Sandia (2015)

3.4. European and International Programmes and Networks

3.4.1. European Technology and Innovation Platform on Deep Geothermal

The European Technology and Innovation Platforms (ETIPs) have been recognised by the EC as a tool to strengthen cooperation with stakeholders under the SET Plan, as part of the H2020 programme. The Geothermal ETIP is an open stakeholder group, including representatives from industry, academia, research centres and sectorial associations, covering the entire deep geothermal energy exploration, production and utilisation value chain. The geothermal sector created the European Technology and Innovation Platform on Deep Geothermal (ETIP-DG) in March 2016, and the European Commission officially recognised it as an ETIP in July 2016. A Geothermal Forum of stakeholders, including large companies, SMEs, academia and research institutions was convened in March 2016. The overarching objective of the new ETIP-DG is to enable deep geothermal technology, in particular EGS, to proliferate and move from the current European R&D and pilot-sites to other European countries and different geological situations. The primary objective is overall cost reduction, including social, environmental and technological costs.

3.4.2. GEOTHERMICA

GEOTHERMICA is an ERA-NET Cofund that combines the financial resources and know-how of 16 geothermal energy research and innovation programme owners and managers from 13 countries, to launch joint actions that demonstrate and validate novel concepts of geothermal energy utilisation within the energy system and that identify paths to commerciality. It runs from January 2017 to December 2021. The joint calls and coordination activities will help strengthen Europe's geothermal energy sector by building a tightly interconnected and well-coordinated network of European funding agents. For a first joint call, some € 30 million were made available for eight demonstration projects. These have a strong industry participation with a targeted 50% contribution towards work programs and budgets.

3.4.3. CREEP - Complex RhEologies in Earth dynamics and industrial Processes

The CREEP Innovative Training Network is a training and career development platform for early stage researchers in geodynamics, mineral physics, seismology, fluid mechanics, and materials sciences. CREEP aims to structure the collaboration in research and doctoral training between 10 leading academic centres in Earth sciences in Europe: the CNRS (FR), represented by Geosciences Montpellier and the FAST Orsay, the universities of Bristol, Durham and UCL (UK), Munster and Mainz (DE), Roma Tre (IT) and Utrecht (NL), and several partner organisations. The research projects cover a large spectrum of applications from the study of the deformation of the Earth surface (earthquakes) and deep layers to geothermal and petroleum exploration and industrial processes.

3.4.4. Global Geothermal Development Plan (GGDP)

The Global Geothermal Development Plan (GGDP) is an ambitious initiative by the World Bank's Energy Sector Management Assistance Program (ESMAP) and other multilateral and bilateral development partners to transform the energy sector of developing countries by scaling up the use of geothermal power. The GGDP differs from previous efforts in that it focuses on the primary obstacle to geothermal expansion: the cost and risk of exploratory drilling.

3.4.5. Global Geothermal Alliance

The Global Geothermal Alliance (GGA) was set up during COP21 in 2015 and is led by IRENA. The alliance aspires to achieve a 500% increase in global installed capacity for geothermal power generation and a 200% increase in geothermal heating by 2030. It brings together public, private, intergovernmental and non-governmental actors. Its key objectives are to:

- identify and promote models for sharing and reducing risks associated with the geothermal business to be able to attract timely and efficient private investments and to integrate geothermal facilities into energy markets;
- help create enabling regulatory and institutional conditions for timely and efficient private investments and efficient operation of geothermal resources and associated network infrastructure;
- help streamline ongoing outreach and awareness-raising efforts in order to give geothermal energy greater visibility in the energy and climate debates at global, regional and national level.

3.4.6. IEA-Geothermal TCP

The IEA runs a Geothermal Technology Collaboration Program (IEA Geothermal) which provides an important framework for wide-ranging international cooperation in geothermal R&D. Efforts concentrate on encouraging, supporting and advancing the sustainable development and use of geothermal energy worldwide both for power generation and direct-heat applications.

3.4.7. The International Partnership for Geothermal Technology (IPGT)

Since 2008, the IPGT has signified the commitment of the world's geothermal energy leaders to advance the energy through the continued development of new technologies. The IPGT provides a forum for government and industry leaders from the five member countries, (Australia, Iceland, New Zealand, Switzerland and the United States) to coordinate their efforts, and collaborate on projects. Partners share information on results and best practices to avoid blind alleys, limit unnecessary duplication, and efficiently accelerate the development of geothermal technologies. The IPGT has set up six working groups on Lower Cost Drilling, zonal isolation/packing, high temperature tools, stimulation procedures, modelling, exploration technologies and induced seismicity.

3.4.8. GEO-ENERGY EUROPE

Funded under the "Clusters Go International" call, which is part of the European Competitiveness of Enterprises and Small and Medium-sized Enterprises (COSME) programme, the project consisted in creating a transnational cluster specifically aimed at increasing the performance and competitiveness of European SMEs in all industries concerned by the use of subsurface for energy, or "geo-energy", on transnational (EU) and world markets.

The GEO-ENERGY EUROPE project officially started in January 2018 and involves eight partners from seven EU and COSME participating countries: POLE AVENIA (coordinator) and GEODEEP in France, EGEC in Belgium, GEOPLAT in Spain, GEOENERGY CELLE in Germany, CAPES in Hungary, JESDER in Turkey and GEOSCIENCE IRELAND.

As reflected by the consortium composition, made of four clusters in applied geoscience or geo-energy at large and four business network organisations specialised in geothermal energy, the funded two-year program primarily targets its networking activities, cross-sectorial skill and technology transfers, market studies and strategic planning towards the promotion and industrial take-off of the emerging deep geothermal energy industry for district and industrial heating and power generation, in line with the European and most national energy transition goals.

3.5. Patenting trends

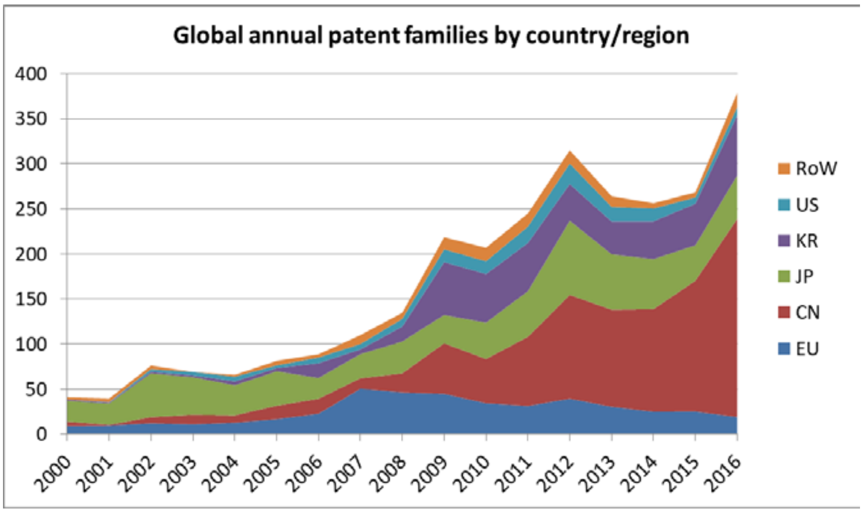
The analysis of patent submissions is a fundamental means to shed light on the R&D and innovation trends for one specific technology. The results reported in this section derive from a JRC analysis based on data from the European Patent Office (EPO). The methodology is described in JRC, 2017a, Pasimeni, 2019, and Pasimeni et al., 2019.

Figure 12 shows the evolution of the number of patent families from 2000 to 2016, highlighting the most important global regions. Patent families (or inventions) measure the inventive activity. If patent families regard more than one country or refer to more than one technology, the relevant fraction is accounted for.

The graph shows a clear growing trend over the past years, as the number of patents families passed from less than 50 in 2000 to more than 350 in 2016.

It is also interesting to note that different regions alternated as global leader in such a short period of time. Japan was the clear leader in early 2000s, being replaced in 2007 and for a couple of years by the EU. The second decade of the century has been characterised by a spectacular growth in the patent families produced in China and, to a lesser extent in the Republic of Korea, while the number of inventions in the EU has progressively diminished. Marginal contributions came from the United States and the other countries of the world.

Figure 12. Global number of annual patent families for geothermal energy in 2000-2016 by country/region.[17] Source: JRC analysis



[17] CN = China, JP = Japan, KR = Republic of Korea, US = United States, RoW = Rest of the World.

Figure 13 shows the cumulative amount of patents over the entire period, highlighting the dominance of China, which features almost 1000 inventions, followed by Japan. The overall number is 2 859.

Figure 13. Global cumulative number of patent families for geothermal energy in 2000-2016 by country/region. Source: JRC analysis

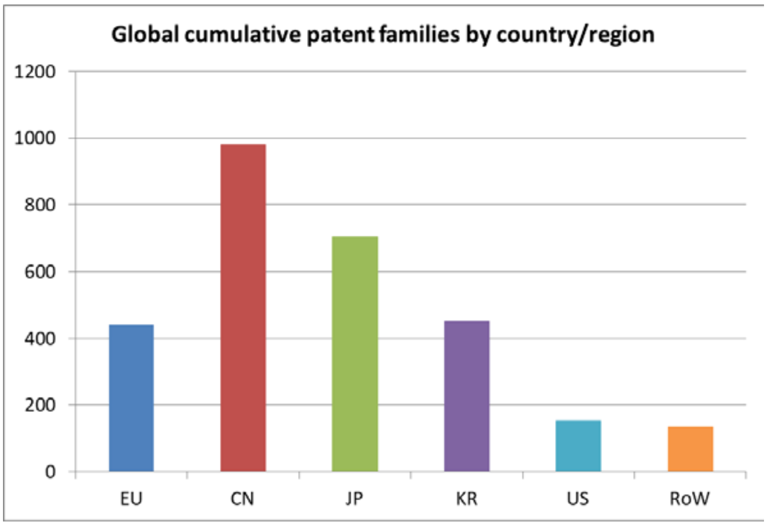
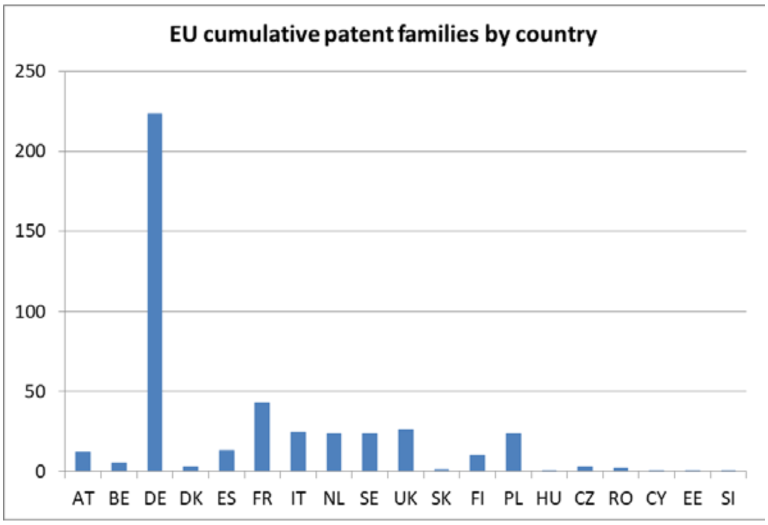


Figure 14 provides a detailed disaggregation of the cumulative number of annual patent families within the European Union. Of the 439 total inventions, half (224) came from Germany, which is by far the leader in the region, followed by France (43) and by a group of countries with some 25 patent families each (Italy, Netherlands, Sweden, United Kingdom, and Poland).

The countries with the highest number of cumulative applications in the Rest of the World were Switzerland (44), Russia (26), Taiwan (19), and Canada (17).

Figure 14. EU cumulative number of patent families for geothermal energy in 2000-2016 by country.[18] Source: JRC analysis



[18] AT = Austria, BE = Belgium, DE = Germany, DK = Denmark, ES = Spain, FR = France, IT = Italy, NL = Netherlands, SE = Sweden, UK = United Kingdom, SK = Slovakia, FI = Finland, PL = Poland, HU = Hungary, CZ = Czech Republic, RO = Romania, CY = Cyprus, EE = Estonia, SI = Slovenia

Similar regional trends are found for the granted patent families, i.e. the inventions which are protected under law, see Figure 15 (annual progress) and Figure 16 (cumulative). Globally, such inventions were 1 733 in the period 2000-2016, i.e. 61% of the total. Some differences can be found across countries, however: granted inventions amount to 75% and 74% of the total number of inventions in China and the Republic of Korea, respectively, while this share is equal to 50%, 44%, and 41% in the EU, Japan, and the United States, respectively, and 54% in RoW.

Figure 15. Global number of annual granted patent families for geothermal energy in 2000-2016 by country/region. *Source:* JRC analysis

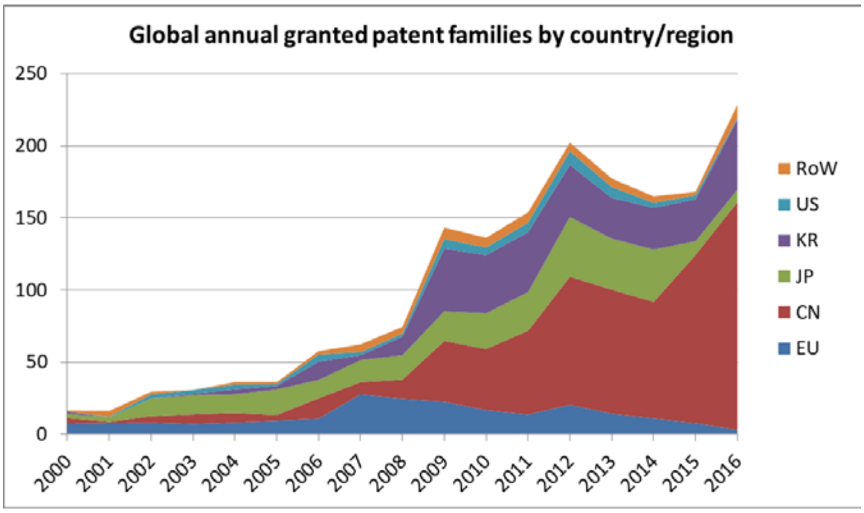
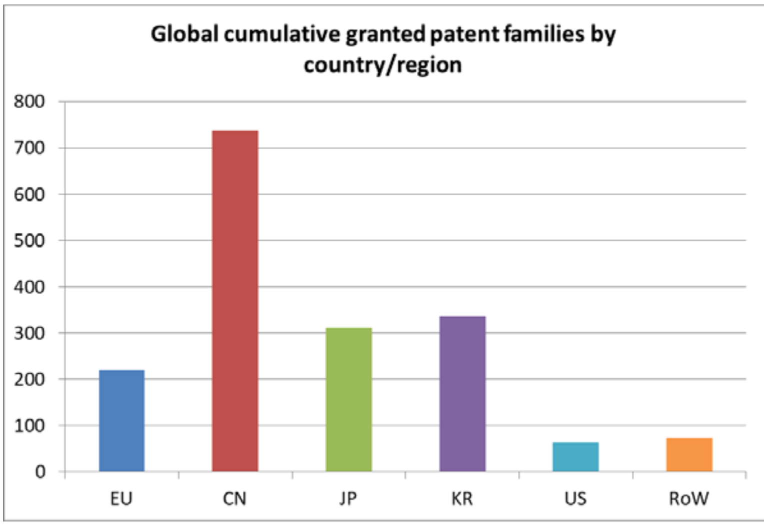
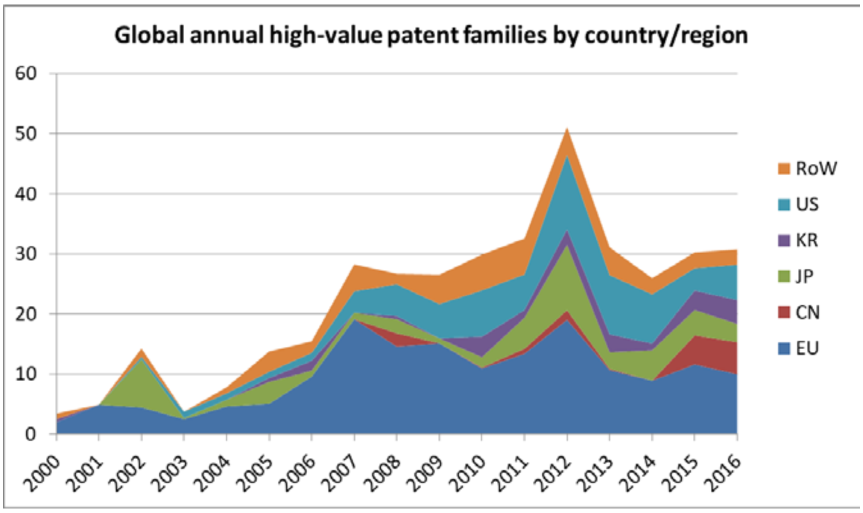


Figure 16. Global cumulative number of annual high-value patent families for geothermal energy in 2000-2016 by country/region. *Source:* JRC analysis



Another meaningful sub-group of inventions is represented by the high-value inventions, which indicate the patent applications filed in more than one patent office. At global level, such inventions amount to 376 over the considered period, i.e. about 13% of the total. As shown in Figure 17, here the regional pattern is quite different from the overall inventions, as the European Union (166 cumulative high-value inventions) and the United States (73) show the highest shares. Within the EU, Germany is again the leader with about half of the total (66).

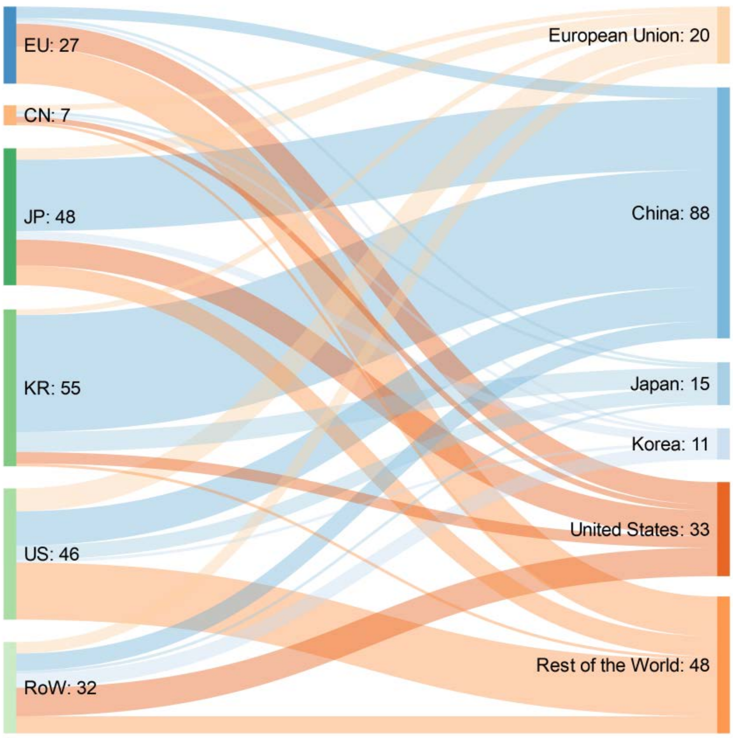
Figure 17. Global cumulative number of granted patent families for geothermal energy in 2000-2016 by country/region. Source: JRC analysis



An interesting exercise is to track the flow of inventions, assessing where (i.e. in which national patent office) inventions are filed, see Figure 18. This indicates where technology developers look for protection for their inventions and thus where they are likely to implement commercialisation plans.

In the considered period, China was marginally interested in exporting its R&D innovations; conversely, the other countries intensively looked for protection in China, especially the Republic of Korea and Japan. This does not fully apply to the EU, as European developers applied for few patents in China as well as in the other two Asian countries, mostly focusing on the United States and the Rest of the World.

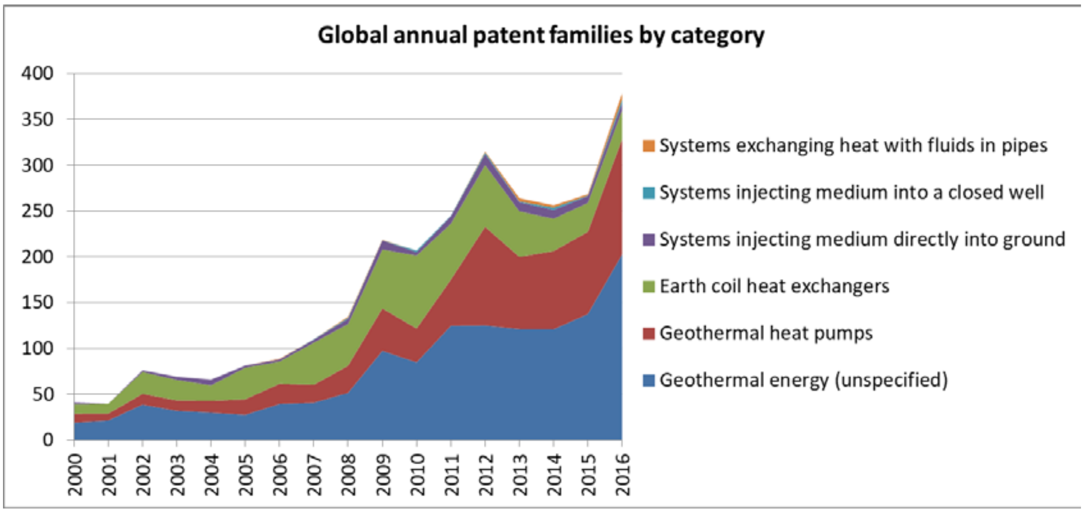
Figure 18. Origin and destination of the geothermal energy inventions protected outside the domestic borders in 2000-2016. Source: JRC analysis.



Finally, Figure 19 shows the global number of inventions in the period 2000-2016, classified not on a geographical basis but sorting the different categories according to the Cooperative Patent Classification

(CPC). Almost half of the cumulative number of patent families over the period (46%) fall within the generic geothermal energy category. This category has experienced the most marked growth over the past decade. The specific category featuring the highest number of inventions is Geothermal heat pumps, which has also been characterised by a tremendous growth over the past decade, followed by Earth coil heat exchangers, which has shown a decreasing interest in recent years, instead. These two categories account for 27% and 23% of the cumulative amount of patent families in the considered period, respectively. The remaining three categories (Systems injecting medium directly into ground, Systems injecting medium into a closed well, and Systems exchanging heat with fluids in pipes) have a marginal role in the invention portfolio, sharing the remaining 4% of the cumulative amount of patent families.

Figure 19. Global number of annual patent families for geothermal energy in 2000-2016 by category. Source: JRC analysis.



4. Impact assessment of H2020 projects

This chapter illustrates the contribution of selected H2020 EU-funded projects towards the advancement of geothermal technologies. Information was gathered from CORDIS, Compass and project websites where available. A complete and categorised list of the EU-funded projects from 2004 (considering all the funding schemes described in Chapter 3) is shown in Annex A.

In Sections from 4.1 to 4.9, projects are categorised according to the R&I Activities identified by the Implementation Plan of the SET Plan on deep geothermal systems (SET Plan TWG, 2018). Section 4.10 describes the projects related to shallow and low-temperature geothermal applications. The projects referring to more than one category are described under the most relevant one.

The abovementioned Implementation Plan identified six targets of the Declaration of Intent (DOI) as well as two Non-Technical Barriers (NTB) (SET Plan TWG, 2018).

The DOI targets are the following:

1. increase reservoir performance (including underground heat storage) resulting in power demand of reservoir pumps to below 10% of gross energy generation and in sustainable yield predicted for at least 30 years by 2030;
2. improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050;
3. reduce production costs of geothermal energy (including from unconventional resources, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) below 10 €ct/kWh$_e$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025;
4. reduce the exploration costs by 25% in 2025, and by 50% in 2050 compared to 2015;
5. reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015;
6. demonstrate the technical and economic feasibility of responding to commands from a grid operator, at any time, to increase or decrease output ramp up and down from 60% - 110% of nominal power.

The two NTBs are the following:

A. increasing awareness of local communities and involvement of stakeholders in sustainable geothermal solutions;

B. risk mitigation (financial/project).

In the following sections, DOIs and NTBs define the targets for the different SET Plan R&I Activities.

4.1. Geothermal heat in urban areas

Current TRL: 7

Areas of interest:

- new urban geothermal heating concepts
- innovative cascading
- matching supply with demand
- heat and cold exchange
- UTES for industry and agriculture
- hybrid systems
- synergies with other industries

SET Plan targets:

DOI 3

NTB A, B

Related H2020 projects
GEO-PAC-RET; GEoTECh; CheapGSHPs; Large enHANCEMENT; **GeoFit; MPC-GT**; **GEOCOND**; **TEMPO**; **GeoCollector**

Since 2000, a number of EU-funded projects have related to district heating in urban areas, however the vast majority of projects in this category before H2020 were concerned with heat pump design or policy support. In terms of maturity, heat pumps are considered to have a high TRL, hence projects of interest in this category relate to urban heating systems in a broader sense. Notable H2020 projects that contribute towards the demonstration and proliferation of geothermal district heating include GeoFit, GEOCOND, MPC-GT, TEMPO and GeoCollector. However, only GeoFit fully refers to this category. All the other projects will be described in other sections: GEOCOND in Section 4.4, while MPC-GT, TEMPO and GeoCollector in Section 4.10.

4.1.1. GeoFit - Deployment of novel GEOthermal systems, technologies and tools for energy efficient building retroFITting

Description

Duration: May 2018 – April 2022

EU contribution: € 7 896 940

GeoFit[19] is an integrated industrially driven action aimed at deployment of cost effective EGS on energy efficient building retrofitting. This entails the technical development of innovative EGS and its components, namely, non-standard heat exchanger configurations, a novel hybrid heat pump and electrically driven compression heat pump systems and suite of heating and cooling components to be integrated with the novel GSHP concepts, all specially designed to be applied in energy efficient retrofitting projects.

Innovation(s)

To make viable the novel EGS in energy efficient building retrofitting, a suite of tools and technologies is developed, including: low invasive risk assessment technologies, site-inspection and worksite building monitoring techniques, control systems for cost-effective and optimised EGS in operation phase and novel dedicated tools for management of geothermal based retrofitting works. Furthermore, the project is committed with the application of novel drilling techniques as the improved low invasive vertical drilling and trenchless technologies.

GeoFit brings these technical developments within a new management framework based on integrated design and delivery solutions for the geothermal based retrofitting process.

Impact/expected impact

By using the five demonstration sites as open case studies in four countries and climates, featuring different representative technical scenarios/business models, GeoFit will leverage its key exploitable results, adapted business models and market oriented dissemination for maximising impact and wide adoption of these novel geothermal technologies and approaches.

4.2. Materials, methods and equipment to improve operational availability

Current TRL: Equipment 5; Materials & methods 4

Areas of interest:

- improved equipment reliability and increased plant utilisation factor
- materials / methods / equipment to minimise operational issues related to high temperatures, scaling, corrosion and gas content

SET Plan targets:
DOI 3, 2, 1

[19] https://cordis.europa.eu/project/id/792210

NTB A
Related H2020 projects
GeoWell; **CHPM2030**; GEOTHERMICA; GeoElectricMixing, ITHERLAB

Very few projects were co-funded in this research area before H2020. The HITI project (FP6, € 4.7 million) was the most significant and involved developing instruments for high temperature (super-critical) environments. The FP7 project MINSC (€ 3.8 million) created a training network around solving the problem of mineral scale formation.

Under H2020, the GeoWell project, although focused also on well design and completion, deals with the materials needed to enhance high temperature well performance and lifetime. The CHPM2030 project is concerned primarily with combining metal extraction with EGS, but could also result in improved performance of geothermal systems.

4.2.1. GeoWell

Description

Duration: February 2016 to January 2019

EU contribution: € 4 704 914

The GeoWell project[20] aimed to address important bottlenecks in geothermal development like high investment and maintenance costs by developing reliable, economical and environmentally friendly technologies for design, completion and monitoring of high-temperature geothermal wells.

This has benefits on the lifetime of high-temperature geothermal wells. The technologies include cement and sealing technologies, material selection and coupling of casings. Methods of temperature and strain measurements in wells, using fibre optic technologies to monitor well integrity, were developed as well as methods for risk assessment with respect to the design and operation of high-temperature geothermal wells. The research focused on both traditional production wells and deeper wells where the pressure is as high as 150 bar and temperatures exceed 400 °C.

Innovation(s)

The following innovations were envisioned:

- reduce down time by optimised well design involving corrosion resistant materials;
- optimise cementing procedures that require less time for curing;
- compensate thermal strains between the casing and the well;
- provide a comprehensive database with selective ranking of materials to prevent corrosion, based on environmental conditions for liners, casings and wellhead equipment, up to very high temperatures;
- develop methods to increase the lifetime of the well by analysing the wellbore integrity using novel distributed fibre optic monitoring techniques;
- develop advanced risk analysis tools and risk management procedures for geothermal wells.

The developed technologies were tested under in-situ conditions in laboratories, and also in existing geothermal environment, moving the TRL from 3-4 to 4-5.

Impact/expected impact

The most significant exploitable results delivered by the project are the development of the flexible coupling technology for lowering thermal strain and risk of buckling of geothermal wells, which is one of the most promising project achievements in terms of industrial exploitation potential and for improving cost-competitiveness and increasing reliability of geothermal wells. An Enhanced Distributed Acoustic Sensing technology for evaluating the degradation of the cement in deep wells was developed to laboratory scale. This technology, also combined in the project with fibre optic cables to perform temperature and strain measurements during casing cementation, has a high potential in future testing and monitoring of

[20] https://cordis.europa.eu/project/id/654497

geothermal well integrity. Optimised High Temperature cements were developed as well as the first steps towards developing better risk assessment tools.

The costs of deep drilling wells targeting depths about 4-5 km, or even deeper, are very high. These costs are strongly related to casing materials, well completion and well integrity. The project will contribute to diminishing the occurrence of operational problems and reducing maintenance cost of geothermal wells.

Overall, the project fully achieved its objectives with significant immediate or potential impact.

4.2.2. CHPM2030

Description

Duration: January 2016 – June 2019

EU contribution: € 4 235 568

The project[21] aimed to convert ultra-deep metallic mineral formations into an "orebody-EGS" that served as a basis for the development of a new type of facility for combined heat, power, and metal extraction (CHPM). The merging of the two, so far unconnected technology areas (renewable energy and minerals extraction) would lead to an increase in the number of potentially viable geothermal resources, with the help of the co-production of valuable metals, since this can improve the economic performance of the geothermal sector and hence attract increased private investments.

The project's specific objectives were:

- deliver proof of concept for the technological and economic feasibility of mobilisation of metals from ultra-deep mineral deposits using a combination of different geo-engineering techniques enhancing interconnected fractures at depths;
- develop innovative technologies for leaching strategic metals from the geological formation and corresponding electrochemical methods for metal recovery within equipment at the surface;
- develop solutions for the co-generation of electricity using salt-gradient power reverse electrodialysis;
- conceptual design of a new type of future facility that is operated from the very beginning as a CHP and mineral extraction system;
- develop an integrated feasibility assessment framework for the environmental and socio-economic impacts of the proposed new technology;
- combine metallogenic models with geothermal datasets to develop a database of suitable sites in selected areas in Europe where the CHPM technique could be feasible;
- create a roadmap in support of the pilot implementation of such system by 2030, and of the full-scale commercial operation by 2050.

Innovation(s)

The metal-bearing geological formation was manipulated so as to allow the co-production of energy and metals, which can be optimised according to the market demands at any given moment in the future. The project investigated whether the composition and structure of orebodies have certain advantages that could be used to our advantage when developing an EGS; whether metals can be leached from the orebodies in high concentrations over a prolonged period of time and substantially influence the economics of EGS; whether the continuous leaching of metals will increase system's performance over time in a controlled way and without having to use high-pressure reservoir stimulation, minimising potential detrimental impacts of both heat and metal extraction.

The project used the current state of the art in geothermal energy development (most recent geo-scientific data and knowledge on the structures of metallic mineral deposits, and extensive laboratory experiments and multiphysics simulations). The proposed technology solutions were brought from TRL 3-4 to TRL 4-5.

[21] https://cordis.europa.eu/project/id/654100

Impact/expected impact

The results of laboratory investigations on metal mobilisation showed evidence for enhanced metal leaching. Carbon-based nano-materials were designed and prepared, which showed enhanced abilities to adsorb dissolved metal ions.

High-pressure, high-temperature metal recovery experiments proved that metals can be successfully electrodeposited at pressures up to 5 MPa and temperatures up to 150 °C. At lower temperatures (20-60 °C), gas-diffusion electroprecipitation and electrocrystallisation experiments resulted in different metallic products at different temperatures, with a broader variety of compounds at higher temperatures. Experiments investigating salinity-gradient power generation by reverse electrodialysis (SGP-RE) using pre-treated geothermal brines, proved that the presence of multivalent ions in geothermal fluids does not eliminate the potential for SGP-RE. Furthermore, the extraction of electrical energy was enhanced by increasing brine temperature.

Overall, the project fully achieved its objectives and milestones. The overall economic feasibility of geothermal energy projects could be dramatically improved if facilities in the future were designed from the very beginning as CHPM facilities. Furthermore, the technology has also the potential to satisfy the needs for critical minerals (including metals used in the energy sector, such as cadmium, nickel, molybdenum, vanadium and niobium).

More specifically, the potential impacts of the CHPM2030 project are as follows:

- the creation of the scientific basis for the future development of the CHPM technology will serve as background for a new generation of geothermal systems in Europe;
- the merging of renewable energy and mineral extraction will change the landscape for geothermal development in Europe and beyond, and will also have a substantial contribution in Europe's need for critical metals;
- the results will support the objectives of the EU Raw Materials Initiative (in particular to the pillars "Foster sustainable supply from European sources" and "Boost resource efficiency and recycling") and its Strategic Implementation Plan;
- the project results will help decision makers in Europe to frame future energy strategies and technologies and to integrate them in roadmapping. When combined with economic feasibility modelling, this will help in the identification of critical pathways;
- the number of economically-viable geothermal resources will be increased, not only in Europe, but globally, with the leverage of the co-production of valuable metals;
- the economic performance of the geothermal sector in Europe will be improved through the combined extraction of metallic raw materials and the enhanced capacity to attract private investments;
- alternative pathways to hydraulic fracturing will be offered through the development of the "leaching" method;
- the results support "Europe 2020", the European Union's growth strategy for the coming decade and its flagship initiative for a "resource-efficient Europe", with the shift towards an energy-efficient, low carbon economy;
- the development of the CHPM technology will challenge other techniques, e.g. improving drilling operations, lowering their costs, and further developing hydraulic stimulation of the bedrock at larger depths.

4.3. Enhancement of reservoirs

Current TRL: 4

Areas of interest:

- demonstration of techniques for reservoir improvement in various geological settings
- upscaling of power plants or heat production

- reservoir development in untested geological conditions (e.g. ultra-deep hydrothermal and petrothermal)
- innovative reservoir exploration methods.

SET Plan targets:
DOI 3, 2 NTB A, B

Related H2020 projects
CHPM2030; **DESTRESS; DEEPEGS**; ITHERLAB; MIGRATE; **GEMex**; GeoElectricMixing; MATHROCKS

DEEPEGS and DESTRESS are the two main projects in this area. GeMex will be described in Section 4.5. CHPM2030 has already been described in Section 4.2.

4.3.1. DEEPEGS – Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business

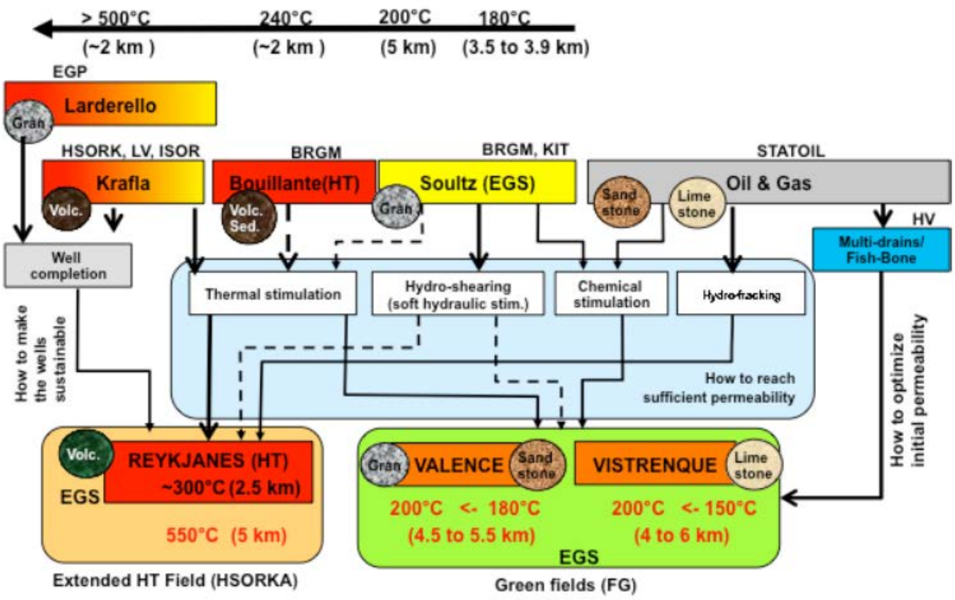
Description

Duration: December 2015 – April 2020

EU contribution: € 18 982 938

The goal of the DEEPEGS project[22] (Figure 20) is to demonstrate the feasibility of EGS for delivering energy from renewable resources in Europe. By testing of stimulating technologies for EGS in deep wells in different geologies, the project expects to deliver new innovative solutions and models for wider deployments of EGS reservoirs with sufficient permeability for delivering significant amounts of geothermal power across Europe.

Figure 20. Testing of EGS in different geological environments in DEEPEGS. Source: DEEPEGS.



[22] https://cordis.europa.eu/project/id/690771

Innovation(s)

DEEPEGS will demonstrate advanced technologies in three geothermal reservoirs with different geological conditions: volcanic environment in Iceland with temperatures up to 550 °C, very deep hydrothermal reservoir at Valence (crystalline and sandstone), Riom-Limagne (limestone) with temperatures up to 220 °C.

The project hopes to demonstrate significant advances in bringing EGS derived energy (TRL6-7) to market exploitation.

Impact/expected impact

The project has managed to drill 4 659 m at Reykjanes, Iceland and find supercritical fluid (at 427 °C, with fluid pressure of 340 bars) at the bottom, in what is being described as a 'significant milestone' for the geothermal industry. As they drilled further down the complexities developed, and since this well went deeper than any that preceded it, DEEPEGS gained new insights into the type of problems that arise. Conventional drilling methods were not an option, so the project had to develop new means of tacking the challenges. All obstacles apart from circulation loss, were overcome. The project found the complete loss of circulation below 3 060 m could not be dealt with through lost circulation materials, or by sealing the loss zone with cement. As a result, drill cores were the only deep rock samples recovered. However, as DEEPEGS set out to drill deep and extract cores, measure temperatures, search for permeability and find fluids at supercritical condition, the main objectives were reached. The retrieved drill cores indicate that the rocks appear to be permeable at depth.

At the end of 2018 stimulation with repeated cycles of heating and cooling to create an EGS system were ongoing in Iceland. The drilling work at the Vendenheim site in France started in 2018 and the first two deep wells were drilled in 2019.

4.3.2. DESTRESS - Demonstration of soft stimulation treatments of geothermal reservoirs

Description

Duration: March 2016 – November 2020

EU contribution: € 10 713 409

DESTRESS[23] is aimed at creating EGS reservoirs with sufficient permeability, fracture orientation and spacing for economic use of underground heat. Recently developed stimulation methods will be adapted to geothermal needs, applied to new geothermal sites and prepared for the market uptake. Risks assessment (technological, business), risk ownership, and possible risk mitigation are also covered by work packages.

The project also deals with the common and specific issues of different types of geothermal site, commonly found in Europe, in order to design a generally applicable workflow for productivity enhancement measures. The project will cover stimulation treatments in several geological settings covering granites, sandstones, and other rock types.

Existing and new project's test sites, pilot and demonstration facilities were chosen to demonstrate the DESTRESS concept (DESTRESS).

Innovation(s)

The overall objective is to develop best practices in creating a reservoir with increased transmissivity, sustainable productivity and a minimized level of induced seismicity.

Impact/expected impact

So far, the necessary preparations for the planned demonstration activities at different test sites have been carried out. During the first period of project implementation, the Klaipeda plant was put out of operation. An alternative geothermal site with similar characteristics has been identified.

A first soft stimulation was tested in Pohang (Korea) and the design for massive stimulation in this site was developed.

[23] https://cordis.europa.eu/project/id/691728

The project will quantify the cost and benefits of specific treatments by calculating the effect on the LCOE. In total, a performance improvement by a factor of 2 is expected for permeable sedimentary rocks and by 10 for impermeable rocks.

Non-standard risk monitoring including slow deformation and low cost real-time building monitoring around active geothermal plants were investigated. Preparation of real-time monitoring capabilities for carrying out vulnerability studies as well as some field and remote surveys for identifying the best building was done.

4.4. Improvement of performance

Current TRL: 5-6
Areas of interest: • improved overall conversion efficiency (especially binary plants) • improved heat exchangers, pumps, working fluids, expanders, cooling systems • bottoming/hybridising new and existing plants • new cycle concepts • flexible supply units for fluctuating heat demand • optimised partial load behaviour and flexible control strategies • hybridisation with other renewables • new uses for geothermal resources
SET Plan targets:
DOI 3, 2 NTB A
Related H2020 projects
DeReco; **GEOCOND**

Very few projects under H2020 involve this research area directly, although numerous projects may touch on some aspects. The most notable H2020 project is GEOCOND.

Before H2020, LOW-BIN (€ 1.9 million) was one of the more significant projects in this research area and aimed to improve the cost-effectiveness, competitiveness and market penetration of geothermal electricity generation from hydrothermal or EGS systems. The project aimed to develop a unit that can generate electricity from lower temperature geothermal resources, with temperature threshold for profitable operation at 65 °C, compared with 90-100 °C of existing units. The project also aimed to develop a Rankine cycle machine for CHP by heat recovery from the cooling water circuit, leading to cogeneration of heat and power from Rankine Cycle units with overall energy efficiency of 98-99%, compared with 7-15% for existing units producing only electricity and for 35-60% of existing geothermal cogeneration schemes. This system would be usable in present and future district heating schemes and based on the project's result, low temperature ORC machines were proposed to be incorporated into the product portfolio of Turboden, although they are currently not available (LOW-BIN).

The FP7 NSHOCK project (€ 1.4 million) involved developing an increased understanding of real-gas dynamics, which enabled an improvement in the design of ORC engines, to be used in small scale energy production from binary geothermal systems.

4.4.1. GEOCOND - Advanced materials and processes to improve performance and cost-efficiency of Shallow Geothermal systems and Underground Thermal Storage

Description

Duration: May 2017 – October 2020

EU contribution: € 3 955 740

The project[24] aims to enhance district heating and cooling via storage technologies like UTES. By a smart combination of different material solutions through sophisticated engineering optimisation, testing and on-site validation, GEOCOND will develop solutions to increase the thermal performance of the different subsystems configuring an SGES and UTES. The project focuses on four key development areas: development of new pipe materials, advanced grouting additives and concepts, advanced Phase Change Materials and system-wide simulation and optimisation (GEOCOND).

Innovation(s)

The innovations that GEOCOND will develop are the following:

- improved coaxial geometries;
- thermal conductive compounds and pipes;
- new high temperature resistant tubes for cooling dominated applications;
- lower diameter pipes and enhanced U-pipe geometries;
- cost-effective SS Phase Change Materials (PCMs) to blend with grouting materials;
- functionalisation of silica with carbon particles;
- grouting materials.

The activities developed in GEOCOND project will be implemented at TRL 4-5, because most the proposed innovations are based on technologies fully validated at laboratory level and some prototypes were performed.

Impact/expected impact

GEOCOND will address first of all the improvement of the installation and operating efficiency of SGES and UTES, reducing the installation costs by nearly 15%. The aim is an overall cost reduction of about 25%.

It is estimated that this will increase the deployment of this technology by at least 10% versus current estimates.

4.5. Exploration techniques

Current TRL: 5-6

Areas of interest:

- high resolution exploration methods
- innovative modelling techniques
- increased measurement precision
- faster analysis of acquired data
- increasing detail of geological complexity of resources and increased target depths

SET Plan targets:

DOI 3, 4

[24] https://cordis.europa.eu/project/id/727583

Related H2020 projects
DESTRESS, **ENIGMA**; **GEMex**; MIGRATE; MATHROCKS

Exploration techniques have not received much attention under H2020, apart from the following projects: DESTRESS (with some related work packages), ENIGMA (which involves the creation of a training network) and GEMex (which focuses on resource assessment in Mexico). DESTRESS has already been described in Section 4.3.

4.5.1. GEMex - Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems and Superhot Geothermal Systems

Description

Duration: October 2016 – May 2020

EU contribution: € 9 999 793

The GEMex project[25] is a complementary effort of a European consortium with a corresponding consortium from Mexico.

The project involves resource assessment at two unconventional geothermal sites, for EGS development at Acoculco and for a super-hot resource near Los Humeros. This part will focus on understanding the tectonic evolution, the fracture distribution and hydrogeology of the respective region, and on predicting in-situ stresses and temperatures at depth. The site at Acoculco, foreseen for EGS development, has previously been explored with two wells which hardly found any fluids but temperatures around 300 °C at a depth of 2 km. The high temperature gradient makes it an interesting target for exploitation and the lack of a clear resource makes it an ideal region for testing existing knowledge on how to constrain an area where EGS can be performed.

Reservoir characterisation will also be carried out using techniques and approaches developed at conventional geothermal sites, including novel geophysical and geological methods to be tested and refined for their application at the two project sites: passive seismic data will be used to apply ambient noise correlation methods and to study anisotropy by coupling surface and volume waves; newly collected electromagnetic data will be used for joint inversion with the seismic data. For the interpretation of these data, high-pressure/ high-temperature laboratory experiments will be performed to derive the parameters determined on rock samples from Mexico or equivalent materials (GEMex).

Innovation(s)

While the main aim of the project is to foster international cooperation between the EU and Mexico, the project also will:

- reduce pre-drill mining risk by in depth understanding of the geological context of the resource;
- improve geophysical imaging and detection of deep reservoir structures by novel approaches;
- improve predictive models for reservoir characterisation and simulation;
- provide conceptual models for sustainable site development.

Impact/expected impact

The project will perform a numerical simulation of the geothermal system and its possible exploitation including:

- design for drilling and stimulation at Acoculco, including a multi-criteria approach for optimisation of stimulation design;
- recommendations for drilling and well completion at Los Humeros North, including material selection for subsurface and surface installations;
- recommendation for environmental risk assessment and mitigation strategies;
- concepts, surveys and scenarios for public engagement.

[25] https://cordis.europa.eu/project/id/727550

At the end, the project will support the actual site development thus speeding up the geothermal development in Mexico and beyond.

The most important achievements so far are:

- development of a high temperature tracer to be used in the geothermal wells for monitoring the geothermal flux (patent is filed by partner IFE);
- necessary data has been collected at the two project sites and all samples needed for the laboratory testing were shipped from Mexico to Europe;
- collaboration between the 31 involved Mexican and European partners has been built and is strong, and the impact in terms of scientific and technological knowledge transferred is excellent.

All existing and newly collected information will be applied to define drill paths, to recommend a design for well completion including suitable material selection, and to investigate optimum stimulation and operation procedures for safe and economic exploitation with control of undesired side effects.

4.5.2. ENIGMA - European training Network for In situ imaGing of dynaMic processes in heterogeneous subsurfAce environments

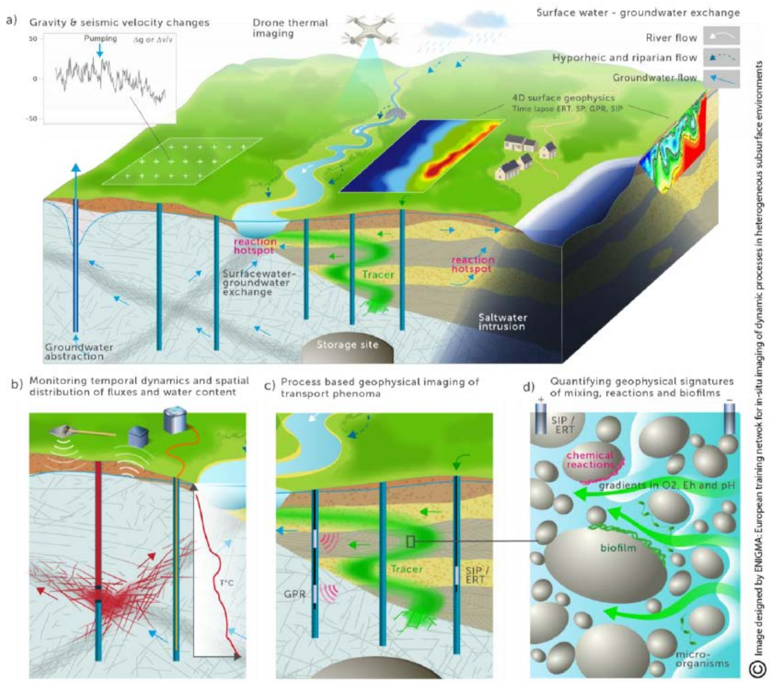
Description

Duration: January 2017 - December 2020

EU contribution: € 3 865 770

The ENIGMA[26] network of eleven institutions will train a new generation of young researchers in the development of innovative sensors, field survey techniques and inverse modelling approaches (Figure 21). This will improve understanding and monitoring of dynamic subsurface processes that are key to the protection and sustainable use of water resources.

Figure 21. Illustration of the novel approaches developed in ENIGMA for imaging dynamic processes in the subsurface. Source: ENIGMA.



[26] https://cordis.europa.eu/project/id/722028

ENIGMA focuses mainly on critical zone observation, but the anticipated technological developments and scientific findings will also contribute to monitoring and modelling the environmental footprint of an increasing range of subsurface activities, including large-scale water abstraction and storage, EGS and subsurface waste and carbon storage. While many subsurface structure imaging methods are now mature and broadly used in research and practice, our ability to resolve and monitor subsurface fluxes and processes, including solute transport, heat transfer and biochemical reactions, is much more limited. The shift from classical structure characterisation to dynamic process imaging, driven by ENIGMA, will require the development of multi-scale hydrogeophysical methods with adequate sensitivity, spatial and temporal resolution, and novel inverse modelling concepts.

Innovation(s)

ENIGMA will gather (1) world-leading academic teams and emerging companies that develop innovative sensors and hydrogeophysical inversion methods, (2) experts in subsurface process upscaling and modelling, and (3) highly instrumented field infrastructures for in-situ experimentation and validation.

Impact/expected impact

ENIGMA will create a creative and entrepreneurial environment for trainees to develop integrated approaches to water management with interdisciplinary field-sensing methods and novel modelling techniques. ENIGMA hopes to foster EU and international cooperation in the water area by creating new links between hydrogeological observatories, academic research groups, innovative industries and water managers for high-level scientific and professional training.

4.6. Advanced drilling/well completion techniques

Current TRL: 5 (improvement), 3 (novel)

Areas of interest:

- process automatisation
- drilling fluids to compensate unwanted loss of circulation zones
- improved cementing procedures and well cladding
- improved stimulation methods for deep wells
- risk assessment and lifetime analysis
- systems to avoid fluid discharge while drilling
- horizontal-multilateral wells clusters in various geological formations
- targeted (e.g. compact and lightweight) equipment and techniques for drilling and well completion in urban areas
- percussive drilling for deep/hot wells
- non-mechanical drilling methods
- benchmark testing in boreholes

SET Plan targets:
DOI 3, 5
Related H2020 projects
DESCRAMBLE; ThermoDrill; DEEPEGS; GeoWell; SURE

Prior to the H2020 framework, no projects have directly related to advanced drilling techniques. DEEPEGS, DESCRAMBLE, SURE, ThermoDrill, and GeoWell are the biggest projects in this area under H2020. DEEPEGS has already been described in Section 4.3, GeoWell in Section 4.2.

4.6.1. DESCRAMBLE - Drilling in supercritical geothermal conditions

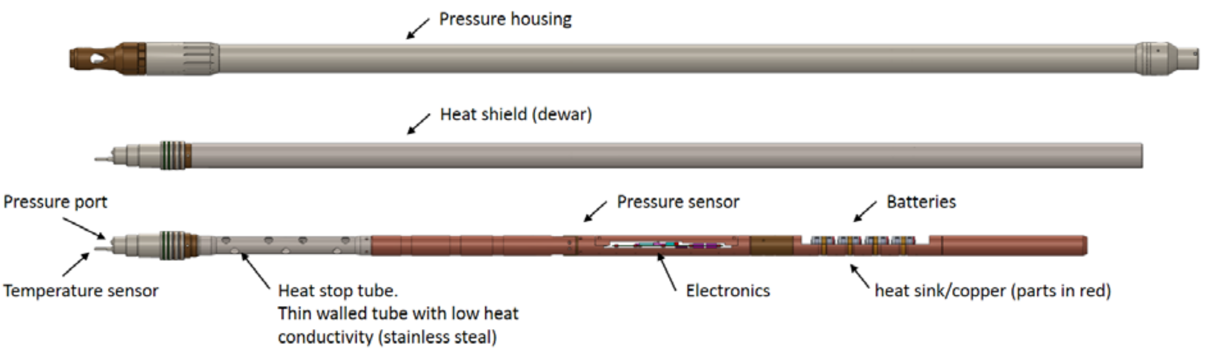
Description

Duration: May 2015 - April 2018

EU contribution: € 6 753 635

The aim of the DESCRAMBLE project[27] (Figure 22) was to develop novel drilling technologies for a proof-of-concept test of reaching deep geothermal resources.

Figure 22. New downhole logging tool developed in the DESCRAMBLE project. Source: DESCRAMBLE.



Innovation(s)

The first drilling in the world in an intra-continental site at a middle-crustal level was performed. The test site is an existing dry well in Larderello, Italy, drilled to a depth of 2.7-2.9 km reaching super-critical conditions with temperatures of up to 507-517 °C. No commercial fluid has been identified. Due to unexpected and above design conditions (450 °C max) it has been decided to not further penetrate into the seismic reflector where an extrapolated temperature of 600 °C could be expected, corresponding to the molten phase of granite.

Impact/expected impact

The project could lead to significant advances in the utilisation of high temperature geothermal fluids, which are of huge economic interest. The seismic methods that have already been introduced within the project at Venelle-2 to evaluate the k-horizon can have high dissemination potentials elsewhere.

Successful implementation of the new drilling procedures, including a new high temperature downhole tool, will be of high interest for all geothermal power companies in the world. Furthermore, the fluid simulations being developed in the project could be of economic interest for the whole geothermal community.

It is hoped that the time-to-market for a geothermal power plant can be reduced from 3-4 years for a standard hydrothermal field down to 2-3 years for a super-critical one, hence achieving a 10-15% reduction in cost, due to a 75% reduction in drilling costs and a possible further 10% reduction due to the learning curve effect. It is also hoped that power output could be increased by a factor of 10 compared to existing geothermal plants.

4.6.2. SURE - Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource

Description

Duration: March 2016 - August 2019

EU contribution: € 5 892 165

Within the SURE project[28] the Radial water Jet Drilling (RJD) technology was investigated and tested as a method to increase inflow into insufficiently producing geothermal wells.

[27] https://cordis.europa.eu/project/id/640573

RJD uses the power of a focused jet of fluids, applied to a rock through a coil inserted in an existing well. This technology is likely to provide much better control of the enhanced flow paths around a geothermal well and does not involve the amount of fluid as conventional hydraulic fracturing, reducing the risk of induced seismicity considerably. RJD was applied to access and connect high permeable zones within geothermal reservoirs to the main well with a higher degree of control compared to conventional stimulation technologies. SURE investigated the technology for deep geothermal reservoir rocks at different geological settings such as deep sedimentary basins or magmatic regions at the micro-, meso- and macro-scale.

Innovation(s)

The proposed technological concept aimed to significantly decrease the environmental footprint of a stimulation treatment while reducing simultaneously the amount of applied fluid volumes compared to established stimulation methods, the number of applied chemicals with environmental impact, and the risk of induced seismicity, advancing the TRL of RDJ technology for geothermal reservoir enhancement from TRL 3 to TRL 4-5. Based on a wide set of experiments, researchers created several tools, including patent-pending components that can be used to improve the water jetting technology. They also developed numerical models that can be used to, for example, determine the rock destruction process and estimate improvement to a well's performance following RJD stimulation.

Impact/expected impact

The project achieved most of its objectives and delivered exceptional results. In particular, the project has achieved the following: state-of-the-art review on stimulation technologies and RJD; rock properties determination at laboratory scale; experimental set-ups for the characterisation of the permeability evolution for different fracture types and the study of lateral's stability and formation damage; 1st field jetting test with industry equipment. More in detail, a downhole geophone was developed and deployed in a geothermal well in Iceland; a post run measurement mini tool for lateral geometry and a cuttings retrieval tool from the well were also developed.

The SURE project has significantly advanced our knowledge about RJD technology beyond the state of the art and across different spatial and temporal scales. This allows increasing the number of economically viable geothermal wells, with positive impacts on the overall economic performance of geothermal energy.

4.6.3. ThermoDrill - Fast track innovative drilling system for deep geothermal challenges in Europe

Description

Duration: September 2015 - August 2019

EU contribution: € 5 3810 995

The starting point of the ThermoDrill project[29] was the consideration that if deep geothermal energy from EGSs becomes a significant cornerstone in future energy strategy, there is an urgent need to provide cost-efficient and novel drilling technologies and concepts in order to open up new European geothermal reservoirs for energy exploitation. In fact, as drilling costs rise exponentially with increasing depth, they represent the main cost drivers of geothermal plants, often accounting for more than half of all investment costs.

Hence, the goal of the project was the development of an innovative drilling system based on the combination of conventional rotary drilling with water jetting allowing at least 50% faster drilling in hard rock, a cost reduction of more than 30% for the subsurface construction and a minimised risk of induced seismic activity..

Innovation(s)

ThermoDrill mainly addressed the following research and development topics:

- enhanced water jet drilling technology for borehole construction and replacement of fracking;
- High temperature and high pressure crystalline rock jetting and drilling fluids;
- systematic redesign of the overall drilling process, particularly the casing design and cementing;

[28] https://cordis.europa.eu/project/id/654662
[29] https://cordis.europa.eu/project/id/641202

- evaluation of drilling technologies and concepts in terms of health, safety and environmental compliance.

The novel hybrid drilling technique combines standard rotary drilling with a technology called water jet cutting. The high-pressure water jet (approximately 2 000 bar) is used to pre-damage the rock on impact with the effect of significantly increasing the rate of penetration and thus the overall efficiency of the drilling process. Technical, economic and safety reasons demand that the high-pressure generation unit is directly placed below the drill bit. Despite several great challenges including confined space and harsh conditions at the borehole bottom, a prototype of the high-pressure generation unit was developed and successfully integrated as essential component of the ThermoDrill drilling system.

Impact/expected impact

The feasibility and efficiency of the innovative drilling technology was initially tested in experiments at various laboratory scales. Final field tests under real environment within an existing 1.3 km deep borehole confirmed the enormous potential of the technology, which is capable of achieving around twice the rate of penetration when compared to standard rotary drilling. Moreover, the tests highlighted that the novel "ThermoDrill-System" can be integrated with existing drilling infrastructure and technology without any difficulties, thereby boosting the acceptance for its deployment as a market-ready system in future.

This is the first time that a jetting system could be tested under borehole conditions and the results could be mapped and directly related to the applied test parameters.

Via the deployment of the "ThermoDrill-System", cost savings of approximately 20% or around € 3 million are expected to be achieved, just for a single deep borehole (5 000 m). Further future advancements will bring this drilling technology to market-readiness, thereby paving the way for intensified utilisation of geothermal as environmentally friendly alternative energy source throughout Europe and even globally.

The partners involved in the manufacturing of the new jet-assisted roller cone drill bits are also expected to receive direct benefits from increased sales to geothermal projects, potentially including conventional high temperature geothermal applications.

4.7. Integration of geothermal heat and power in the energy system and grid flexibility

Current TRL: 4-5

Areas of interest:

- demonstration ramping up/ramping down on demand
- demonstration of automatic generation control (load following / ride-through capabilities to grid specifications) and ancillary services of geothermal power plants.
- flexible heat/cold and electricity supply from binary cycles and EGS power plants, including coupling with renewable energy sources
- solving specific problems of geothermal power production in isolated energy networks (islands).
- thermoelectric energy storage integrated with district heating networks and dedicated equipment (heat pumps, ORC turbo-expanders) and heat exchanger networks, with hot and cold reservoirs able to cover variable demand of heat, cold and electricity

SET Plan targets:
DOI 6, 3 NTB B

Related H2020 projects
GeoSmart; TESSe2b; STORM; OPTi; FLEXYNETS

This topic had not been addressed to a great degree until H2020, and several significant projects are now underway, such as GeoSmart, STORM, FLEXYNETS and OPTi. Very few demonstrations of ancillary services of geothermal power plants exist to date, whereas more focus has been on flexible district heating/cooling networks (OPTi, FLEXYNETS) and integration with renewables and storage methods (TESSe2B). FLEXYNETS will be described in Section 4.10.

4.7.1. GeoSmart - Geothermal energy made flexible and cost-effective

Description

Duration: June 2019 – May 2023

EU contribution: € 17 363 898

Renewables like the Sun and wind increase the uncertainty and variability in energy generation and delivery to consumers. Geothermal plants can help balance fluctuations by operating in a more flexible mode to respond to sudden changes in energy use. The GeoSmart project[30] is working on methods to store heat energy when demand is low so that it can be released when demand is high. The project also plans to create a hybrid cooling system for the ORC plant that will prevent efficiency degradation due to seasonal changes.

Innovation(s)

GeoSmart aims to optimise and demonstrate innovations to improve the flexibility and efficiency of geothermal heat and power systems. However, there are some techno-economic challenges which need to be addressed to facilitate highly flexible operation of geothermal power plants.

GeoSmart proposes to combine thermal energy storages with flexible ORC solutions to provide a highly flexible operational capability of a geothermal installation. During periods with low demand, energy will be stored in the storage to be released at a later stage when the demand is higher. As this approach does not influence the flow condition at the wellhead, critical infrastructures will be unaffected under variable energy generation. To improve efficiency, a hybrid cooling system for the ORC plant to prevent efficiency degradation due to seasonal variations is proposed. Efficiency will be further improved by larger power plant heat extraction enabled due to a scaling reduction system consisting of specially design retention tank, heat exchanger, and recombining with extracted gases. The scaling reduction system has the potential to almost double power production of many medium enthalpy geothermal plants.

The GeoSmart technology will be demonstrated in a medium/high and a low temperature field to show its potential benefits and applicability in different settings, with the aim of bringing it to TRL 7/8.

Impact/expected impact

Overall, GeoSmart technologies will drastically reduce geothermal energy costs, thus allowing geothermal plants to cost-effectively respond to different heat and power demands, making them cost competitive with its fossil fuel-based counterparts.

More specifically, the two main impacts are (1) cost reduction from CHP generation, and (2) improved environmental performance and energy security.

4.7.2. TESSe2B - Thermal Energy Storage Systems for Energy Efficient Buildings. An integrated solution for residential building energy storage by solar and geothermal resources

Description

Duration: October 2015 - September 2019

EU contribution: € 4 311 700

The target of TESSe2b[31] was to design, develop, validate and demonstrate a modular and low cost thermal storage technology based on solar collectors and highly efficient heat pumps for heating, cooling and domestic hot water production. The idea was to develop advanced compact integrated PCM thermal energy storage (TES) tanks exploiting renewable energy sources (solar and geothermal) in an efficient manner

[30] https://cordis.europa.eu/project/id/818576
[31] https://cordis.europa.eu/project/id/680555

coupled with enhanced PCM borehole heat exchangers (BHEs) taking advantage of the increased underground thermal storage and maximising the efficiency of the ground coupled heat pumps (GCHP).

Innovation(s)

Two paraffins and two hydrated salts, for the hot PCM tanks (HTES), two paraffins and two hydrated salts for the cold tanks (CTES) and two paraffins and two hydrated salt for the DWH tanks (DHW-PCM). Three paraffins for the PCM in BHEs were also selected, one per demo site of the project (in Austria, Cyprus, and Spain) according with the soil temperature and operating modes. The PCM was introduced in the BHE in encapsulation.

New nano-composite enhanced paraffins PCM (NEPCM) were also developed in order to improve the low thermal conductivity and enhance the overall heat transfer performance without compromising heat of fusion.

A protective and inexpensive thin film coating against the corrosivity of salt-hydrates to the heat exchanger (HE) was developed. The coated heat exchanger is not attacked by the PCM and in addition it exhibits better performances due to the very high thermal conductivity of the coating.

Compact modular TES tanks including a high performance HE designed, optimized and developed. A numerical analysis was conducted via computational fluid dynamics and finite element analysis. Compatibility between thermoplastic materials with the paraffin based PCMs was solved applying a coating with a special epoxy resin.

In hydrated salt tanks, an appropriate geometry was developed to ensure the stability of the hydrated salts over time. The HTES, CTES and DHW tanks pre-prototypes using paraffins and hydrated salts were developed and tested in laboratory, then developing the relevant prototypes that were installed in the demo sites. The performance of the tanks was validated and demonstrated in the demo sites.

A self-learning smart model-based control system for efficient TESSe2b operation was developed, then validated and demonstrated in the three demo sites.

Demonstration, on-site monitoring and technology validation of prototypes of a single building in three pilot sites was performed.

Table 2 shows the TRL of the TESSe2b components.

Table 2. TRL of TESSe2B components

Component/module	TRL
Modular TESSe2b PCM storage tank	6
PCM Geothermal HE	6
Advanced smart control system	6
HE protective thin film coating	4

Source: TESSe2B

Impact/expected impact

The project achieved most of its objectives and milestones.

The energy management of the TESSe2b solution is based on a self-learning optimisation algorithm. The solar radiation intensity and the energy demand of the residents vary only partly predictably and therefore constitute the stochastic variables of the system. Thus, a stochastic optimisation method is used, that dynamically adapts itself during the operation of the system in order to achieve the chosen optimisation objective. The system learns by itself what is the best way to operate under different conditions and optimises its performance during the operation of the system, with positive impacts on the overall efficiency of the system.

The stability of the selected PCMs was studied and according to the paraffin characteristics there is no stability problem. The problem of the incompatibility of paraffins with the thermoplastics used in the tanks was solved by a coating with a special epoxy resin. Tests were made to ensure the longevity of the solution. The PCM tanks using hydrated salts, are airtight, and height of the tank modules does not exceed 50 mm, allowing a long term stability.

It was proven that an adequate increase in system efficiency is achieved with a total storage volume, hot tanks, cold tanks and DHW tanks, without exceeding 2.5 m^3. The number of PCM tanks for each demo site, as a result of the optimisation studies, is 0.8 m^3 in Austria and 1.12 m^3 in Cyprus and Spain.

Cost-effectiveness analysis of the TESSe2b solution was carried out based on the monitoring data analysis and simulations of demo sites. The indicative values of the reduction of energy primary consumption varies from 80% to 90%, based in conventional systems for the demo sites corresponding to a simple pay-back period passing from 8.7 to 9.8 years.

The main scientific/technological achievements of the project to date are related to new products, namely coatings development and the PCM microencapsulation. Significantly improved products compared to the state-of-the-art were also developed, such as nano-composite paraffin waxes compact modular design of storage tanks and smart control system.

4.7.3. OPTi – Optimisation of District Heating Cooling systems

Description

Duration: March 2015 – April 2018

EU contribution: € 2 100 130

The OPTi project[32] aimed to rethink the way District Heating and Cooling (DHC) systems are architected and controlled. The project delivered methodologies and tools to enable accurate modelling, analysis and control of current and envisioned DHC systems.

The methodology was deployed both on a complete system level, and on the level of a building(s). OPTi aimed to dynamically control the DHC system and treat thermal energy as a resource to be controlled for DHC systems towards saving energy and reducing peak loads.

Innovation(s)

Projects results include:

- user interaction system design (Virtual Knob) implemented in an office building
- estimation method for baseline consumption of consumers in a DHC network
- smart energy algorithm tool to estimate the optimal energy generation mix
- cloud data storage system;
- tools for optimisation and control.

The OPTi framework has reached TRL 7 during the course of the project.

Impact/expected impact

A DHC in Luleå City was enhanced. The envisaged energy savings of 30% for water and heating on a system level and 30-40% of peak consumption of houses/clusters of houses was not reached.

4.7.4. STORM - Self-organising Thermal Operational Resource Management

Description

Duration: March 2015 - March 2019

EU contribution: € 1 972 126

STORM[33] built on the experiences of the (Interreg) Minewater project (see Section 3.2.3), which was transformed into an intelligent DHC network, the so-called "Minewater 2.0" project. All buildings are connected

[32] https://cordis.europa.eu/project/id/649796

to local cluster networks. The ambition was to make these clusters energy self-sufficient by energy exchange between buildings and energy storage. Since energy is transported over shorter distances, this would result in lower distribution losses. In this way, more clusters and thus more buildings could be connected to the backbone mine water system. As a result, expansion of the network would become possible. However, for fully deploying this system, an automated and smart control system would be necessary. Based on this, the STORM project tackles energy efficiency at district level by developing an innovative DHC network controller.

The following measures were envisioned to guarantee the general applicability:

- applying self-learning control techniques instead of model-based control approaches, making the controller easy to implement in different configuration and generations of DHC networks;
- inclusion of three control strategies in the controller (peak shaving, market interaction, cell balancing);
- conceivement of the controller to be an add-on to many existing DHC network controllers and systems of supervisory control and data acquisition, demonstrating it in two existing grids: one highly innovative low-temperature DHC network (Mijnwater BV in Heerlen, Netherlands) and a more common medium-temperature district heating grid in (Växjö Energi in Rottne, Sweden).

Innovation(s)

The main innovations were planned to be:

- develop a generic controller applicable to a wide range of DHC networks;
- demonstrate the newly developed generic controller in two existing DHC networks;
- quantify the benefits of developed generic control;
- develop innovative business models needed for the large-scale roll-out of the newly developed controller;
- increase awareness of the need for smart control of DHC networks and quantify and demonstrate the benefits of smart control;
- ensure market-uptake of the new technology.

A previous version of the controller algorithms was already demonstrated in the FP7 Ehub – project on a lab scale (TRL 4). The STORM project aimed at bringing the controller to TRL 7 (technology demonstrated in operational environment) by applying the controller to two existing district heating grids.

The main achievements for the project have been the following. The algorithms for the STORM controller were developed, demonstrated, evaluated and implemented on the two demo sites. The features peak reduction, cell balancing and market interaction were developed and implemented on the NODA smart heat platform (NODA was one of the partners of the project). The algorithms were implemented on the commercial NODA platform and tested in the demonstration sites. The performance of the STORM controller was determined for the two demo. Commercial deployments are explored with some large district heating companies.

Hence, practical applications of the STORM controller technology were realised and the involvement of industry was addressed. These demonstrations have delivered lessons for further market roll out of the technologies as part of the replication plan that was made.

The consortium looked at the market potential of the controller and how the controller can be exploited on a wider scale: activities as licensing, setting up of a spin off company, third party licensing, etc. are investigated. A lot of commercial interest emerged in relation to the STORM technology and the digitalisation of the DHC system. In particular, a joint ownership agreement was signed in 2016 by the partners NODA and VITO ensuring their long term cooperation.

Impact/expected impact

The expected impact was:

- reduce the energy consumption of space and water heating by 30 to 50% compared to today's level.

[33] https://cordis.europa.eu/project/id/649743

- contribute to wider use of intelligent district heating and cooling systems and integration of renewables, waste and storage.

The project has developed the STORM controller based on self-learning algorithms, which can learn the behaviour of the network and the buildings, then experimented in two STORM demo sites, , where the resulting energetic, economic and environmental gains were evaluated.

The control system is claimed successful and innovative by the project consortium, which may constitute a contribution to a range of DHC grids. However, overall the project did not deliver results with significant immediate or potential impact, taking into consideration the EU call requirements and also the target quoted above), as the target of 30% to 50% savings was not reached/demonstrated.

4.8. Zero emissions power plants

Current TRL: 5-6

Areas of interest:

- CO_2 capture, storage and reinjection schemes for reservoirs with high CO_2-content
- Demonstration of capture of non-condensable gases
- capture and reinjection of chemical compounds associated with produced geothermal fluids.
- development of new equipment (compressors, pumps, intercoolers, mixing nozzles, and possibly refrigeration equipment)

SET Plan targets:
DOI 2, 3 NTB B
Related H2020 projects
CARBFIX2

Zero emission (or negative emission) power plants, with regard to power plants using high temperature resources, are of interest where geothermal fluid is not reinjected and condensed gases are emitted to the atmosphere. The two projects of interest are GECO and CARBFIX2, both building on the previous FP7 CARBFIX project. (Section 3.2.4).

4.8.1. GECO – Geothermal Emission Gas Control

Description

Duration: October 2018 – September 2022

EU contribution: € 15 599 843

GECO[34] will advance in the provision of cleaner and cost-effective non-carbon and sulphur emitting geothermal energy across Europe and the World. The core of this project is the application of an innovative technology, recently developed and proved successfully at pilot scale in Iceland, which can limit the production of emissions from geothermal plants by condensing and re-injecting gases or turning the emissions into commercial products. To both increase public acceptance and to generalise this approach, it will be applied by GECO in four distinct geothermal systems in four different European countries: 1) a high temperature basaltic reservoir in Iceland; 2) a high temperature gneiss reservoir in Italy; 3) a high temperature volcano-clastic reservoir in Turkey; and 4) a low temperature sedimentary reservoir in Germany.

Innovation(s)

Gas capture and purification methods will be advanced by lowering consumption of resources (in terms of electricity, water and chemicals) to deliver cheaper usable CO_2 streams to third parties. The approach to waste

[34] https://cordis.europa.eu/project/id/818169

gas storage is to capture and inject the soluble gases in the exhaust stream as dissolved aqueous phase. This acidic gas-charged fluid provokes the dissolution of subsurface rocks, which increases the reservoir permeability, and promotes the fixation of the dissolved gases as stable mineral phases. This approach leads to the long-term environmentally friendly storage of waste gases, while it lowers considerably the cost of cleaning geothermal gas compared to standard industry solutions. A detailed and consistent monitoring program, geochemical analysis, and comprehensive modelling will allow characterising the reactivity and consequences of fluid flow in the geologically diverse field sites thus allowing the creation of new and more accurate modelling tools to predict the reactions that occur in the subsurface in response to induced fluid flow. Finally, gas capture for reuse will be based on a second stage cleaning of the gas stream, through amine separation and burn and scrub processes, producing a CO_2 stream with H_2S levels below 1 ppm, which is the prerequisite for most utilisation pathways such as the ones that will be applied within the project.

Impact/expected impact

The expected impacts are the following:

- lower emissions from geothermal power generation by capturing them for either reuse or storage;
- turn captured emissions into commercial products, allowing for cost reductions through increased revenues;
- demonstrate cost competitiveness of developed gas capture and injection methods through a comprehensive economic analysis of gas capture, injection and monitoring at each field site;
- gain better understanding of subsurface reactions occurring in response to induced fluid flow during and after the injection of fluids into the subsurface;
- achieve safer injection procedures by integrating new technology, such as detecting CO_2 fluxes via remote sensing, in-situ laser isotope analyser and corrosion monitoring system.

The project will also train a new generation of scientist and engineers in the current best practice work-flow for lowering emissions from deep geothermal operations as well as, ultimately, aid in the public acceptance of geothermal energy throughout the continent.

4.8.2. CARBFIX2 - Upscaling and optimizing subsurface, in situ carbon mineralization as an economically viable industrial option

Description

Duration: August 2017 - January 2021

EU contribution: € 2 200 318

CarbFix2[35] builds upon the success of the original FP7 CarbFix project. TheCarbFix2 project aims to make the CarbFix geological storage method both economically viable with a complete CCS chain, and to make the technology transportable throughout Europe.

Innovation(s)

- co-injection of impure CO_2 and other water-soluble polluting gases into the subsurface;
- developing the technology to perform the CarbFix geological carbon storage method using seawater injection into submarine basalts;
- integrating the CarbFix method with novel air-capture technology.

CarbFix2 will 1) extend the original approach to implementation under more diverse conditions; 2) install and demonstrate an capture process; 3) lower the cost of CCS by capturing gas mixtures rather than pure CO_2; 4) increase the safety and geographical applicability of CCS.

The progress will advance TRL of various parts and components. For example, fluid rocks experiments where currently proof of concept was carried out (TRL 3), will be further developed and demonstrated in real environment (TRL 5). Technologies at TRL 5 will be further demonstrated bringing them to TRL 6-7.

[35] https://cordis.europa.eu/project/id/764760

Impact/expected impact

Swiss cleantech company Climeworks has partnered with Reykjavik Energy to combine direct air capture (DAC) technology for the first time with safe and permanent geological storage. A Climeworks DAC module has been installed at Hellisheidi to capture CO_2 from ambient air for permanent storage underground. Climeworks' technology draws in ambient air and captures the CO_2 with a patented filter. The filter is then heated with low-grade heat from the geothermal plant to release the pure CO_2 which then can be stored underground. Combining the two technologies at Hellisheidi has led to the plant being termed as 'carbon negative' since it captures more carbon than it produces.

CarbFix2 aims at reducing capture costs by 50% due to capture and store of impure CO_2 (specifically a mixture of water-soluble gases dominated by CO_2 and H_2S/SO_2). CarbFix2 will also eliminate all long-term monitoring costs after carbon mineralisation has occurred.

4.9. Cross-cutting / non-technical issues

Non-technical issues have been identified as a research priority for geothermal energy proliferation. These include increasing awareness of local communities and involvement of stakeholders in sustainable geothermal solutions and risk mitigation. Areas of interest are as follows:

- reinjection of incondensable gases in deep geothermal plants;
- seismicity control;
- increased understanding of the socio-economic dimension of geothermal energy;
- promotion of change in community responses to new and existing geothermal installations;
- risk management strategies;
- collation of good practices on risk mitigation and lessons learned;
- development of advanced approached and guidelines for addressing and quantifying exploration risk;
- development of financial tools to help mitigate risks;
- stakeholder consultation, creation of a task force / working group, development of European concepts.

Under H2020 many technical projects implicitly deal with aspects such as reinjection of incondensable gases and seismicity control (e.g. ThermoDrill and SURE), which are indirectly related to gaining community support for geothermal projects. However, projects with non-technical aims have had much less focus under H2020 compared to previous framework programmes. Examples include projects such as GEOFAR (IEE), which aimed to identify non-technical difficulties and barriers hindering the initial stages of geothermal energy projects and propose workable solutions. Other projects included RESTMAC (FP6), which aimed to create markets for renewable energies, and ECOHEAT4EU (IEE), which supported the creation of effective legislative mechanisms to develop district heating and cooling throughout Europe. The IEE projects GEOELEC and GEODH also aimed to overcome the non-technical barriers to the development of geothermal district heating and electricity, by increasing awareness amongst policy and decision makers from national authorities about the potential of this technology; developing strategies for the simplification of the administrative and regulatory procedures and, in some cases, the filling of regulatory gaps; developing innovative financial models and training technicians, civil servants and decision-makers of regional and local authorities in order to provide the technical background necessary to approve and support projects.

Under H2020, few projects directly address non-technical issues apart from network-building projects such as GEOTHERMICA or DG-ETIP, which aims to reduce social and environmental costs and strengthen the stakeholder net-work. The DESTRESS project also includes risks assessment (technological, business), risk ownership, and possible risk mitigation in its work packages. ThermoDrill includes development of methods for risk assessment with respect to the design and operation of high-temperature geothermal wells. The GEMex project is to include appropriate measures and recommendations for public acceptance and outreach as well as for the monitoring and control of environmental impact. The TEMPO project also states that stakeholder engagement and consumer empowerment will be high priority.

The DG-ETIP project also has a primary objective of cost reduction, including social and environmental costs. The Geothermal ETIP is an open stakeholder group, including representatives from industry, academia, research centres, and sectoral associations, covering the entire deep geothermal energy exploration, production and utilisation value chain.

4.10. Shallow and low-temperature geothermal

4.10.1. MPC-GT – Model Predictive Control and Innovative System Integration of GEOTABS in Hybrid Low Grade Thermal Energy Systems

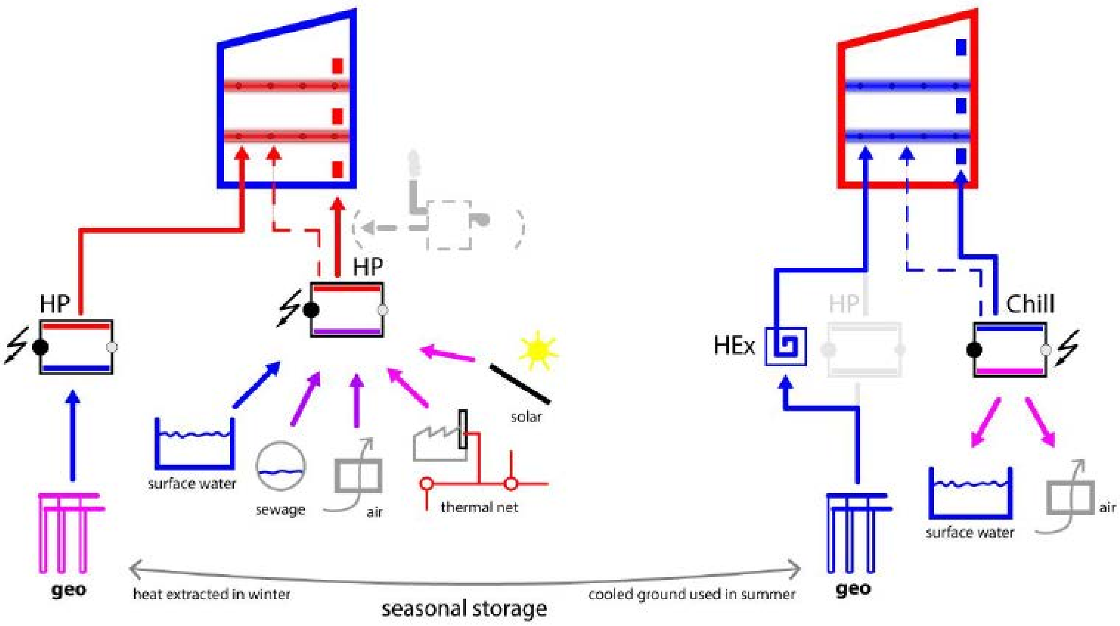
Description

Duration: September 2016 - August 2020

EU contribution: € 3 989 951

The MPC-GT project[36] builds on previous research from the EU-Funded FP7 GEOTABS project which involved developing solutions to improve the combination of geothermal heat pumps and thermally activated building systems. The project aims to increase the share of low-grade energy sources by using low exergy systems as well as upgrading low/moderate temperature resources (Figure 23).

Figure 23. Low grade energy sources upgraded by the low exergy systems in MPC-GT. Source: MPC-GT.



Innovation(s)

Optimal integration of GEOTABS and secondary supply and emission systems. To allow for an optimal use of both the GEOTABS and the secondary system, a split will be made between a so-called “base load” that will be provided by the GEOTABS and the remaining energy needs that should be supplied by the secondary system. The second part of the proposed solution aims at developing a Model Predictive Control (MPC) system with precomputed model inputs such as disturbances and thermal power for heating, ventilation and air conditioning to avoid case by case development.

TRL 7 will be achieved within the project. The project outcomes will be tested on real buildings, under real conditions and it will be implemented such that it can be used in a similar way for other instances.

Impact/expected impact

The project aims at improving the overall efficiency of thermally activated building systems to by up to 25%. The solution will support mainly SMEs and help them strengthen their competitiveness.

[36] https://cordis.europa.eu/project/id/723649

4.10.2. TEMPO – TEMPerature Optimisation for Low Temperature District Heating across Europe

Description

Duration: October 2017 – September 2021

EU contribution: € 3 130 868

The main objectives of TEMPO[37] are the development of technological innovations for low-temperature (LT) DH networks for increased network efficiency and integration options for renewable and residual heat sources, through demonstration in three different sites. The project aims to empower the end users of a LT DH network and develop innovative business models, showing their replication potential for the roll-out of sustainable and economically viable DH networks across the EU. This would be supported by developing an exploitation and replication plan.

Innovation(s)

Expected technological innovations include for example a supervision ICT platform for detection and diagnosis of faults in DH substations; visualisation tools for expert and non-expert users; smart DH network controller to balance supply and demand and minimise return temperature (i.e. STORM controller); an innovative piping system; optimisation of the building installation and decentralised buffers at the consumer side.

Six innovations related to networks, digitisation thereof and building optimisation undergo final development and will reach TRL 7-8.

Impact/expected impact

The demonstration sites include a new urban LT network (Vattenfall), a new rural LT network (Enerpipe) and existing network (A2A), currently operating at a very high supply temperature (Euroheat & Power). In addition, each solution package will be coupled to a business model allowing cost savings.

4.10.3. GeoCollector – Geothermal energy for cost-effective and sustainable heating and cooling

Description

Duration: July 2017 – June 2019

EU contribution: € 2 089 675

The GeoCollector project[38] moved from the consideration that the near-surface geothermal energy offers good prospects for big energy savings and the reduction of greenhouse emissions, and also ensures an ideal room climate in summer and winter within buildings. Due to the complex installation, connection and function, however, existing system solutions (especially in the near-surface geothermal energy) could not establish at the market yet. Another unsolved problem is the large space requirement of the heat source system and the unfavorable cost/benefit relation. Based on this, the objective of the project was to develop an innovative geothermal heat absorber system called "GeoCollector", aiming to reduce the cost and complexity of installation and connection of near-surface geothermal energy systems as well as reducing the large space requirement of the heat source system.

Innovation(s)

The project output was the ability to produce the current Prototype GeoCollectors (TRL 6/7) with:

- low installation effort
- low investment costs
- high surface extraction rate of heat from the ground
- low land use.

[37] https://cordis.europa.eu/project/id/768936
[38] https://cordis.europa.eu/project/id/768292

Impact/expected impact

The project resulted in increased benefits and uptake by companies fitting the housing sector, industrial companies, public institutions and private owners of houses and properties.

At the end of the first year, the second version of the product/system named GC3 was developed. Its partially automatised production process was tested with single/small batches. The sales process was further developed included a design tool for users/resellers.

The second part of the project dealt mainly with the realisation of the packaging concept, with the demonstration and optimisation of the product/system as well as with an intensified sales activity outside Germany (the country where the two partners of the consortium were located).

The project fully achieved it objectives and milestones.

4.10.4. FLEXYNETS - Fifth generation, Low temperature, high EXergY district heating and cooling NETworkS

Description

Duration: July 2015 – December 2018

EU contribution: € 1 999 364

District heating networks at typically high operating temperatures (about 90 °C) suffer from significant heat losses and the integration potential of different available energy sources remains unexplored. FLEXYNETS[39] tackles these problems by focusing on the development of DHC networks working at "neutral" (15-20 °C) temperatures, strongly reducing heat losses.

Reversible heat pumps were used to exchange heat with the DHC network on the demand side, providing the necessary cooling and heating for buildings.

Thanks to the low operating temperature, it will be possible to directly absorb waste heat from usually unexploited sources, like, e.g., supermarket chillers or data centres. Even the heat rejected for building cooling during summer will be fed into the network and recycled for the production of domestic hot water. As well as being a new option for cities, the solution is also relevant to traditional networks as low temperature networks could be partly supplied by the return pipes of traditional networks. This would allow traditional utilities to sell additional energy with the same infrastructure and with higher generation efficiency, due to the lower return temperature to the supply station.

Innovation(s)

The project advanced TRL level of various components of the system from TRL 4-5 to TRL 5-6.

Impact/expected impact

It is hoped that the project can contribute to strongly reduce the final energy consumption for space heating and cooling and water heating. The low adopted temperatures could allow the use of cheaper network pipes, thereby possibly compensating the additional investment costs for the introduction of heat pumps.

Finally, energy savings would correspond to lower energy bills for users. In addition, FLEXYNETS could create profit opportunities on a new heating and cooling market, transforming users into prosumers. This could be especially interesting for southern countries, where traditional DHC is less diffused and the FLEXYNETS reversibility would find a natural application.

[39] https://cordis.europa.eu/project/id/649820

5. Technology deployment outlook

The JRC-EU-TIMES model (JRC, 2013b) offers a tool for assessing the possible impact of technology and cost developments. It represents the energy system of the EU plus, Switzerland, Iceland and Norway[40], with each country constituting one region of the model. It simulates a series of nine consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050.

In the context of the LCEO project, the JRC-EU-TIMES model was run with three general storylines:

- *Baseline*: continuation of current trends; no ambitious carbon policy outside of Europe; only 48% CO_2 reduction by 2050 with respect to 1990;
- *Diversified*: usage of all known supply, efficiency and mitigation options (including CCS and new nuclear plants) to achieve 80% CO_2 reduction by 2050 with respect to 1990;
- *ProRES*: 80% CO_2 reduction by 2050 with respect to 1990; no new nuclear; no CCS.

Starting from the Diversified and ProRES scenarios, further 12 sensitivity scenarios were run (JRC, 2018c). In addition to the three main storylines described above, this report focuses on three scenarios of interest to geothermal chosen among those 12 sensitivity scenarios:

- *Diversified without CCS in the power sector*;
- *ProRES Near Zero Carbon*, achieving a 95% CO_2 reduction by 2050 with respect to 1990;
- *ProRES SET Plan targets*.

5.1. Deployment trends

Table 3 summarises the main results regarding geothermal energy in the EU in the six considered scenarios. It is useful to note that the installed power capacity in the EU is currently about 1 GW_e (almost entirely located in Italy), while the geothermal heat is assessed at 43 PJ in 2020 by JRC-EU-TIMES (it was 32 PJ in 2010).

Table 3. Scenarios and sensitivities of interest with regard to geothermal energy deployment

Scenario	CAPEX and FOM	Geothermal heat in 2050	Power production in 2050		Thermal use in district heating in 2050	
		(PJ)	(GW)	(PJ)	(GW)	(PJ)
Baseline	Reference learning	225	1.4	42	0	0
Diversified		333	1.8	51	0	0
ProRES		2 357	9.8	279	0	0
Diversified without CCS in the power sector		1 912	8.1	239	3.9	25
ProRES Near Zero Carbon		1 816	4.2	61	180	1 134
ProRES SET Plan targets	SET Plan learning	3 876	16.5	450	17.2	109

Source: JRC-EU-TIMES (JRC, 2018c)

[40] The EU still includes the United Kingdom because the scenarios, as well as the whole analysis presented in this report, refer to the period before the UK withdrawal from the EU.

For geothermal energy, the specific inputs include CAPEX and fixed operating and maintenance (FOM) cost trends, together with learning rate values for four geothermal deployment options: new hydrothermal with flash, new hydrothermal with ORC, enhanced geothermal dedicated power and enhanced geothermal dedicated heat. Each country has a sustainable potential based on heat in place. The sustainable potential in the EU was assumed to be 5 171 PJ for total heat.

Using sustainable potential as a limiting factor in the model results in a much lower production than other models that use only technical or economic potential, yet geothermal energy still represents a significant contribution to the energy mix. The sustainability of production could further be improved with the development of hybrid power plants, i.e. using combinations of geothermal and other renewable energy sources to increase the efficiency of power generation. Also, it is important to note that the model assumes that EGS technologies will be proven under various geological conditions and therefore usable in most EU countries. Without EGS, the sustainable potential would be significantly reduced by 90%.

5.2. Deployment under each scenario

Additional insights on the different scenarios are presented in the following. More details can be found in JRC, 2018c.

Figure 24 describes the allocation of the different types of geothermal technology (existing plant, hydrothermal flash, hydrothermal ORC, EGS with ORC) in the electricity mix, showing that EGS becomes the dominant technology in most scenarios by 2050 with the exception of the Diversified scenario (geothermal with EGS is not deployed when power can be produced with CCS technology).

Figure 25 reports the progress over time of the relevant CAPEX trends for geothermal power plants. Although the scenarios are six, only four trends are shown (Baseline, Diversified, ProRES, all with reference learning, and ProRES with SET Plan learning), as the "Diversified without CCS in the power sector" and the "ProRES Near Zero Carbon" scenarios have the same patterns as the two main Diversified and ProRES scenarios. Among the SET Plan DOI targets (see introduction to Section 4), points 2 and 5, i.e. conversion efficiency and drilling costs, have the largest impact on CAPEX.

5.2.1. Baseline

In the Baseline scenario, no marked increase in geothermal power is envisioned in the next decades, while a moderate expansion of geothermal heat does take place.

5.2.2. Diversified

In the Diversified scenario, only a small portion of the sustainable potential is utilised due to the competition with power production with CCS.

5.2.3. ProRES

In the ProRES scenario, just under half of the sustainable potential of geothermal energy is utilised solely for electricity production. The absence of learning does not allow cost reductions to the same extent as in the ProRES SET Plan target, meaning that it cannot compete in certain countries.

5.2.4. Diversified without CCS in the power sector

In the diversified scenario without CO_2 capture in the power sector, geothermal utilisation is also substantial at 1912 PJ. Due to the lack of power production with CCS, the total installed capacity of geothermal amounts to 8 GW_e in 2050. Similar to the ProRES scenario, in some countries geothermal cannot compete with solar and wind.

5.2.5. ProRES Near Zero Carbon

In the ProRES Near Zero Carbon scenario, a substantial share of the geothermal heat potential is used for district heating (around 20%).

5.2.6. ProRES SET Plan targets

Geothermal plays a role in all scenarios, but its most significant role is in the ProRES SET-Plan targets scenario, where use of geothermal heat for electricity and other applications reaches 3876 PJ in 2050, which is 75% of the full sustainable potential. This represents 6% of total EU gross energy consumption and 1.5% of the EU electricity production. The model does not currently take into account the possibility of combined use of heat and power from geothermal power plants.

The strong increase of geothermal is mainly driven by the foreseen cost reductions from SET-Plan learning, bringing the CAPEX of EGS to below 6 000 €/kW$_e$, compared to around 9-10 000 €/kW$_e$ in the other scenarios (see Figure 25). Under this scenario, JRC-EU-TIMES depicts a total installed capacity of 16.5 GW$_e$ for geothermal (mainly from EGS with ORC).

Figure 24. Breakdown of the geothermal power plant categories in 2050. Source: JRC analysis

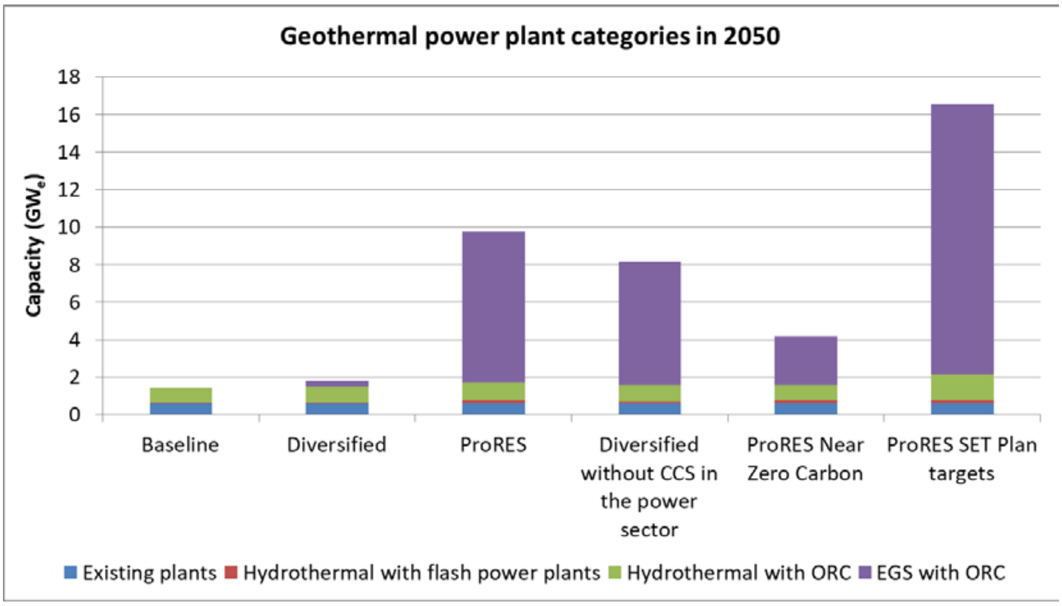
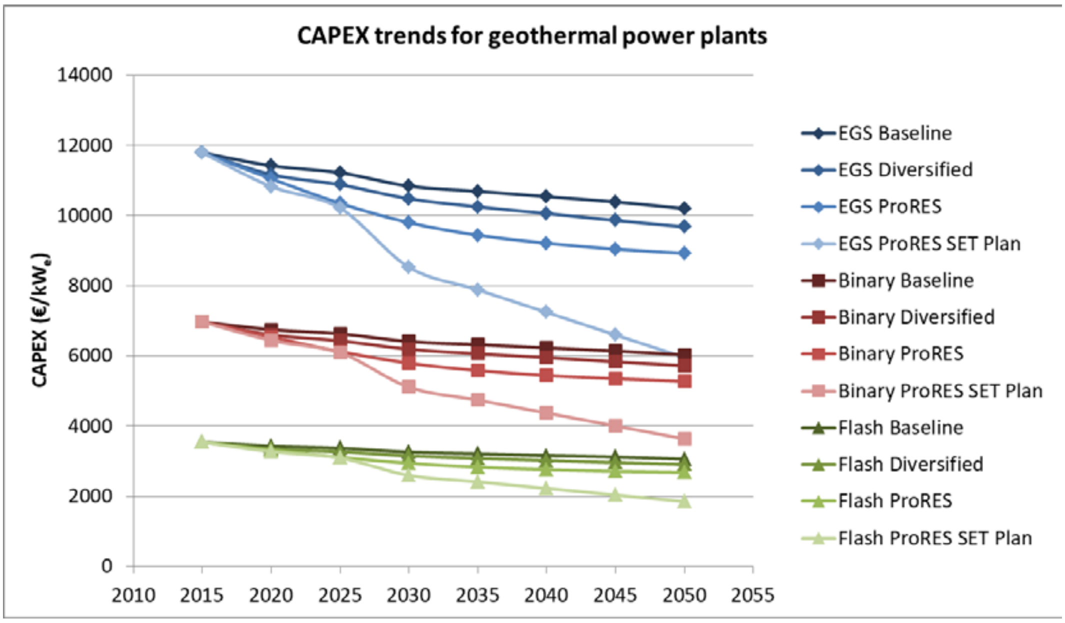


Figure 25. CAPEX trends for geothermal power plants. Source: JRC analysis



6. Conclusions and recommendations

6.1. Summary

Geothermal energy has significant untapped potential for both electrical and direct-use applications in the EU. Currently, 'traditional' hydrothermal applications are most common for electricity production, but if EGS technology is proven the technical potential increases significantly.

The technologies for hydrothermal applications, direct use (including GSHP) can be considered mature. R&D in those areas is needed to further lower the costs by e.g. developments in new materials, drilling techniques, higher efficiency, optimisation of maintenance and operation. The use of unconventional geothermal (EGS) is only now moving its first steps in the demonstration phase (see e.g. the promising results of the DEEPEGS project), thus R&D support in various areas (deep drilling, reservoir creation and enhancement, seismicity prediction and control) is still highly needed.

The Implementation Plan of the SET Plan Temporary Working Group describes the current level of market or technical readiness of specific research areas in geothermal. The areas with the lowest TRL relate to the enhancement of reservoirs (4); advanced drilling (5); equipment and materials to improve operational availability (4-5); integration of geothermal heat and power into the energy system (4-5).

More funding has been allocated to geothermal energy during H2020 than any previous funding programme. Although the timeframe of this report (which covers until the end of 2019) precludes a full assessment of the impact of H2020 projects, as a number of projects are still at an early stage of execution, a preliminary analysis on the completed projects highlights a general achievement of the objectives.

On the other hand, analysing the distribution of the funding allocated up to now, it can be pointed out that the areas relating to 'Equipment / Materials and methods and equipment to improve operational availability', 'Improvement of performance' and 'Exploration techniques' may need additional attention. In addition, non-technical barriers are still important but extend beyond the issue of public acceptance.

Past and current EU-funded projects have been and are advancing the state-of-the art, mainly for exploration (drilling), new materials/tools and the enhancement of reservoirs. Projects have also helped to address non-technical issues such as (financial) risk assessment and mitigation, public acceptance, training.

Patenting trends highlight that over the last decade the European Union progressively lost the role as leader that it had gained around 2007-2008, being replaced by the Far-East countries, i.e. China, Republic of Korea, and Japan, which now clearly dominate the innovation sector.

6.2. Recommendations

6.2.1. Technical barriers

The technical barriers to the uptake of geothermal energy are reflected in the SET Plan priority areas. The urgency of each of these research areas may need to be clarified in the near future, since there appears to be some disparity between the attention given to each area although their relative importance is not clear.

Research areas that have received the most attention (in financial terms) under H2020 relate to drilling, EGS and district heating systems. The research areas 'Geothermal heat in urban areas' has already reached higher level of technological readiness, therefore progress should be reassessed in the near future. The areas 'Enhancement of reservoirs' (TRL 4) and 'Advanced drilling techniques' (TRL 3-5) are in greater need of support given their low TRLs. The research area 'Equipment / Materials and methods and equipment to improve operational availability' requires a significant jump to a higher TRL. Yet, this research area has not received much funding under H2020. The research areas 'Improvement of performance' and 'Exploration techniques' may require a more targeted focus in the future, since they are not specifically covered by particular projects at present.

It is difficult to assign levels of importance to each research area. The areas that are most urgently in need for funding should be identified to better focus the support. It should also be assessed whether cross-cutting issues which were highly funded in previous frameworks are still in need of similar funding now or in the future.

To complete this analysis, it is worth discussing two important aspects addressed by relevant initiatives of the European Commission, i.e. circularity and materials.

The recent report on EU Taxonomy produced by the EU Technical Expert Group (TEG) on Sustainable Finance (TEG, 2020) has identified geothermal energy (both in the power and heat/cooling sectors) as a relevant environmental contributor in the fields of climate change mitigation, climate change adaptation, water, pollution and ecosystems, but not for the circular economy. Thus, relevant strategies should be conceived to tackle this issue.

The European Commission has recently announced an Action Plan on Critical Raw Materials (European Commission, 2020). In this perspective, it should be noted that critical raw materials are not a major issue for the geothermal sector. The two main raw materials of the supply chain are concrete and steel. Concrete is used in the casing of boreholes. Steel is adopted to manufacture power turbines and the pipes used to carry the geothermal brine to the surface or to distribute the hot water in the district heating network. Plastics for pipes and aluminium in plant construction are also relevant materials. On the other hand, projects exist (see e.g. CHPM2030) that explore the possibility of extracting minerals from the geothermal brine.

6.2.2. Non-technical barriers

Targeted research should be designed to effectively overcome non-technical barriers. Although funding was allocated to these areas prior to H2020, the most important remaining non-technical barriers still need to be overcome to ensure the uptake of geothermal energy.

Public acceptance is indeed a barrier, but further barriers have been identified (Dumas et al., 2018). These relate to the factors that need to be addressed in any regulatory system for geothermal energy, i.e. legal and financial aspects as well as other supporting measures such as education, training and standards. A clear definition of geothermal energy and the ownership of geothermal resources is required to ensure appropriate regulations are adopted. Administrative procedures for geothermal licensing need to be streamlined. In order to reduce up-front costs and gain public acceptance, geothermal energy needs financial incentives similar to those received by other renewable energy sources in order to reduce the high risk associated with geothermal projects in the initial stages (EGEC, 2013).

Furthermore, there is a shortage of geothermal engineers and trainers in the geothermal industry (IRENA, 2017; JRC, 2018b). There are also skills shortages in non-technical jobs such as accounting and finance staff, surveyors, auditors, and lawyers. These skill gaps must be addressed if geothermal energy is to be successfully expanded in the future.

Public acceptance has long been a major barrier to all renewable energy projects, due to a generally limited knowledge and understanding of geothermal energy among the general public (Vargas Payera, 2018). Public acceptance is also a 'Catch 22' situation: if geothermal energy applications (in particular EGS) are not effectively demonstrated and shown to be free from hazards such as seismicity, then public acceptance will be more difficult to obtain. At the same time, adding new technical requirements, for instance for environmental impact and seismicity assessments, increases the challenges for technology development.

However, if public acceptance is not gained from the outset, then projects cannot begin. Approaches such as risk communication may improve the situation (Vargas Payera, 2018), however, in many cases, it is the process of energy policy making which simply fails to take account of the concerns of citizens, hence creating a lack of trust and increasing the likelihood of opposition (Sovacool and Dworkin, 2015). There is need for methods to ensure that the ethical concerns of citizens regarding energy projects are taken into account, whilst at the same time providing transparent information and education on the projects. More research in this area would be beneficial, as well as in relation to improved communication and promotion of geothermal applications in the EU. Using successful community projects such as the Heerlen energy project in the Netherlands (Verhoeven et al., 2014) may help to showcase the community benefits that can be enjoyed from the use of geothermal energy (and other) sources.

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List of abbreviations

ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CHPM	Combined Heat, Power, and Metal
COP	Coefficient of Performance
CPC	Cooperative Patent Classification
DAC	Direct Air Capture
DHC	District Heating Cooling
DOI	Declaration of Intents
EGS	Engineered/Enhanced Geothermal System
GCHP	Ground Coupled Heat Pump
GSHP	Ground Source Heat Pump
H2020	Horizon 2020 Programme
HSA	Hot Sedimentary Aquifer
LCOE	Levelised Cost of Energy
LT	Low Temperature
MPC	Model Predictive Control
MRL	Manufacturing Readiness Level
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
RJD	Radial water Jet Drilling
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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Annex

Annex 1. List of EU-funded projects per SET Plan R&I category 2004-2019

Frame work	**Acronym**	**Start Date**	**SET Plan category**								
			Geothermal heat in urban areas	Materials, methods and equipment	Enhancement of reservoirs	Improvement of performance	Exploration techniques	Advanced drilling / well completion techniques	Integration of geothermal heat and power in the energy system	Zero emissions power plants	Cross-cutting / non-technical issues
FP6	EGS PILOT PLANT	01/04/2004			X	X					
FP6	GROUNDHIT	01/06/2004	X								
IEE	K4RES-H	01/01/2005									X
IEE	OPTRES	01/01/2005									
FP6	ENGINE	01/11/2005			X						X
FP6	I-GET	01/11/2005					X				
FP6	ATOMIC TO GLOBAL	01/01/2006					X				
IEE	GROUNDREACH	01/01/2006	X								X
FP6	LOW-BIN	01/03/2006				X					
FP6	RESTMAC	01/06/2006									X
IEE	GTR-H	01/11/2006									X
FP6	ASAP	01/12/2006					X				
IEE	PROHEATPUMP	01/12/2006	X								X
FP6	HITI	01/01/2007		X							
FP6	FUTURE ENERGY	19/03/2007									X
FP6	TERRA THERMA	15/12/2007	X								
FP7	CLUSTHERM	01/05/2008									X
IEE	GEOFAR	01/09/2008									X
IEE	GEOTRAINET	01/09/2008									X

Frame work	Acronym	Start Date	SET Plan category								
FP7	AEGOS	01/12/2008					X				X
FP7	GROUND-MED	01/01/2009	X								
IEE	ECOHEAT4EU	01/06/2009	X								X
IEE	QUALICERT	01/07/2009									X
FP7	GEISER	01/01/2010			X		X				X
FP7	GEOCOM	01/01/2010	X			X					X
IEE	INSTALL+RES	01/05/2010									X
FP7	ECO-GHP	01/06/2010	X								
IEE	ECOHEAT4CITIES	26/06/2010									X
FP7	CAPWA	01/09/2010				X					
FP7	ThermoMap	01/09/2010									
FP7	E-HUB	01/12/2010					X		X		
FP7	SECRHC-PLATFORM	01/01/2011									X
IEE	GEOELEC	01/06/2011					X				X
FP7	EFFIHEAT	01/10/2011	X								
NER 300	South Hungarian EGS Demon.	01/01/2012			X		X	X			
FP7	CREEP	01/02/2012	X								
IEE	GEODH	01/04/2012	X				X				X
IEE	REPOWERMAP	01/04/2012									X
IEE	REGEOCITIES	01/05/2012									X
FP7	HYSM	14/05/2012			X						
FP7	MINSC	01/06/2012		X		X					
FP7	NXTHPG	01/12/2012	X								
FP7	SINGULAR	01/12/2012	X						X		
FP7	FLUIDEQ	01/08/2013		X							
FP7	IMAGE	01/11/2013		X			X				
NER 300	GEOSTRAS	01/01/2014			X	X		X			

Frame work	Acronym	Start Date	SET Plan category								
NER 300	GEOTHERMAE	01/01/2014			X	X					
FP7	GREAT	01/01/2014			X					X	X
FP7	NSHOCK	01/03/2014				X					
FP7	EFFIHEAT-DEMO	01/04/2014									
IEE	STRATEGO	01/04/2014									
H2020	DeReco	01/10/2014				X					
H2020	GEO PAC RET	01/10/2014	X								
H2020	GEAGAM	01/01/2015					X				
H2020	OPTi	01/03/2015	X						X		
H2020	STORM	01/03/2015	X						X		
H2020	DESCRAMBLE	01/05/2015				X	X	X			
H2020	GEOTeCH	01/05/2015	X								
H2020	Cheap-GSHPs	01/06/2015	X								
H2020	FLEXYNETS	01/07/2015	X						X		
H2020	ThermoDrill	01/09/2015						X			
H2020	Tesse2b	01/10/2015	X						X		
H2020	TERRE	01/10/2015									X
H2020	DEEPEGS	01/12/2015			X		X	X			
H2020	MIGRATE	01/01/2016	X		X		X				
H2020	CHPM2030	01/01/2016		X	X	X	X				
H2020	GeoWell	01/02/2016		X				X			
H2020	SURE	01/03/2016			X			X			
H2020	DESTRESS	01/03/2016			X		X				
H2020	MPC-. GT	01/09/2016	X			X					
H2020	ITHERLAB	01/10/2016		X			X				
H2020	GEMex	01/10/2016			X		X	X			X
H2020	ENIGMA	01/01/2017					X				X
H2020	GEOTHERMICA	01/01/2017		X			X	X	X		X

Frame work	Acronym	Start Date	SET Plan category								
H2020	Large enHANCEMENT	01/01/2017	X								
H2020	GeoElectricMixing	01/04/2017		X	X					X	
H2020	GEOCOND	01/05/2017	X	X		X					
H2020	DG ETIP	01/07/2017									X
H2020	GeoCollector	01/07/2017	X								
H2020	TEMPO	01/10/2017	X			X					X
H2020	BigMac	01/11/2017			X						
H2020	EUROVOLC	01/02/2018									X
H2020	Geo-Coat	01/02/2018		X							
H2020	MATHROCKS	01/04/2018	X		X		X				
H2020	GEO4CIVHIC	01/04/2018	X								
H2020	GeoFit	01/05/2018	X								
H2020	MEET	01/05/2018			X		X				
H2020	GECO	01/10/2018								X	
H2020	GeoTwinn	01/10/2018									X
H2020	ENeRAG	01/10/2018									X
H2020	GEORISK	01/10/2018									X
H2020	NERUDA	01/11/2018		X			X				
H2020	GEOENVI	01/11/2018									X
H2020	SU-DG-IWG	01/02/2019									X
H2020	GEoREST	01/02/2019					X				
H2020	Geo-Drill	01/04/2019		X				X			
H2020	GeoSmart	01/06/2019							X		
H2020	CROWDTHERMAL	01/09/2019									X
H2020	GEOPRO	01/11/2019		X							
H2020	GeoHex	01/11/2019		X							

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