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LOW CARBON ENERGY OBSERVATORY

GEOTHERMAL ENERGY

Technology development report

Joint Research Centre

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ACRONYMS AND ABBREVIATIONS

ATES	Aquifer Thermal Energy Storage
CAP	Long-term decarbonisation scenario
CAPEX	Capital Expenditure
CF	Capacity Factor
COP	Coefficient of Performance
CPI	Current Policy Initiative
EC	European Commission
EGS	Engineered/Enhanced Geothermal System
EU	European Union
FP6	6^{th} Framework Programme
FP7	7^{th} Framework Programme
GSHP	Ground Source Heat Pump
H2020	Horizon 2020 Programme
HSA	Hot Sedimentary Aquifer
IEE	Intelligent Energy Europe
IPA	Instrument for Pre-accession assistance
IPC	International Patent Classification
LCOE	Levelised Cost of Energy
MRL	Manufacturing Readiness Level
MS	Member State
MT	Magnetotelluric
NREAP	National Renewable Energy Action Plan
OPEX	Operating Expenditure
ORC	Organic Rankine Cycle
Rb	Thermal Resistance
SME	Small-medium Enterprise
SPF	Seasonal Performance Factor
TRL	Technology Readiness Level
UTES	Underground Thermal Energy Storage

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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 2018, 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 base-load or flexible energy production, or for both heat and power generation combined. 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 EGS); direct use (district heating and other use); and shallow geothermal energy (GSHP, UTES/ATES). Previous reports also include in-depth descriptions of the various technologies and their design [JRC 2015a, JRC 2015b].

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 underlaying 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 power production and the heat in place is therefore often translated to economic potential using levelised cost of energy (LCOE).[1] Traditional geothermal systems

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

currently extract energy up to 3-4 km. Enhanced geothermal (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 MS is 11 TWh according to their National Renewable Energy action plan (NREAP) for 2020. The current economic potential however, is 21.2 TWh assuming a LCOE value less than 150 EUR/MWh [Miranda-Barbosa et al. 2017] which is considerably higher than the NREAP planned production.

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

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 stage flashing, 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 re-injection.

Combined-cycle flash steam plants use the heat from the separated geothermal brine in binary plants (described in next section) to produce additional power before re-injection. 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 and producing heat.

[2] using LCOE of EUR 100/MWh [JRC 2015b]

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 (EGS - also known as Engineered Geothermal Systems) have been 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.

HSA have more widespread occurrence than hydrothermal reservoirs.

In both HSA and petrothermal EGS, 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 re-injected to start another cycle.

In petrothermal systems, fluid is injected into the subsurface under carefully controlled conditions, which cause pre-existing fractures to re-open, 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 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 & Boyd 2015]. 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, for instance, greenhouses heating, followed by aquaculture applications, etc.

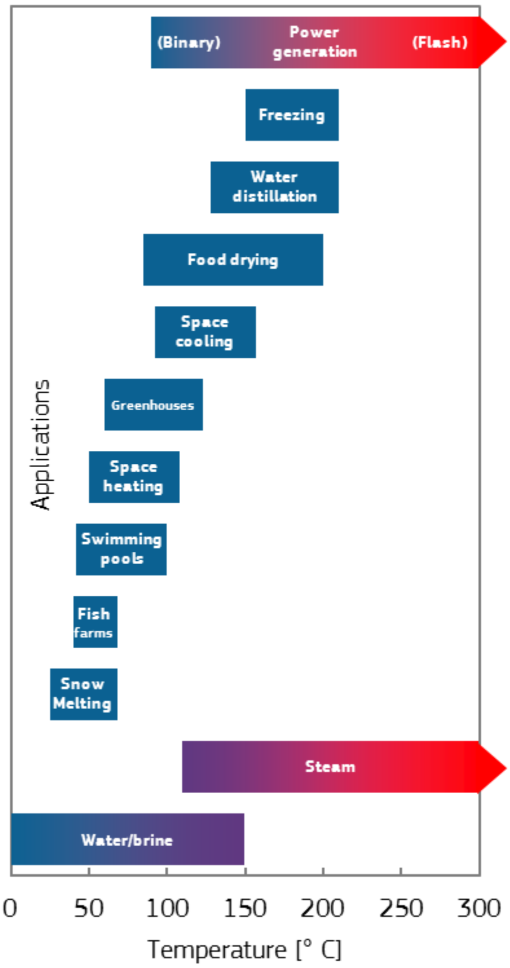

Figure 1 A Lindal diagram of temperature of geothermal water and steam suitable for various applications

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 2018].

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 DHs can vary in size (whole cities to small villages or areas).

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 (GSHP)
- Underground Thermal Energy Storage (UTES)

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 kWth to over 500 KWth. 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) [Vellei 2014, Fischer & 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 [Geotherm. Energy 2011, Puttagunta & Shapiro 2012, Carlsson et al. 2013].

The depths of geothermal heat exchange range from a few meters to more than 200 m, depending upon technology used, geological situation, demand profile, and other design considerations. For space cooling, in certain regions with moderate climate, direct cooling from the ground via cooling ceilings etc. is possible, 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 [RHC 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 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 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[3] as a storage medium. Deeper systems typically utilize 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 in press).

Closed loop BTES (borehole thermal energy storage) 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

[3] Aquifers composed of unconsolidated materials, such as silt or clay, sand or gravel.

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 (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 the work consist of the EU Corda 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 [ETRI 2014, 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, it can be said that the technologies used for traditional hydrothermal geothermal plants and direct uses are mature (TRL 9), with some room for improvement remaining. However, challenges remain for technologies like EGS, which uses many of the same components but has yet to be demonstrated to a high enough 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 (e.g. in drilling at greater depth) need to be made which mitigate the high costs and risks for EGS.

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 1shows the starting TRL levels 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: [SET-Plan TWG 2018], adapted

2.2 Indicators

Relevant indicators to monitor the development of geothermal energy technologies are cost, conversion efficiency, GHG emissions, reservoir performance. They will be presented below in more detail.

2.2.1 Costs

According to a recent IRENA report, geothermal in 2017 largely fell within the range of generation costs for fossil-based electricity. For new geothermal projects, the global weighted average LCOE was around USD 0.07/kWh [International Renewable Energy Agency 2018].

A study by Bloomberg Finance shows geothermal LCOEs to be relatively stable over the 5 year 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. CAPEX has been estimated based on the international literature as EUR 3 540 for flash plants, EUR 6 970 for ORC binary plants and EUR 11 790 for EGS plants [JRC 2018a]. Operating costs are in the range of 1.6-2.2 % of CAPEX.

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_{el} for electricity and 5 €ct/kWh_{th} for heat by 2025.

SET Plan group recommendations: 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. In order to improve equipment reliability and to increase the plant utilization factor, improved materials, methods and equipment such as pumps and heat exchangers will need to be developed.

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 & 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 & 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 utilization has been proposed to be 'sustainable' [Sanyal 2005, Rybach & 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, i.e. up to 300 years. Plants with this type of utilization tend to extract heat around 10 times the natural 'renewable' recharge rate– i.e. that rate of replenishment that occurs due to natural heat flow.

Some power plants however, 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 prolonging the economic life of a given reservoir [Rybach & Mongillo 2006]. Further studies are required to determine the natural recovery of a broad variety geothermal systems and extraction strategies after economic abandonment [Pritchett 1998, 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.

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 for geothermal power plants, less than 80 g/kWhe for projected EGS, and between 14 and 202 g/kWhth for district heating systems and GSHPs (IPCC, 2011). More recently, the World Bank estimated a range of 2 - 20 g CO_2e/kWh for plant cycle emissions for geothermal projects, assuming a project lifetime of 30 years [ESMAP 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 compared to 5-100 g CO_2/kWh 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 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 a lack of support for future projects.

SET Plan group recommendations: To address environmental and social concerns that pose barriers to geothermal energy, public concerns and perceptions of geothermal installations must be addressed. 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

This analysis included FP5, FP6, FP7 and H2020 projects as well as Intelligent Energy Europe (IEE), ERA-NETs, and NER 300 projects [Sigfusson & Uihlein 2016]. As can be observed from Figure 2, the EU funding received in 2017 from H2020 was less in 2017 compared to recent years. The projects with the largest number of participants were GEMex (24) and GEOTHERMICA (18). More R&D funding has been allocated to geothermal energy during H2020 than in any other previous funding programme, however, in 2017, EU contributions were significantly reduced compared to recent years.

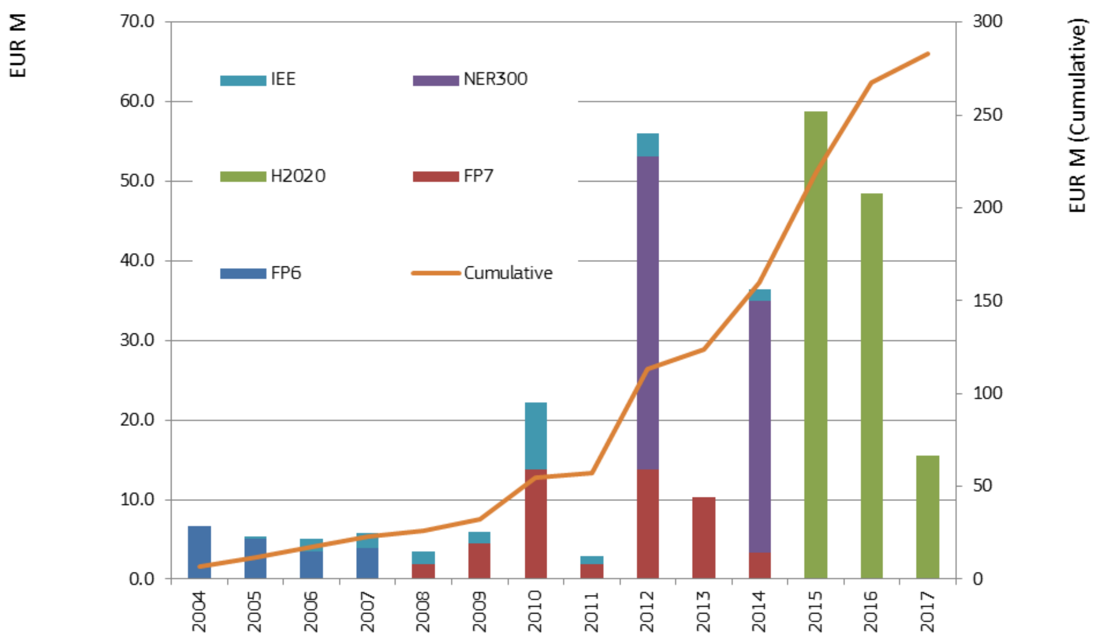

Figure 2 EU contribution to co-funded projects since 2004. Source: CORDIS / JRC own analysis

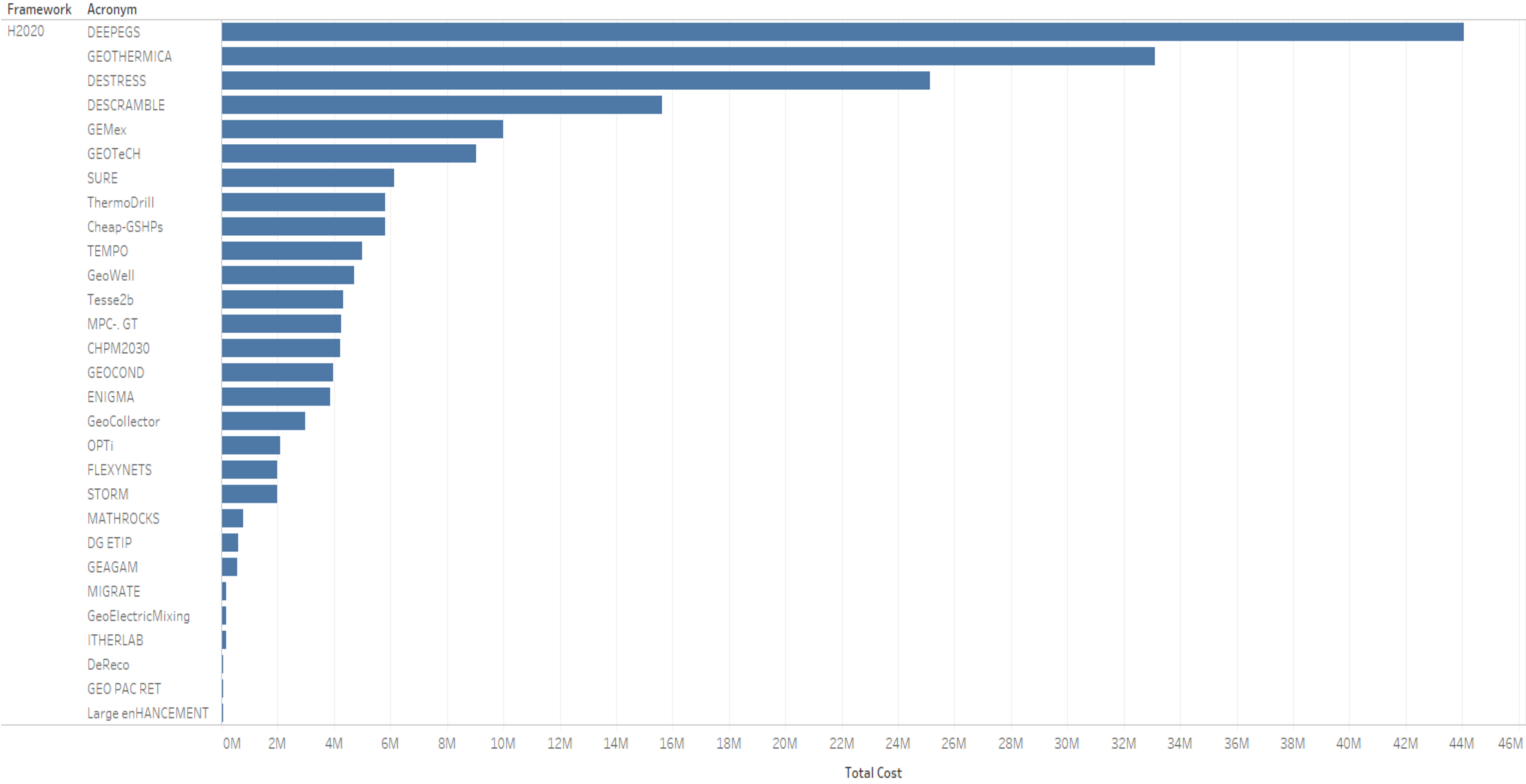

Figure 3: Total cost of H2020 geothermal-related projects

The project with the highest total costs (Figure 3) is DEEPEGS (EUR 44 million). GEOTHERMICA, a funding programme received EUR 33 million and will be used to fund smaller projects. Average participation per project is shown in Figure 4. The total cost of projects was greatest under H2020 compared to other frameworks (Figure 5).

The most expensive projects under H2020 are related to drilling, EGS, network creation and district heating systems.

Historically, projects related to EGS have been the highest funded.

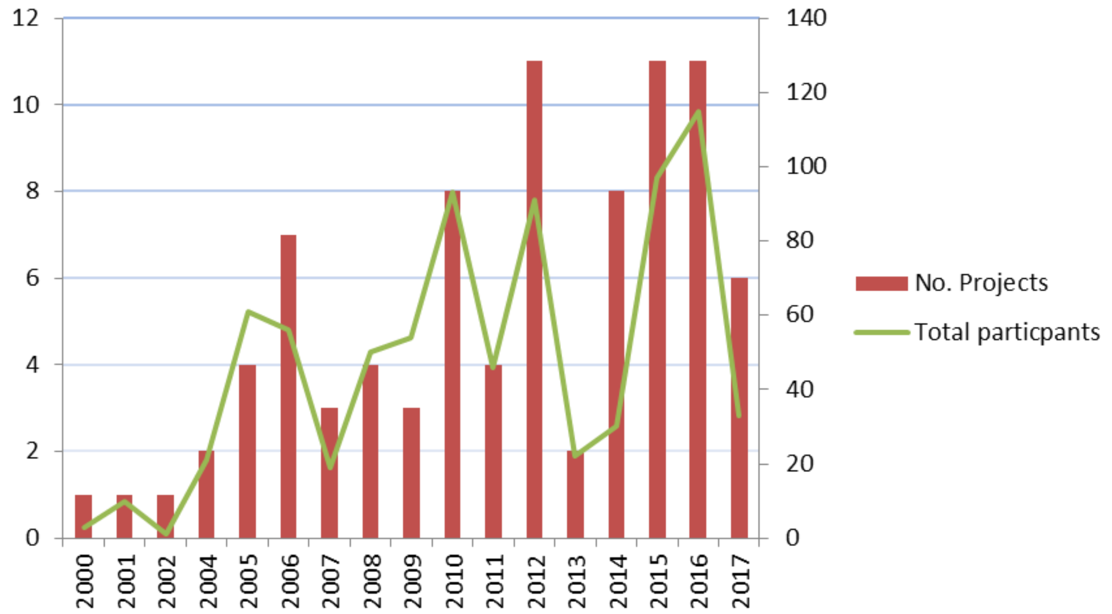

Figure 4: Number of EU funded geothermal related projects per year with average number of participants. Source CORDA / JRC

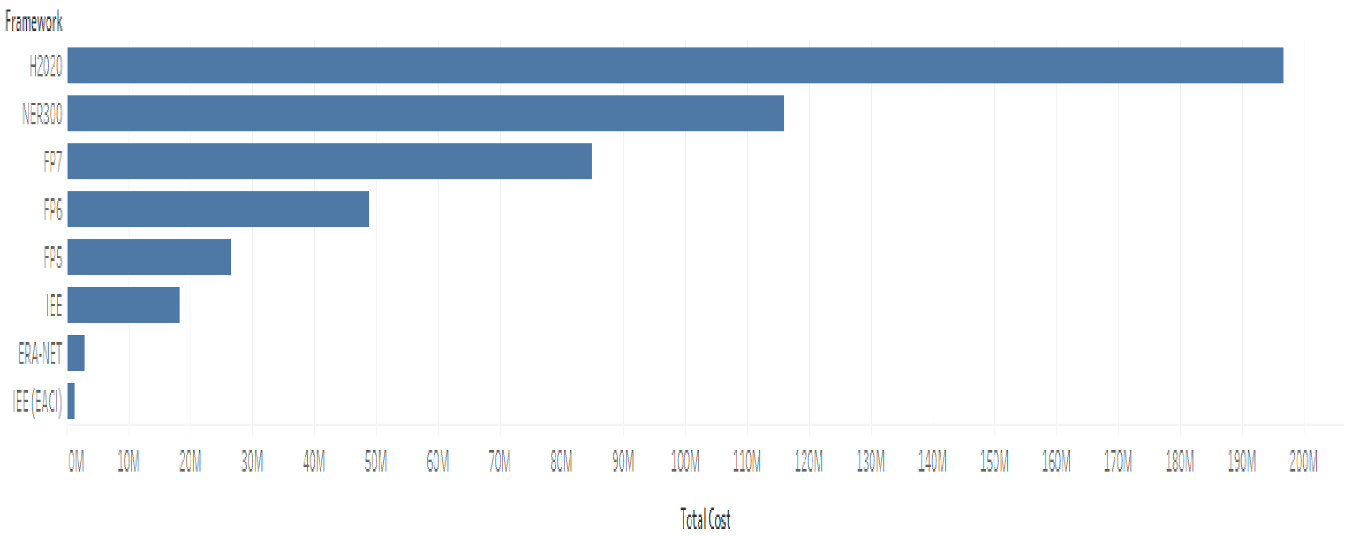

Figure 5: Total cost of projects per funding programme

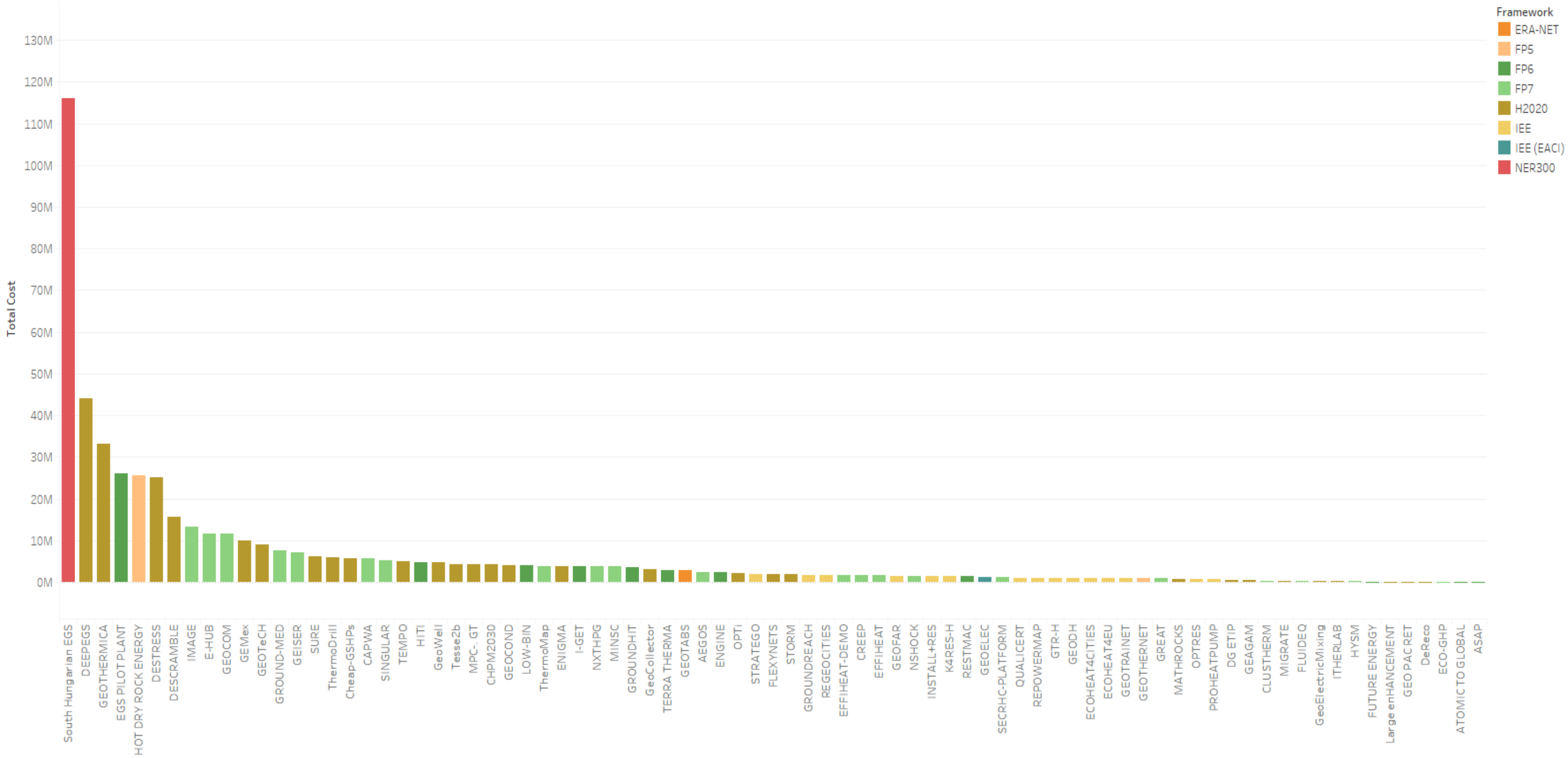

Figure 6: Project total cost of EU-funded projects relating to geothermal energy 2000-2017
Note: projects for which total cost was unavailable were not included. Source eCORDA

3.2 Flagship areas of the SET-Plan

The SET-Plan working group for deep geothermal energy have identified a number 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 5 (Impact Assessment). Relevant projects not under H2020, in the above four categories, are described in this section.

3.2.1 Geothermal heat in urban areas

AAT GEOTHERMAE

A Croatian company, with co-funding from the NER300 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 1800 to 2300 meters and utilising binary-cycle geothermal power plant technology[4].

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 Organic Rankine Cycle turbine (geothermal electricity output min. 3.1 MWe) in a closed loop process (gross energy output of 18.6 MWe). 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 geothermal 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 MWe and 60-70 MWth and the power plant will enter into operation in 2021.

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 EUR 11 million project was to implement pilot-scale demonstration of the geothermal energy utilisation on the 3 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

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

integration; (2) and also on the socio-economic aspects of the current and future investments.

A district heating system was installed in Morahalom (population of about 5800) 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 (DHW) 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 1590 t of CO_2, 585 kg of NO_x and 1113 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 recued by about 23 % on average. CO_2 emissions were reduced by about 70 % [Marino & Pagani 2015]..

The city of Galanta (population of 16 500) is situated in the SW part of Slovak Republic. A district heating system of the two production wells (FGG-2 (drilled in 1982) and FGG-3 (in 1984)) - 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 DHW 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. This investment has triggered the erection of three new municipal housing units (total 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 1 250) is located in the Larderello Geothermal District in Tuscany. The GEOCOM activities involved the whole community delivering three distinct actions: 1) Building a brand new and highly efficient district heating system to utilize high enthalpy geothermal steam from the Montieri-4 well; 2) Retrofitting a number of selected public buildings and 3) deploying 8.5 kW 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 2015b]. Certain projects of interest to this category are detailed here below.

Soultz EGS Demonstration Site

The EGS project at Soultz-sous-Forets 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 MWe 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.

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), heat (810 GWh) 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 mid-2020.

South Hungarian EGS

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[5]. The project will develop an Enhanced Geothermal System (EGS) reservoir in a high compressional stress field in crystalline rocks and build a geothermal power plant to produce 8.9 MWe (net) of electric power utilizing a total production flow rate of 280 kg/s with inlet temperature of 170 °C and 90 °C outlet temperature The EGS resource will be developed by drilling approximately 10 wells 3 000 - 3 500 m depth intervals. For multi-zone stimulation AltaRock's TZIM Technology will be used [Ádám & Cladouhos 2016]. The plant will use ORC (Organic Rankine Cycle) technology and is expeted to enter into operation at the end of 2019.

[5] https://setis.ec.europa.eu/NER300

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

Minewater 2.0

The region of Parkstad Limburg, 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 (Verhoeven R. e., 2013) 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 polygeneration system using bio-CHP, 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 pressurized 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

CO_2 DISSOLVED

The objective of the CO_2-DISSOLVED project is to assess the technical-economic feasibility of a novel Carbon Capture and Storage 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 mineralization.

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 2018].

CARBFIX and CARBFIX2

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

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

CarbFix2, the successor of CarbFix under H2020, is described in Section 4.8.

3.3 Significant 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.[6]

Research priorities in each country very much depend on the available resources (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 2017]. 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:

- Improved performance of production technologies;
- Life-extension of projects;
- Development of new geothermal sensors, development of adapted geometries and innovative devices

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

- 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 2017 were:

- data collection;
- corrosion and scaling;
- advanced drilling technologies;
- machinery;
- district heating [IEA Geothermal 2018].

The priority goal of all projects is to lower costs to make geothermal energy economically viable. the following presents some major ongoing research projects.

GeotIS

The GeotIS project has prepared geological, geophysical and hydraulic data relevant for planning of geothermal direct use facilities in Germany. GeotIS can be accessed online. 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.

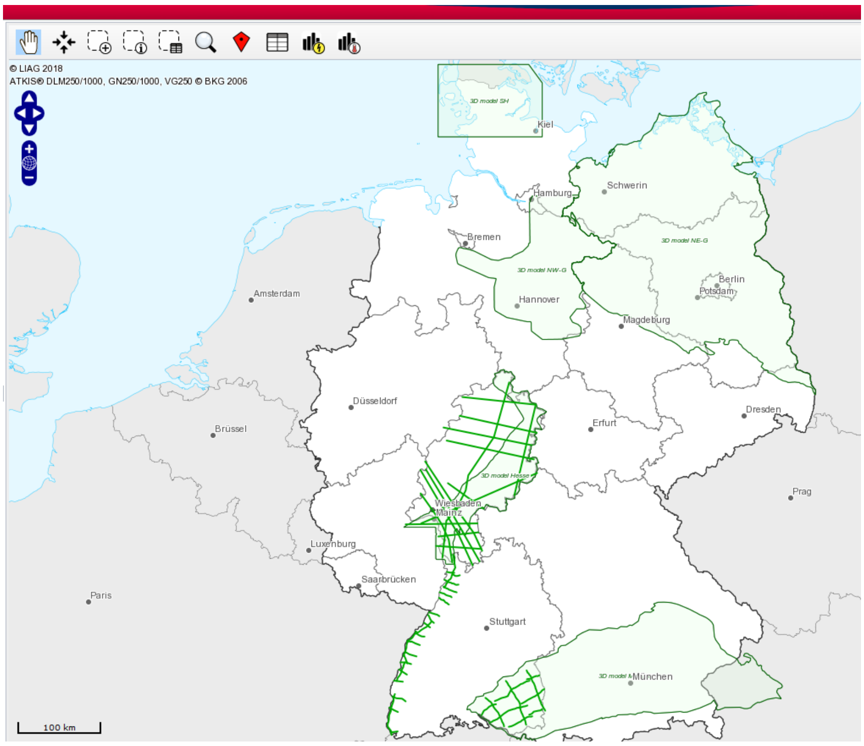

Figure 7 GeotIS screenshot

Geothermal heat for Munich

SWM (Stadtwerke München) plans to supply the whole district heating network in Munch from renewable source. GRAME, a large joint project from SWM and LIAG aims at develop a sustainable and optimal reservoir exploitation in the Molasse basin of Bavaria. Current geothermal heat projects usually foresee 2 sites with 1 doublet at maximum per exploitation field. The projects wants to optimise exploitation through:

- development of techniques for improved seismic measurements;
- inclusion of S-waves zo 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_{el} power plant and exploration of 400 MW_{th} for district heating in Munich.

KollWeb 4.0

This project develops a machine to install heat collectors in shallow depths.[7] In addition, a guideline for the installation and operation of collectors and cooling networks will be developed [Doppelacker 2018].

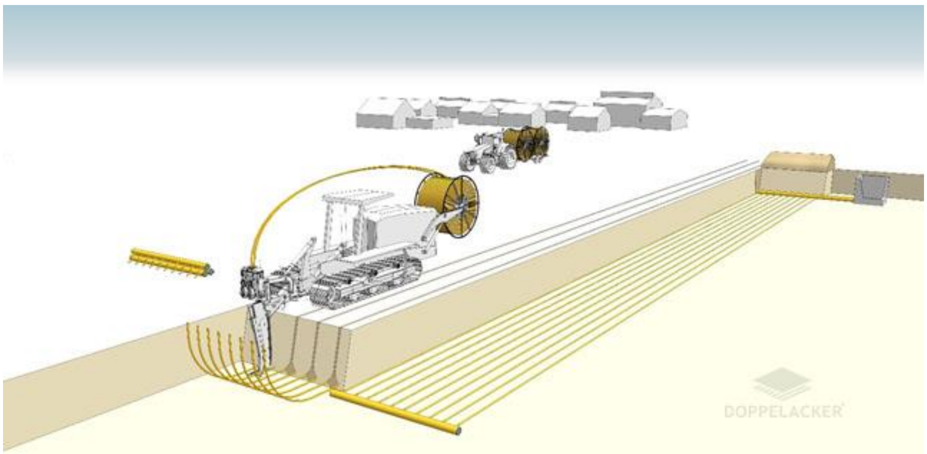

Figure 8 Ground collector installation machine

3.3.3 Iceland

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

Iceland Deep Drilling Project (IDDP)

The IDDP was founded in the year 2000 by a consortium of three Icelandic energy companies.[8] 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

[7] http://www.doppelacker.de/index.php/forschung-entwicklung/kollweb-4-0
[8] https://iddp.is/

has been awarded ISK 342 million (about EUR 2.6 million) of funding and also received some support through H2020.

Deep Roots of Geothermal Systems

The project (2013-2017) is a collaboration project set up by GEORG, the Geothermal Research Group in Iceland.[9] It has strong links with the international research community. The project focussed on :

- Study of the geology of extinct and exposed volcanic geothermal systems
- Advancing modelling of the physical processes occurring in the roots of volcanic geothermal systems
- Design of 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 JOGMEC and NEDO. Priorities of JOGMEG include:

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

A recent project of JOGMEC has developed a method to perform airborne geophysical surveys by helicopter and several areas were mapped in 2017. The project will make geophysical surveys more environmentally friendly and will help to largely reduce modification of land.[10]

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.

3.3.5 Mexico

Currently 32 geothermal research projects are carried out in Mexico by the Mexican-Center for Innovation in Geothermal Energy (CeMIE-Geo); a consortium of academic and industrial partners in the areas:

- regional resource assessment;
- exploration techniques;
- technological developments;
- direct use.

[9] http://georg.cluster.is/deep-roots-of-geothermal-systems/

[10] 80 % of geothermal resources in Japan are located in national parks thus the need for airborne methods [IEA Geothermal 2018].

The main focus is on technological developments (10 projects), followed by exploration techniques (9 projects).[11]

In addition 2 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

New Zealand funded geothermal research with NZD 3.4 million per year (about EUR 1.9 million). Research priorities are:

- low enthalpy resources;
- understanding structure and dynamics of the Taupo Volcanic Zone (TVZ);
- understanding source and circumstances of the TVZ;
- environment and sustainability.

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 about EUR 3.5 million over 5 years.

In the framework of an innovative MBIW funded project, the Geothermal Institute and GNS Science are developing next-generation approaches to the numerical modelling of geothermal systems [NeSi 2018]. 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. 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 and the main federal institutes (e.g. ETH Zurich, EPF Lausanne) also carry out research in the area.

Current research priorities are [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 20 ongoing projects in geothermal with a total project cost of about CHF 7.9 million.[12]

Echtzeit Expertensystem zur Analyse und Kontrolle des Risikos von Indizierten Erdbeben

Jan 2016 - Jan 2019 , CHF 0.8 million

This project wants to utilise micro seismicity in a controlled way to create a deep heat exchanger [Aramis 2018a]. The project will enable the worldwide potential of deep

[11] http://cemiegeo.org/

[12] https://www.aramis.admin.ch/Projektsuche/ (search therm"Geothermie")

geothermal. In addition, the product will help the involved partners to portray themselves as global market leaders in seismic risk assessment.

GEOSIM

Aug 2012 – Mar 2020 , CHF 0.6 million

There is a need to estimate seismic risks due to induced earth quakes from geothermal projects. GEOSIM will develop the scientific basis for algorithms and software tools that will allow to determine the seismic risk in real-time during [Aramis 2018b].

Geothermische Ressourcenanalyse im Bereich KGZ Davos

Nov 2009 – Jun 2018 , CHF 0.5 million

Successful drilling of a 400 m borehole for the congress centre Davos has been carried out in the past [Aramis 2018c]. The project will determine 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.

Other highlights from recent research include the completion of hydraulic stimulation and fracking tests at the Grimsel test site [SCCER-SoE 2018]. Currently, a project team of 10 persons is analysing the data obtained from the measurement campaigns.

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 maximize the probability of intersection with potential feed zones and to maximize borehole stability

Figure 9 Underground lab Grimsel

3.3.8 United States

In 2014, the FORGE subsurface laboratory (Frontier Observatory for Research in Geothermal Energy) initiative was launched in the USA. 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 .

The main funding body for geothermal research in the US is the Geothermal Technologies Office (GTO) of DoE. Research is funded in four areas [US DoE 2018]:

- Enhanced Geothermal Systems;
- Hydrothermal Resources;
- Low Temperature & Coproduced resources;
- Systems Analysis.

With the 2019 budget proposal, R&D funding risks a reduction of up to 63 % , since it would involve elimination of the low-temperature and coproduced resources subprogram; a 54 % reduction in the EGS subprogram, including the flagship FORGE laboratory; a 70 % reduction in the Hydrothermal subprogram. A USD 2.4-million increase is however foreseen in the Systems Analysis subprogram, with new funding going to the cross-cutting Beyond Batteries initiative, which supports improved grid reliability and resilience.

The website of the GTO provides ample information about the ongoing research.[13] The most important research highlights in 2017 are described below.

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

With E4D-RT, a fracture network was imaged in real-time using supercomputers.[14] The understanding gained in the project will help to improve current models for the prediction of fracture networks [US DoE 2017].

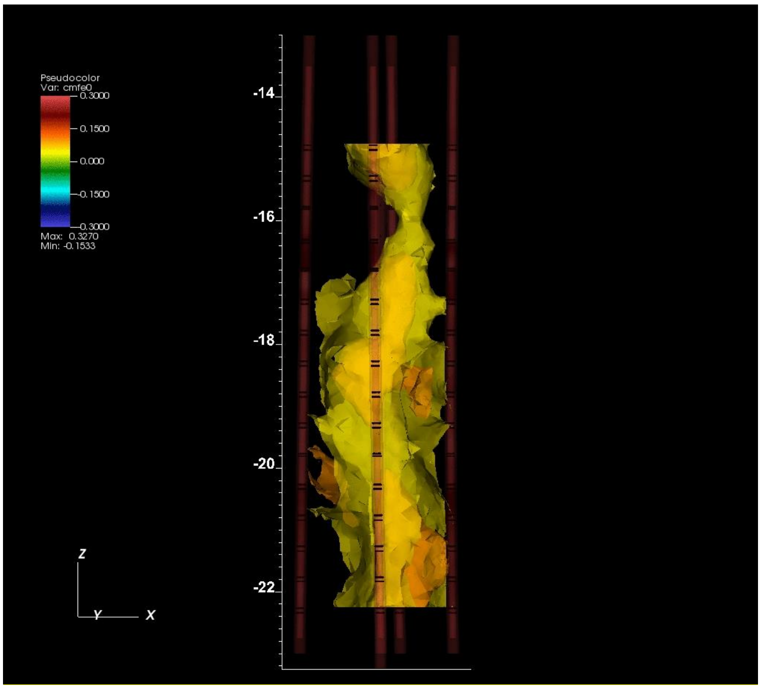

Figure 10 Example of image from E4D-RT

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

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

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

High Temperature Downhole Motor

Sandia National Laboratory developed a downhole motor for geothermal drilling [Sandia 2017]. The motor can produce wells with multilateral completions which improves geothermal resource recovery and well construction economics. A prototype will be completed and currently, the TRL of this technology is estimated at four [Sandia 2018].

Figure 11 High temperature downhole motor

3.4 European and International Programmes and Networks

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 Strategic Energy Technology Plan (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 utilization 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 has been convened in March 2016. The overarching objective of the new ETIP-"Deep Geothermal" is to enable deep geothermal technology, in particular Enhanced Geothermal Systems (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 [EGEC, 2016].

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 con-cepts of geothermal energy utilization 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 EUR 30 million were made available for eight demonstration projects. These have a strong industry participation with a tar-geted 50 % contribution towards work programs and budgets.

CREEP - Complex RhEologies in Earth dynamics &and indus-trial Processes

The CREEP Innovative Training Network is a training and career development platform for early stage researchers (ESRs) in Geodynamics, Mineral Physics, Seismology, Fluid Mechanics, and Materials Sciences. CREEP aims to structure the collaboration in re-search 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 as a part-ner organization: ETH (CH), and 11 partner organi-zations whose activity encompasses a variety of industrial applications of rheology: oil and chemical industries (AkzoNo-bel), glass (Schott) and steel (APERAM) producers, and high-technology SMEs (Rock-field, IGEM, GMuG, MP Strumenti, Geospatial Re-search, Reykjavik Geothermal). The research projects cover a large spectra of applica-tions from the study of the deformation of the Earth surface (earthquakes) and deep layers to geothermal and petroleum exploration and industrial processes.

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 expan-sion: the cost and risk of exploratory drilling.

Global Geothermal Alliance

The Global Geothermal Alliance (GGA) was set up during COP21 in 2015 and is led by the International Renewable Energy Agency (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 [UNFCCC, 2016].

IEA-Geothermal TCP

The International Energy Agency's Geothermal Technology Collaboration Program or IEA Geothermal, 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.

The International Partnership for Geothermal Technology (IPGT)

Since 2008, the IPGT signifies 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 [IPGT, 2016].

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 will consist in creating a transnational cluster specifically aimed at increasing the performance & 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 on January 1, 2018 for a duration of 2 years, and involves 8 partners from 7 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 4 clusters in applied geoscience or geo-energy at large and 4 business network organizations specialized in geothermal energy, the funded 2 years program will primarily target its networking activities, cross-sectorial skill & 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.

4 IMPACT ASSESSMENT OF H2020 PROJECTS

In this section, the contribution of significant H2020 EU-funded projects towards the advancement of geothermal technologies is analysed. Information was gathered from CORDIS, Compass and project websites where available. A categorised list of the projects from 2000 onwards is shown in Appendix A. The sections 4.1 to 4.9 look at the projects that contribute to the R&I Activities identified by the Implementation Plan of the SET-Plan on deep geothermal systems [SET-Plan TWG 2018]. In section 4.10, projects related to shallow and low-temperature geothermal applications are discussed.

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
Related SET-Plan KPIs:
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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025
Related H2020 Projects
GEO-PAC-RET; GEoTEch; CheapGSHPs; Large enHANCEMENT; MPC-GT; **GEOCOND**; GeoCollector; TEMPO

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, however, 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.

4.1.1 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: EUR 3 955 700

The project aims to enhance district heating and cooling via storage technologies like UTES.[15] By a smart combination of different material solutions through sophisticated engineering optimization, 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 optimization [Geocond 2018].

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 PCM to blend with grouting materials;
- Functionalization 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 full 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.

4.2 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.
Related SET-Plan KPIs:
DOI2: Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10 % in 2030 and 20 % in 2050 NTB A, B DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025.

[15] https://cordis.europa.eu/project/rcn/209743_en.html

Related H2020 Projects
CHMP2030; **DESTRESS; DEEPEGS**; ITHERLAB; MIGRATE; **GEMex**; GeoElectricMixing; MATHROCKS

Projects directly related to EGS have been some of the highest funded projects in the past: Hot Dry Rock Energy (FP5)- EUR 24.6 million; EGS Pilot Plant (FP6) – EUR 26 million; DESTRESS (FP7)- EUR 25 million. The most notable projects directly relating to EGS in H2020 are DEEPEGS (EUR 44 million) and DESTRESS (EUR 25 million). GEMex (EUR 10 million) also involves the resource assessment, reservoir characterisation and investigation of stimulation techniques for a potential EGS site in Mexico.

4.2.1 DESTRESS - Demonstration of soft stimulation treatments of geothermal reservoirs

Description

Duration: March 2016 – February 2020

EU contribution: EUR 10 713 400

DESTRESS is aimed at creating EGS (Enhanced geothermal systems) reservoirs with sufficient permeability, fracture orientation and spacing for economic use of underground heat.[16] 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.

Existing and new project's test sites, pilot and demonstration facilities were chosen to demonstrate the DESTRESS concept [Destress 2018].

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.

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.

[16] https://cordis.europa.eu/project/rcn/199957_de.html

4.2.2 DEEPEGS - Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business

Description

Duration: Dec 2015 – November 2019

EU contribution: EUR 6 263 000

The goal of the DEEPEGS project is to demonstrate the feasibility of enhanced geothermal systems (EGS) for delivering energy from renewable resources in Europe.[17] 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.

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.

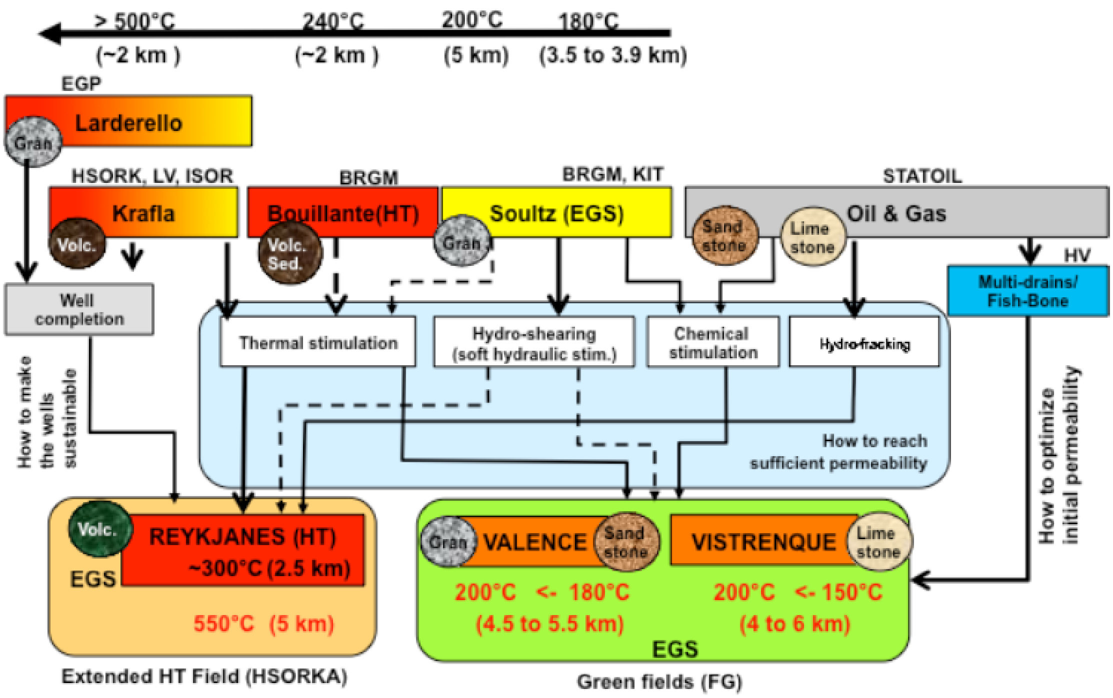

Figure 12 Testing of EGS in different geological environments in DEEPEGS. Source DEEPEGS project – see https://deepegs.eu/publications/

[17] https://cordis.europa.eu/project/rcn/199917_de.html

Impact/expected impact

So far, 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, 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 are ongoing in Iceland. The drilling work at the Vendenheim site in France started in 2018 and the first half of 2019 two deep wells have been drilled.

4.2.3 GEMex

Description

Duration: October 2016 – May 2020

EU contribution: EUR 9 999 800

The GEMex project is a complementary effort of a European and Mexican consortia[18] See also section 4.5.2. It involves the resource assessment of two unconventional geothermal sites: one for EGS development and one a super-hot resource. 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 been explored previous with two wells which found hardly 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 [GEMex 2018].

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.

[18] https://cordis.europa.eu/project/rcn/205825_en.html

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

Ultimately the project will support 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; impact in terms of scientific and technological knowledge transferred is excellent.

4.3 Equipment / Materials and methods and equipment to improve operational availability

Current TRL: Equipment 5; Materials & methods 4

Areas of interest:

- Improved equipment reliability and increased plant utilization factor
- Materials / methods / equipment to minimise operational issues related to high temperatures, scaling, corrosion and gas content

Related SET-Plan KPIs:

DOI1: Increase 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

DOI2: Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10 % in 2030 and 20 % in 2050

DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025

Related EU-Funded Projects

CHMP2030; **GeoWell**; GEOTHERMICA; GeoElectricMixing, ITHERLAB

It is noted that there have been very few EU co-funded projects in this research area pre-H2020. The project HITI (FP6, EUR 4.7 million) was the most significant, and involved developing instruments for high temperature (supercritical) environments. The FP7 project, MINSC (EUR 3.8 million) created a training network around solving the problem of mineral scale formation.

Under H2020, the project GeoWell (EUR 4.7 million), although focussed also on well design and completion, deals with the materials needed to enhance high temperature well performance and lifetime. The CHPM2030 project (EUR 4.2 million) is concerned primarily with combining metal extraction with EGS, but could also result in improved performance of geothermal systems.

4.3.1 CHPM2030

Description

Duration: January 2016 – June 2019

EU contribution: EUR 4 235 600

The project aims at converting ultra-deep metallic mineral formations into an “ore-body-EGS” that will serve as a basis for the development of a new type of facility for combined heat & power and metal extraction.[19] It is hoped that the merging of the two, so far unconnected technology areas (renewable energy and minerals extraction) will 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 metal-bearing geological formation will be manipulated in a way that the co-production of energy and metals will be possible, and may be optimised according to the market demands at any given moment in the future. The project aims to investigate 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, minimizing potential detrimental impacts of both heat and metal extraction.

Innovation(s)

The project will use the current state of the art in geothermal energy development (most recent geo-scientific data & knowledge on the structures of metallic mineral deposits, and extensive laboratory experiments and multiphysics simulations).

The proposed technology solutions will be brought from TRL 3-4 to TRL 4-5.

[19] https://cordis.europa.eu/project/rcn/199012_de.html

Impact/expected impact

So far, the results of laboratory investigations on metal mobilisation show evidence for enhanced metal leaching. Carbon-based nano-materials are being designed and prepared, which show enhanced abilities to adsorb dissolved metal ions.

Related to metal recovery, an electrochemical reactor system has been designed and constructed, to be operated at temperatures up to 250 °C and pressures up to 20 MPa. Preliminary experiments evaluating the kinetics of copper electrolysis at pressures of up to 1 MPa and 150 °C have been also conducted. The preparation of experimental setups to carry out the gas-diffusion electroprecipitation process was made. The experimental setup to measure performance of ion exchange membranes with a single pair of membranes was achieved.

The overall economic feasibility of geothermal energy projects could be dramatically improved if facilities in the future were designed from the very beginning as combined heat, power and metal facilities. Furthermore, the technology has also the potential to satisfy the needs for critical minerals (including metals used in the energy sector, such as Cd, Ni, Mo, V, Nb).

4.3.2 GeoWell

Description

Duration: February 2016 to January 2019

EU contribution: EUR 4 704 900

The GeoWell project aims 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.[20]

This will significantly enhance 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, will be developed as well as methods for risk assessment with respect to the design and operation of high-temperature geothermal wells. The research is 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)

- Reducing down time by optimised well design with corrosion resistant materials
- Optimisation of 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

[20] https://cordis.europa.eu/project/rcn/199591_de.html

- To develop methods to increase the lifetime of the well by analysing the wellbore integrity using novel distributed fiber optic monitoring techniques
- To develop advanced risk analysis tools and risk management procedures for geothermal wells.

The developed technologies will be 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 during the reporting period 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 (EDAS) technology for evaluating the degradation of the cement in deep wells has been 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 geothermal well integrity. Optimized HT (High Temperature) cements have been developed as well as the first steps towards developing better risk assessment tools.

Particularly 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 help diminishing the occurrence of operational problems and reduce maintenance cost of geothermal wells.

4.4 Improvement of Performance

Current TRL: 5-6
Areas of interest: • improved overall conversion efficiency esp. binary plants • improved heat exchangers, pumps, working fluids, expanders, cooling systems • bottoming/hybridizing new and existing plants • new cycle concepts • flexible supply units for fluctuating heat demand • optimized partial load behaviour and flexible control strategies • hybridisation with other renewables • new uses for geothermal resources
Related SET-Plan KPIs:
DOI2: Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10 % in 2030 and 20 % in 2050 DOI3: 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_{el} for electricity and 5 €ct/kWh_{th} for heat by 2025.
Related EU-funded 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 (EUR 4 million). The project aims to enhance district heating and cooling via storage technologies like UTES. By a smart combination of different material solutions through sophisticated engineering optimization, testing and on-site validation, GEOCOND will develop solutions to increase the thermal performance of the different subsystems configuring an SGES and UTES. The aim is an overall cost reduction of about 25 %. 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 optimization [Geocond 2018].

Before H2020, the LOW-BIN project 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 cogeneration of heat and power 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.[21] 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 but currently they are not available [LOW-BIN 2018].

The FP7 NSHOCK project (EUR 1.4 million, ongoing) involves developing an increased understanding of real-gas dynamics, which will enable an improvement in the design of Organic Rankine Cycle Engines, to be used in small scale energy production from binary geothermal systems.

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
Related SET-Plan KPIs:
DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025** DOI4: Reduce the exploration costs by 25 % in 2025, and by 50 % in 2050 compared to 2015

[21] https://cordis.europa.eu/project/rcn/85717_en.html

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

Exploration techniques have not received much attention under H2020, apart from the projects DESTRESS (EUR 25 million), with some related work packages, ENIGMA (EUR 3.8 million), which involves the creation of a training network and GEMex (EUR 10 million) which focuses on resource assessment in Mexico.

4.5.1 DESTRESS

Description

The DESTRESS project 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. See also section 4.2.1 for more information.

The project includes a work package dealing with risk identification related to operational stimulation, including seismic risk assessment.

Impact/expected impact

Non-standard risk monitoring including slow deformation (GPS, InSar) 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.

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

Description

See section 4.2.3 for a general project description.

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.

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.

Impact/expected impact

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.

4.5.3 ENIGMA – European training Network for In situ imaGing of dynaMic processes in heterogeneous subsurfAce environments

Description

Duration: January 2017 to December 2020

EU contribution: EUR 3 865 800

The ENIGMA 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.[22] This will improve understanding and monitoring of dynamic subsurface processes that are key to the protection and sustainable use of water resources.

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, enhanced geothermal systems 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 characterization 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 (i) world-leading academic teams and emerging companies that develop innovative sensors and hydrogeophysical inversion methods, (ii) experts in subsurface process upscaling and modelling, and (iii) highly instrumented field infrastructures for in-situ experimentation and validation.

[22] https://cordis.europa.eu/project/rcn/205566_en.html

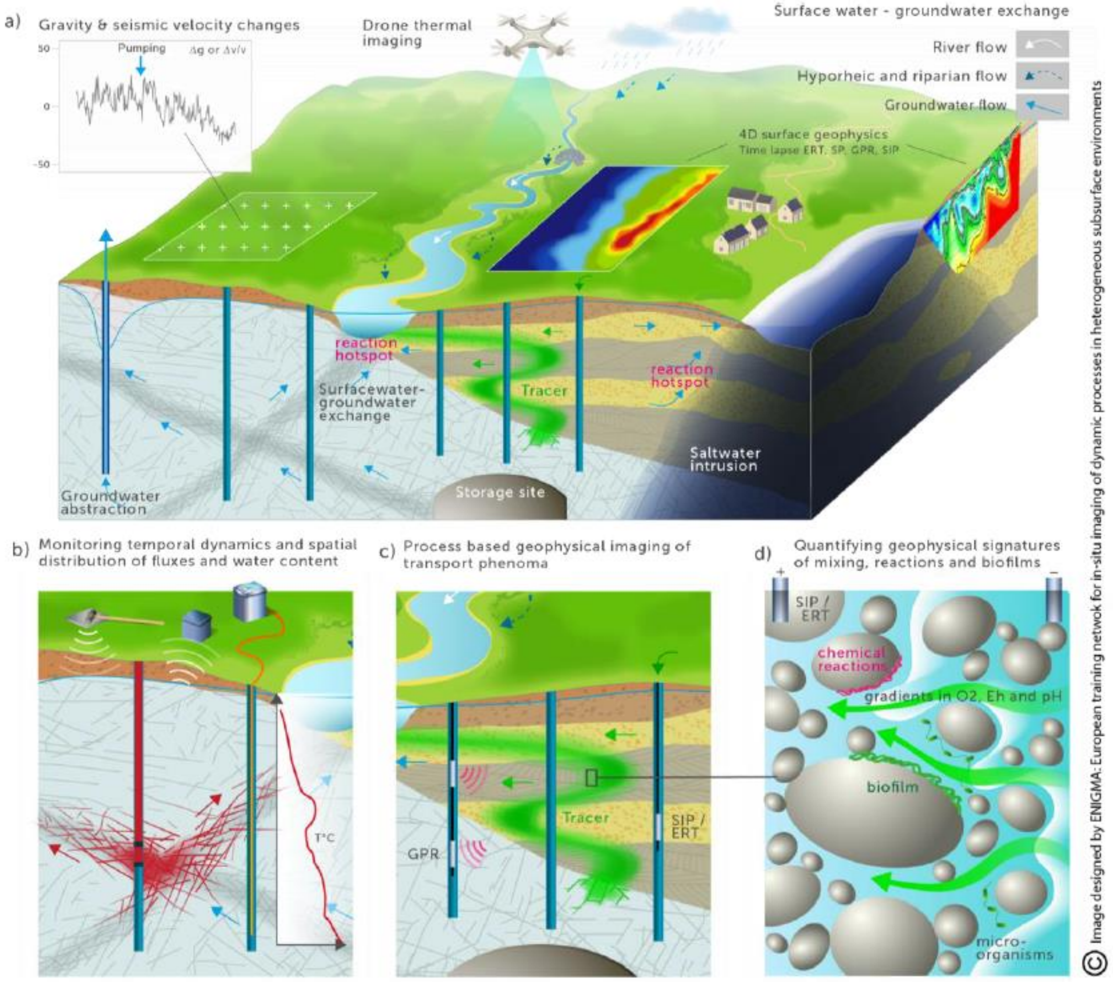

Figure 13 Illustration of the novel approaches developed in ENIGMA for imaging dynamic processes in the subsurface. Source: ENIGMA project

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 automatization
- 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 will be also considered.
- 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

Related SET-Plan KPIs:

DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025**

DOI5:Reduce the unit cost of drilling (€/MWh) by 15 % in 2020, 30 % in 2030 and by 50 % in 2050 compared to 2015.

Related H2020 Projects

DESCRAMBLE; ThermoDrill; DEEPEGS; GeoWell; **SURE**

Prior to the H2020 framework, no projects have directly related to advanced drilling techniques. Under H2020, DEEPEGS (EUR 44 million), DESCRAMBLE (EUR 15.6 million), SURE (EUR 6.1 million) and ThermoDrill (EUR 5.8 million) are the biggest projects in this area. GeoWell (EUR 4.7 million) (See section 5.3) mainly focuses on high temperature geothermal well design and completion.

4.6.1 DESCRAMBLE - Drilling in supercritical geothermal conditions

Description

Duration: May 2015 to April 2018

EU contribution: EUR 6 753 600

The aim of the DESCRAMBLE project was to develop novel drilling technologies for a proof-of-concept test of reaching deep geothermal resources..[23]

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.

[23] https://cordis.europa.eu/project/rcn/193730_de.html

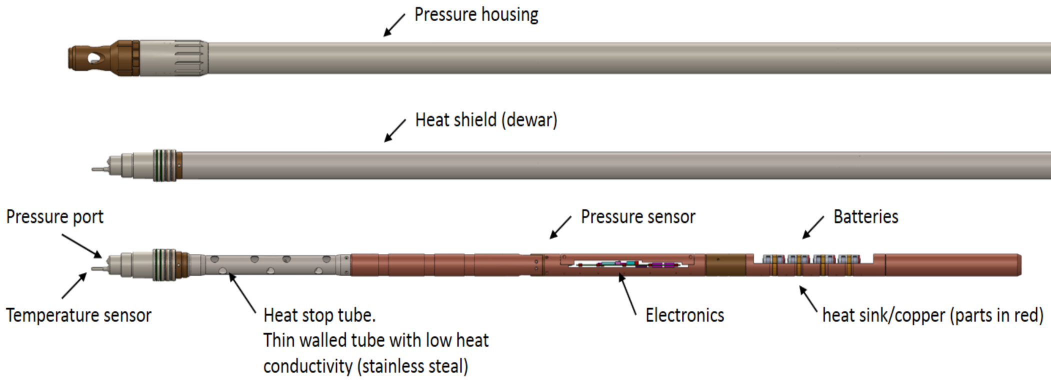

Figure 14 New downhole logging tool developed. Source: DESCRAMBLE project.

Impact/expected impact

The project could lead to significant advances in the utilization 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 supercritical 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 DEEPEGS - Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business

Description

A general description of the project can be found in Section 4.2.2. The goal of the DEEPEGS project is to demonstrate the feasibility of enhanced geothermal systems (EGS) for delivering energy from renewable resources in Europe.[24]

DEEPEGS will also demonstrate advanced technologies in three geothermal reservoirs with different geological conditions. EGS will be demonstrated for the widespread exploitation of high enthalpy heat in a volcanic environment in Iceland with temperatures up to 550 °C and in a very deep hydrothermal reservoir at Valence (crystalline and sandstone) and Riom-Limagne (limestone) with temperatures up to 220 °C in France.

[24] https://cordis.europa.eu/project/rcn/199917_en.html

Innovation(s)

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

Impact/expected impact

So far, the project has managed to drill 4 659 m in 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 (see section 4.2.2).

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

Description

Duration: September 2015 to August 2018

EU contribution: EUR 5 381 000

The goal of ThermoDrill is the development of an innovative drilling system based on the combination of conventional rotary drilling with water jetting.[25]

Innovation(s)

ThermoDrill will mainly address the following research and development topics:

- enhanced water jet drilling technology for borehole construction and replacement of fracking;
- HT/HP crystalline rock jetting and drilling fluids;
- systematic redesign of the overall drilling process, particularly the casing design and cementing;
- evaluation of drilling technologies and concepts in terms of HSE (health, safety and environmental) compliance.

Impact/expected impact

The proposed increased penetration rate, up to 50 % greater, resulting in an overall cost reduction of 30 % for each well, is of major significance and directly exploitable.

The ThermoDrill consortium claim that the results from the first half of the project clearly indicate that the proposed jetting/rotary system will outperform the initially goals. 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.

[25] https://cordis.europa.eu/project/rcn/193791_de.html

The partners involved in the manufacturing of the new jet-assisted roller cone drillbits are also expected to receive direct benefits from increased sales to geothermal projects, potentially including conventional high temperature geothermal applications [EC 2018].

The work has already resulted in the hybrid design of a high pressure jetting system built into commercial roller cone bit using a pressure intensifier that guarantees high flow rate at high pressure, using the selected drilling fluid.

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

Description

Duration: March 2016 to August 2019

EU contribution: EUR 5 892 200

Within the project SURE the radial water jet drilling (RJD) technology will be investigated and tested as a method to increase inflow into insufficiently producing geothermal wells.[26]

Radial water jet drilling 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 shall be 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 will investigate 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 aims 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.

SURE will advance the TRL of RDJ technology for geothermal reservoir enhancement from TRL 3 to TRL4-5.

Impact/expected impact

The main achievements of the project so far: the state-of-the-art review on stimulation technologies and RJD; the rock properties determination at laboratory scale; the experimental set-ups for the characterisation of the permeability evolution for different fracture types and the study of lateral's stability and formation damage; and the 1st field jetting test with industry equipment.

[26] https://cordis.europa.eu/project/rcn/199554_en.html

Once proven for geothermal sites, RJD allows to significantly increase the number of economically viable geothermal wells.

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

This topic had not been addressed to a great degree until H2020, and several significant projects are now underway, such as STORM (EUR 19 million), FLEXYNETS (EUR 19 million) and OPTi (EUR 2 million). 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).

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
Related SET-Plan KPIs:
DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025 DOI6: 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.
Related H2020 Projects
TESSe2b; STORM; OPTi; FLEXYNETS

4.7.1 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 - Sep 2019

EU contribution: EUR 4 311 700

The target of TESSe2b is 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 (DHW) production.[27]

Innovation(s)

The idea is to develop advanced compact integrated PCM TES tanks exploiting RES (solar and geothermal) in an efficient manner coupled with enhanced PCM borehole heat exchangers (BHEs) that will take advantage of the increased underground thermal storage and maximize the efficiency of the ground coupled heat pumps (GCHP).

The two TES tanks developed within TESSe2b project will be integrated with different PCM materials; (i) enhanced paraffin PCM, (ii) salt-hydrates PCM, while in both of them a highly efficient heat exchanger will be included.

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

Impact/expected impact

The overall objective is to develop a solution to decrease net energy consumption by 25-30 % and have a return-on-investment period of 8-9 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 are also underway of development, such as nano-composite paraffin waxes compact modular design of storage tanks and smart control system.

The work done so far shows that it is possible to reduce a net energy consumption by 25- 30 % and have a return-on-investment period of 8-9 years.

4.7.2 OPTi – Optimisation of District Heating Cooling systems

Description

Duration: March 2015 – October 2017

EU contribution: EUR 4 311 700

The OPTi project aimed to rethink the way 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.[28]

[27] https://cordis.europa.eu/project/rcn/198369_en.html
[28] https://cordis.europa.eu/project/rcn/196635_en.html

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 optimization 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.

4.7.3 STORM – Self-organising Thermal Operational Resource Management

Description

Duration: March 2015 - March 2019

EU contribution: EUR 1 972 100

STORM builds on the experiences of the (Interreg) Minewater project (see section 3.2.3), which was transformed into an intelligent DHC network, the so-called "Mine Water 2.0" project. All buildings are connected to local cluster networks. The ambition is to make these clusters energy self-sufficient by energy exchange between buildings and energy storage. Since energy is transported over shorter distances, this results in lower distribution losses. In this way, more clusters and thus more buildings can be connected to the backbone mine water system. As a result, expansion of the network becomes possible. However, for fully deploying this system, an automated and smart control system is necessary.

The STORM project tackles energy efficiency at district level by developing an innovative district heating & cooling (DHC) network controller.[29]

Innovation(s)

- Develop a generic controller for district heating and cooling (DHC) networks 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;

[29] https://cordis.europa.eu/project/rcn/194614_de.html

- 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 aims at bringing the controller to TRL 7 (technology demonstrated in operational environment) by applying the controller to two existing district heating grids.

Impact/expected impact

The project has developed a first version of the STORM controller based on self-learning algorithms, algorithms which can learn the behaviour of the network and the buildings, which is currently experimented in two STORM demo sites, Mijnwater BV in Heerlen (NL) and Växjö Energi in Rottne (SE), where the resulting energetic, economic and environmental gains are evaluated.

So far, simulations have shown that for the demo site in Rottne a peak reduction of the district heating load up to 20 % compared to a classic DH controller can be reached. This is in line with the project objectives and gives large energy saving potentials for other DH networks.

Besides these development and implementation activities, the partners have identified the key exploitable results of the project and are now in the phase of investigating how the future of the STORM project can be handled.

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 (NCGs) • capture and re-injection of chemical compounds associated with produced geothermal fluids. • development of new equipment (compressors, pumps, intercoolers, mixing nozzles, and possibly refrigeration equipment)
Related SET-Plan KPIs:
DOI2: Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10 % in 2030 and 20 % in 2050 DOI3: 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_{el} for electricity and 5 €ct/kWh_{th} for heat by 2025.
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 the CARBFIX (FP7) (Section 3.2.4) and CARBFIX2 (H2020) projects.

4.8.1 CARBFIX2 – Upscaling and optimizing subsurface, in situ carbon mineralization as an economically viable industrial option

Description

Duration: August 2017 - January 2021

EU contribution: EUR 2 200 300

CarbFix2 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.[30]

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 develop and demonstrated in real environment (TRL 5). Technologirs at TRL 5 will be further demonstrated bringing them to TRL 6-7.

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.

[30] https://cordis.europa.eu/project/rcn/211576_en.html

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. reas 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. in projects 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, which aimed to create markets for renewable energies, ECOHEAT4EU, 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 network. 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 utilization value chain.

4.10 Shallow and low-temperature geothermal

4.10.1 MPC-GT

Description

Duration: September 2016 - August 2020

EU contribution: EUR 774 000

The MPC-GT project builds on previous research from the EU-Funded FP7 GEOTABS project which involved developing solutions to improve the combination of geothermal HP 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.[31]

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 HVAC thermal power 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 to strengthen their competitiveness.

[31] https://cordis.europa.eu/project/rcn/205707_en.html

4.10.2 TEMPO - TEMPerature Optimisation for Low Temperature District Heating across Europe

Description

Duration: October 2017 – September 2021

EU contribution: EUR 774 000

The main objectives of TEMPO are the development of technological innovations for low-temperature (LT) district heating (DH) networks for increased network efficiency and integration options for renewable and residual heat sources, through demonstration in three different sites.[32] 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 2018]. 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: EUR 2 089 700

This project aims to reduce the cost and complexity of installation and connection of near-surface geothermal energy systems, and to reduce the large space requirement of the heat source system. GeoCollector is an innovative geothermal heat absorber system.[33]

Innovation(s)

[32] https://cordis.europa.eu/project/rcn/212364_en.html
[33] https://cordis.europa.eu/project/rcn/211146_en.html

The expected project output is 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, and low land use.

Impact/expected impact

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

In July 2018, the 2nd version of the product/system named GC3 was developed. Its partially automatized production process including is working in a test phase with single/small batches. The sales process was further developed incl. a design tool for users/resellers.

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

Description

Duration: July 2015 – December 2018

EU contribution: EUR 1 999 360

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 tackles these problems by focusing on the development of District Heating and Cooling (DHC) networks working at "neutral" (15-20 °C) temperatures, strongly reducing heat losses.[34]

Reversible heat pumps will be 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 will advance 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 tempera-

[34] https://cordis.europa.eu/project/rcn/194622_en.html

tures 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.

5 TECHNOLOGY DEVELOPMENT OUTLOOK

The JRC-EU-TIMES model offers a tool for assessing the possible impact of technology and cost developments – a note to explain the main features of the model is included in a dedicated report. It represents the energy system of the EU28 plus Switzerland, Iceland and Norway, with each country constituting one region of the model. It simulates a series of 9 consecutive time periods from 2005 to 2060, with results reported for 2020, 2030, 2040 and 2050. The model was run with three general scenarios:

- *Baseline*: Continuation of current trends; no ambitious carbon policy outside of Europe; only 48 % CO_2 reduction by 2050
- *Diversified*: Usage of all known supply, efficiency and mitigation options (including CCS and new nuclear plants); 2050 CO_2 reduction target is achieved
- *ProRES*: 80 % CO_2 reduction by 2050; no new nuclear; no CCS

In addition, a further 13 sensitivity cases were run. Deliverable report D4.7 presents all the scenarios and the overall results. This technology development report focusses on 5 scenarios of interest to geothermal (Table 3) looking at geothermal deployment in the EU as a whole. Further analysis including country breakdowns will be included in the technology market report.

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
ProRES SET-Plan targets	SET-Plan learning	5 046	75.9	602	8	51
ProRES (Res1)		2 357	9.8	279	0	0
ProRES Nearly Zero Carbon		1 816	4.2	61	180	1 134
Diversified without capturing of CO_2 in power sector	Reference learning	1 912	8.1	239	3.9	25
Diversified (Div1)		333	1.8	51	0	0

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-28 was assumed to be 5171 PJ for total heat [Chamorro et al. 2014].

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 %.

5.1 Deployment Trends

Figure 15 shows an overview of the results for the five scenarios. Figure 16 shows the results of the scenarios in more detail by extracting the installed capacity values for geothermal and plotting these as a function of time period.

5.2 Deployment under each scenario

5.2.1 ProRES SET-Plan Targets

Geothermal plays a role in all scenarios, but its most significant role is in the ProRES SET-Plan targets scenario (Res4_SET), where use of geothermal heat for electricity and other applications reaches 5046 PJ in 2050, which is almost the full sustainable potential. This represents 8 % of total EU gross energy consumption and 2 % of the EU electricity production. The model does not currently take account of 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 EUR 800/kW, compared to around EUR 9 000/kW in the other scenarios. Under this scenario, JRC-EU-TIMES depicts a total installed capacity of 75 GW for geothermal (mainly from EGS with ORC). The geothermal power plants operate with low full load hours as to be able to provide peak capacity, bringing the average use of the capacity to 20 GW.

5.2.2 ProRES

In the ProRES scenario (Res1), just under half of the sustainable potential of geothermal energy is utilized solely for electricity production. The absence of learning does not allow cost reductions to the same extent as the ProRES SET-Plan target meaning it cannot compete in certain countries.

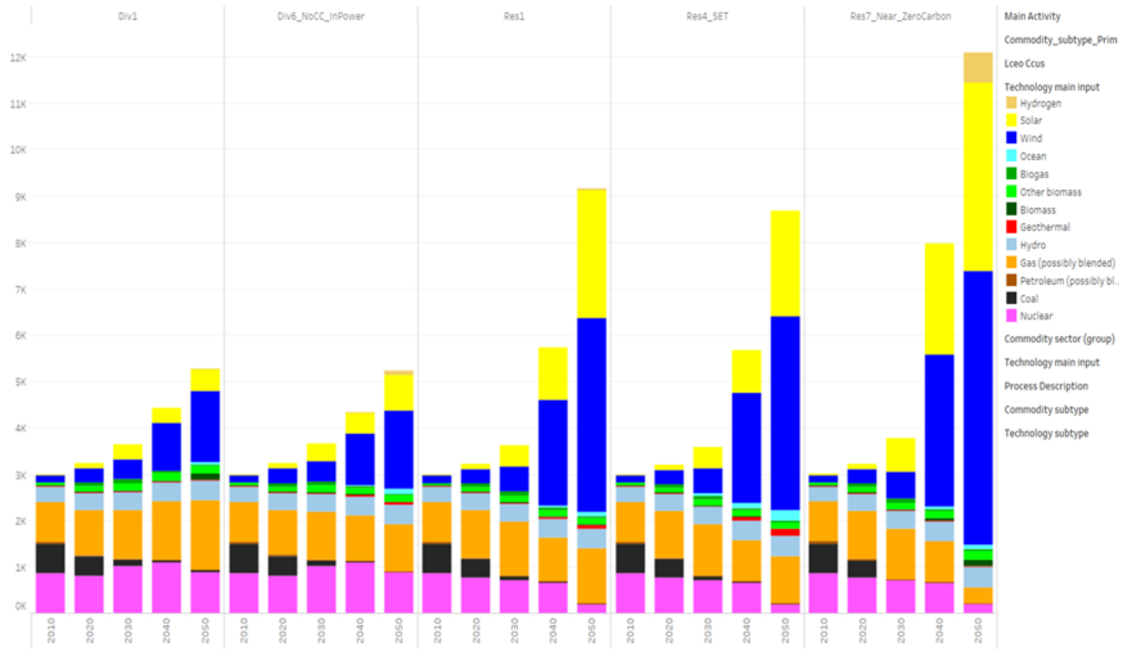

Figure 15: JRC-EU-TIMES model: distribution of power generation (TWh) by technology for five different scenarios. Geothermal is represented by the red segments

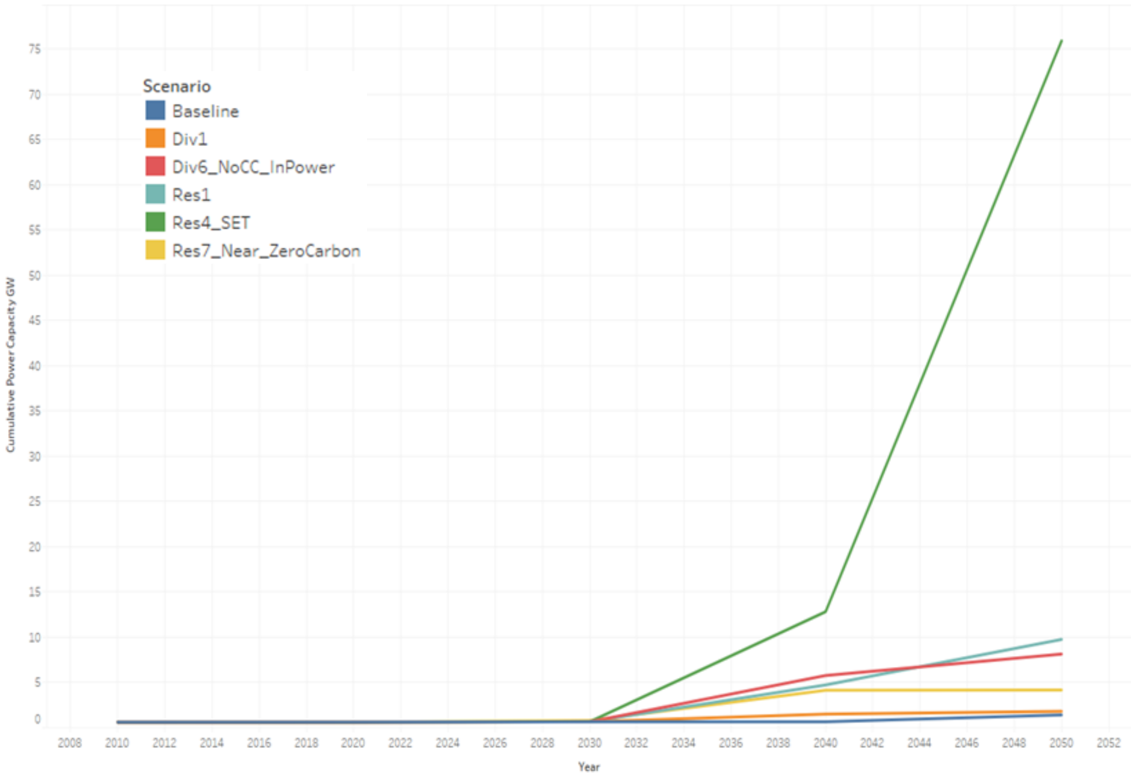

Figure 16: Growth of geothermal capacity over time in the baseline and five different scenarios

5.2.3 ProRES Nearly Zero Carbon

In the additional sensitivity that includes a 95 % reduction of energy related CO_2 (Res7_Near-ZeroCarbon), a substantial share of the geothermal heat potential is used for district heating (around 20 %).

5.2.4 Diversified without capturing of CO_2 in the power sector

In the diversified scenario without CO_2 capture in the power sector (Div6_NoCC_inPower scenario), geothermal utilization 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. Similar to the ProRES scenario, in some countries geothermal cannot compete with solar and wind.

5.2.5 Diversified

In the diversified (Div1) scenario, only a small portion of the sustainable potential is utilized due to the competition with power production with CCS.
Figure 17 describes the allocation of the different types of geothermal technology (existing plant, EGS with ORC, hydrothermal flash and hydrothermal ORC) in the energy mix. Geothermal with EGS becomes the dominant technology in most scenarios by 2050 with the exception of the diversified scenario (Div1). Geothermal with EGS is not deployed when power can be produced with CCS technology.

Figure 17: Breakdown of the geothermal deployment categories for the each scenario by 10-year period

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, and 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 efficieny, optimisation of maintenance and operation. The use of unconventional geothermal (EGS) still has to be demonstrated and R&D support in various areas (deep drilling, reservoir creation and enhancement, seismicity prediction and control) is highly needed.

The SET-Plan Deep Geothermal Implementation Plan recognises 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. The timeframe of this report (to th end of 2018) however precludes an assessment of the impact of H2020 projects since these largely are an early stage of execution.

It is however noted that in terms of distriobution of the funding allocated up to now, 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.

6.2 Recommendations: 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, yet 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 of funding should be identified to better focus the support. It should also be considered whether cross-cutting issues, which were highly funded in previous frameworks are still in need of similar funding now or in the future.

6.3 Recommendations: non-technical barriers

Targeted research should be designed to effectively overcome non-technical barriers. Although prior to H2020, funding has been allocated to these areas, 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 assesments, 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 & Dworkin 2015]. 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 are needed. 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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APPENDIX A: EC-FUNDED PROJECTS PER SET-PLAN R&I CATEGORY 2000-2017

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 issues	Non-technical issues
FP5	GEOTHERNET	01/01/2000									☒	
FP5	HOT DRY ROCK ENERGY	01/04/2001			☒			☒				
FP6	EGS PILOT PLANT	01/04/2004			☒	☒						
FP6	GROUNDHIT	01/06/2004	☒									
IEE	K4RES-H	01/01/2005										☒
IEE	OPTRES	01/01/2005										
FP6	ENGINE	01/11/2005			☒						☒	
FP6	I-GET	01/11/2005					☒					
FP6	ATOMIC TO GLOBAL	01/01/2006					☒					
IEE	GROUNDREACH	01/01/2006	☒								☒	☒
FP6	LOW-BIN	01/03/2006				☒						
IEE	GTR-H	01/11/2006									☒	
FP6	RESTMAC	01/06/2006										☒
FP6	ASAP	01/12/2006					☒					
IEE	PROHEATPUMP	01/12/2006	☒								☒	☒
FP6	HITI	01/01/2007		☒								
FP6	FUTURE ENERGY	19/03/2007									☒	☒
FP6	TERRA THERMA	15/12/2007	☒									
FP7	CLUSTHERM	01/05/2008									☒	
IEE	GEOFAR	01/09/2008									☒	☒
IEE	GEOTRAINET	01/09/2008									☒	
FP7	AEGOS	01/12/2008					☒				☒	
FP7	GROUND-MED	01/01/2009	☒									

Frame work	Acronym	Start Date	SET Plan category									
IEE	ECOHEAT4EU	01/06/2009	☒									☒
IEE	QUALICERT	01/07/2009									☒	
FP7	GEISER	01/01/2010			☒		☒					☒
FP7	GEOCOM	01/01/2010	☒			☒					☒	☒
IEE	INSTALL+RES	01/05/2010									☒	
FP7	ECO-GHP	01/06/2010	☒									
IEE	ECOHEAT4CITIES	26/06/2010										☒
FP7	CAPWA	01/09/2010				☒						
FP7	ThermoMap	01/09/2010										
FP7	E-HUB	01/12/2010					☒		☒			
FP7	SECRHC-PLATFORM	01/01/2011									☒	
ERA-NET	GEOTABS	01/02/2011	☒									
IEE (EACI)	GEOELEC	01/06/2011					☒				☒	☒
FP7	EFFIHEAT	01/10/2011	☒									
NER300	HU GEOb South Hungarian (EGS) Demonstration Project	01/01/2012			☒		☒	☒				
IEE	GEODH	01/04/2012	☒				☒				☒	☒
IEE	REPOWERMAP	01/04/2012									☒	
	GEOTHERMAL ERA NET	01/05/2012									☒	
IEE	REGEOCITIES	01/05/2012									☒	☒
FP7	HYSM	14/05/2012			☒							
FP7	MINSC	01/06/2012		☒		☒						
FP7	NXTHPG	01/12/2012	☒									
FP7	CREEP	01/02/2012	☒									
IPA	LEGEND	11/12/2012	☒									
FP7	SINGULAR	1/12/21012	☒						☒			
FP7	FLUIDEQ	01/08/2013		☒								
FP7	IMAGE	01/11/2013		☒			☒					
NER300	GEOSTRAS	01/01/2014			☒	☒		☒				
NER300	GEOTHERMAE	01/01/2014			☒	☒						
FP7	GREAT	01/01/2014			☒					☒	☒	
FP7	NSHOCK	01/03/2014				☒						
FP7	EFFIHEAT-DEMO	01/04/2014										
IEE	STRATEGO	01/04/2014										

Frame work	Acronym	Start Date	SET Plan category									
H2020	DeReco	01/10/2014				☒						
H2020	GEO PAC RET	01/10/2014	☒									
H2020	GEAGAM	01/01/2015					☒					
H2020	OPTi	03/01/2015	☒						☒			
H2020	STORM	03/01/2015	☒						☒			
H2020	FLEXYNETS	07/01/2015	☒						☒			
H2020	Tesse2b	10/01/2015	☒						☒			
H2020	CREEP	01/04/2015					☒				☒	
H2020	DESCRAMBLE	01/05/2015				☒	☒	☒				
H2020	GEOTeCH	01/05/2015	☒									
H2020	Cheap-GSHPs	01/06/2015	☒									
H2020	ThermoDrill	01/09/2015						☒				
H2020	DEEPEGS	01/12/2015			☒		☒	☒				
H2020	CHPM2030	01/01/2016		☒	☒	☒	☒					
H2020	GeoWell	01/02/2016		☒				☒				
H2020	SURE	01/03/2016			☒			☒				
H2020	DESTRESS	01/03/2016			☒		☒					
H2020	ITHERLAB	14/03/2016		☒			☒					
H2020	MIGRATE	31/03/2016	☒		☒		☒					
H2020	ENIGMA	16/08/2016					☒				☒	
H2020	MPC-. GT	22/08/2016	☒			☒						
H2020	GEMex	15/09/2016			☒		☒	☒				☒
H2020	GEOTHERMICA	16/11/2016		☒			☒	☒	☒		☒	☒
H2020	Large en-HANCEMENT	02/12/2016	☒									
H2020	GeoElec-tricMixing	02/03/2017		☒	☒					☒		
H2020	GEOCOND	04/04/2017	☒	☒		☒						
H2020	DG ETIP	07/06/2017									☒	
H2020	GeoCollector	09/06/2017	☒									
H2020	TEMPO	13/09/2017	☒			☒						☒
H2020	MATHROCKS	25/09/2017	☒		☒		☒					

APPENDIX B: DEEP GEOTHERMAL SET-PLAN R&I PRIORITIES

R&I Activity	KPIs as set out in Declaration of Intent
Geothermal heat in urban areas	DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025. NTB a, b
Equipment / Materials and methods and equipment to improve operational availability	DOI1: Increase 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 DOI2: Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050 DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025** NTB A
Enhancement of conventional reservoirs and development of unconventional reservoirs	DOI2: Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050 NTB A, B DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025** NTB A, B
Improvement of performance (conversion to electricity and direct use of heat)	DOI2: Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050 DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025** NTB A
Exploration techniques (including resource prediction and exploratory drilling)	DOI3: 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$_{el}$ for electricity and 5 €ct/kWh$_{th}$ for heat by 2025** DOI4: Reduce the exploration costs by 25% in 2025, and by 50% in 2050

R&I Activity	KPIs as set out in Declaration of Intent
	compared to 2015;
Advanced drilling/well completion techniques	DOI3: 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_{el} for electricity and 5 €ct/kWh_{th} for heat by 2025** DOI5:Reduce the unit cost of drilling (€/MWh) by 15% in 2020, 30% in 2030 and by 50% in 2050 compared to 2015
Integration of geothermal heat and power in the energy system and grid flexibility	DOI3: 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_{el} for electricity and 5 €ct/kWh_{th} for heat by 2025 DOI6: 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. NTB B
Zero emissions power plants	DOI2: Improve the overall conversion efficiency, including bottoming cycle, of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050 DOI3: 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_{el} for electricity and 5 €ct/kWh_{th} for heat by 2025** NTB B
Increasing awareness of local communities and involvement of stakeholders in sustainable geothermal solutions	NTB A NTB B
Risk mitigation (finan-cial/project)	DOI1: Increase reservoir performance* resulting in power demand of reservoir pumps to below 10% of gross energy generation and in sustain-able yield predicted for at least 30 years by 2030 DOI3: 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_{el} for electricity and 5 €ct/kWh_{th} for heat by 2025 NTB A

APPENDIX C: SET-PLAN KEY R&I AREAS

R&I Activities	Key areas for R&I	Associated SET-Plan Target(s)
Geothermal heat in urban areas	• 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	DOI 3, NTB A, B
Materials, methods and equipment to improve operational availability (high temperatures, corrosion, scaling)	• improved equipment reliability and increased plant utilization factor • materials / methods / equipment to minimise operational issues related to high temperatures, scaling, corrosion and gas content	DOI 3, 2, 1 NTB A
Enhancement of conventional reservoirs and deployment of unconventional reservoirs	• 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	DOI 3, 2 NTB A, B
Improvement of performance (conversion to electricity and direct use of heat)	• improved overall conversion efficiency esp. binary plants • improved heat exchangers, pumps, working fluids, expanders, cooling systems • bottoming/hybridizing new and existing plants • new cycle concepts • flexible supply units for fluctuating heat demand • optimized partial load behaviour and flexible control strategies • hybridisation with other renewables • new uses for geothermal resources	DOI 3, 2 NTB A
Exploration techniques (including resource prediction and exploratory drilling) *precision of pre-drilling exploration*	• 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	DOI 3, 4
Advanced drilling/well completion techniques	• process automatization • 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	DOI 3, 5

R&I Activities	Key areas for R&I	Associated SET-Plan Target(s)
	drilling • horizontal-multilateral wells clusters in various geological formations will be also considered. • 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	
Integration of geothermal heat and power in the energy system and grid flexibility	• 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	DOI 6, 3; NTB B
Zero emissions power plants	• CO_2 capture, storage and reinjection schemes for reservoirs with high CO2-content. • Demonstration of capture of non-condensable gases (NCGs) • capture and re-injection of chemical compounds associated with produced geothermal fluids. • development of new equipment (compressors, pumps, intercoolers, mixing nozzles, and possibly refrigeration equipment)	DOI 2, 3 NTB B
Increasing awareness of local communities and involvement of stakeholders in sustainable geothermal solutions	• stakeholder consultation, creation of a task force / working group, development of European concepts	NTB A NTB B
Risk mitigation (financial/project)	• 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	

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