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# 2015 JRC Geothermal Energy Status Report

*Technology, market and economic aspects of geothermal energy in Europe*

Bergur Sigfússon
Andreas Uihlein

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Abstract
This report presents the current status of the major geothermal energy technologies ranging from ground source heat pump systems, direct use facilities to geothermal power plants. Power production from hydrothermal resources where natural permeability coincides with hot bedrocks is a mature technology. The same is true for direct use systems and ground source heat pumps. Power and heat production from engineered geothermal systems where there is either a lack of thermal convection or where permeability has to be artificially created is less mature and needs further development and support. Currently, geothermal energy provides 0.2 % of EU final electricity demand. In addition, about 36000 GWh of heat are produced by direct use systems and ground source heat pumps. In order to expand the potential for geothermal power production, focus should be made on facilitating the deployment of engineered geothermal systems. A special chapter in this year's edition gives an overview of past and current engineered geothermal systems projects worldwide and identifies issues needed to overcome in order to enable further deployment of the technology. Increased deployment may be achieved by first proofing the applicability of the method in various geological media, followed by decreasing the risk of project failure by continuous development on reservoir identification, stimulation and management methods, both leading to higher chance of more favourable financing. The advances should progress alongside development of cheaper drilling technologies. Finally there is a need for increasing public awareness of the technology.

# 2015 JRC Geothermal Energy Status Report

Joint Research Centre

Institute for Energy and Transport

Bergur Sigfússon & Andreas Uihlein

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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| CAPEX | Capital expenditure |
| CF | Capacity factor |
| COP | Coefficient of performance |
| DOE-GTO | US Department of Energy Geothermal Technologies Office |
| EGEC | European Geothermal Energy Council |
| EGS | Engineered Geothermal System or Enhanced Geothermal System |
| ESCO | Energy Service Companies |
| EU | European Union |
| FIP | Feed-in-premium |
| FIT | Feed-in-tariff |
| GSHP | Ground Source Heat Pump |
| HSA | Hot Sedimentary Aquifer |
| LCOE | Levelised cost of energy |
| MS | Member State |
| NREAP | National Renewable Energy Action Plan |
| OPEX | Operating expenditure |
| ORC | Organic Rankine Cycle |
| PDC | Polycrystalline diamond compact bits |
| R&D | Research and Development |
| RD&D | Research, Development and Deployment |
| ROP | Rate of penetration |
| RSS | Rotary steerable systems |
| TD | Total depth |
| WSA | Wet sulphuric acid process |

# 1 INTRODUCTION

This report is an update of the 2014 JRC Geothermal Energy Status Report by the Joint Research Centre's Institute for Energy and Transport. While the 2014 report gave an overview of the geothermal sector in the EU, including technology descriptions, this second version focuses more on identification of research needs as well as market status, developments and outlook. Finally a special chapter is provided on Engineered Geothermal Systems (EGS).

Geothermal energy is derived from the thermal energy generated and stored in the earth interior. The energy is accessible since groundwater transfers the heat from rocks to the surface either through bore holes or natural cracks and faults. The geothermal resource is a renewable resource because there is a constant heat flow to the surface and atmosphere from the immense heat stored within the earth while the groundwater transferring the heat is replenished by rainfall and circulation within the crust. Geothermal energy is a commercially proven renewable form of energy that can provide constant power and heat.

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. The technologies associated with hydrothermal power and heat production may be considered as mature. A hot sedimentary formation where there is no natural convection and heat is distributed by *conduction* is on the other hand termed Hot Sedimentary Aquifer (HSA) which is a sub-category of Engineered Geothermal Systems (EGS). 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. In 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. The EGS technologies are proven on small scale since 2007 but are still in development process. To date, the large majority of geothermal energy stems from hydrothermal resources whereas one petrothermal EGS and three HSA EGS in operation exist within the EU.

The geologic potential (heat in place) for geothermal power in Europe and the World is very large and exceeds the current electricity demand in many countries. However only a small portion of the heat in place can be realistically extracted for power production and the heat in place is therefore often translated to economic potential using levelised cost of energy (LCOE). The geothermal energy potential using LCOE value less than 150 EUR/MWh in 2020 is 21.2 TWh which is considerably higher than the planned 11 TWh production in the EU member states (MS) according to their National Renewable Energy action plan (NREAP) for the same year. For 2030, using LCOE of 100 EUR/MWh, the economic potential amounts to 34 TWh or 1 % of the projected total electricity production in the EU [van Wees et al. 2013]. 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]. However, innovative drilling concepts not relying on mechanical drilling have been in development for many years and to date, none has been demonstrated to reach the depth needed for high temperature geothermal applications and it is clear that EGS have to be demonstrated more fully before the 2030 and 2050 predictions are realised.

Hydrothermal resources are categorised into low (<100 °C), medium (100 – 180 °C) and high (>180 °C) enthalpy resources. In addition to the geothermal resources mentioned above, use of supercritical unconventional resources (temperature > 374 °C and pressure > 222 bar referring to pure water) is under investigation through the Icelandic Deep Drilling Project and the more recent DESCRAMBLE project.. The process involves transferring supercritical fluids to the surface and converting all the mass flow (compared to 20-30 % for flash power plants) into superheated steam thus increasing the overall efficiency of the process [Friðleifsson et al. 2014].

Due to their tectonics, hydrothermal reservoirs tend to be fractured, therefore facilitating movement of water that can be extracted through production wells to the surface either to turn turbines or for direct use for heating. In addition to electricity production, the thermal capacity of the ground can provide heating or cooling with the aid of ground source heat pumps either extracting heat from shallow soils or deeper boreholes.

Geothermal energy provides an opportunity to be exploited by cascade utilisation (stepwise usage at progressively lower temperatures) and therefore increase the total efficiency which results in economic benefits. The most important cascade applications present in today's market are power generation, district heating and cooling, industrial processing, greenhouses, fisheries, de-icing, and spa bathes.

Geothermal power and heat installations draw their energy from resources of variable depths and temperatures. So far, no general consensus has been agreed on how to classify geothermal heat sources and production. In this report, when reporting on production values, the following classification according to [Antics et al. 2013] and Directive 2009/28/EC [EU 2009] which has been adopted by Eurostat and national statistics offices, will be used:

- Power generation
- Direct use
- Ground source heat pumps

The report aims to highlight R&D challenges of the different sectors of the geothermal industry in Europe. Chapter 2 describes briefly the sub-technologies and identified R&D opportunities. Chapter 3 describes the EU market status, targets and projections. Chapter 0 analyses the economic aspects and implications: cost aspects focus on capital costs (CAPEX), the operational expenditure (OPEX), and the resulting cost of the energy produced. Chapter 5 investigates EU policies related to geothermal energy. Chapter 6 describes past and current EGS projects worldwide and identifies issues needed to be overcome enabling large scale deployment of the technology. The reader is referred to the 2014 JRC Geothermal Status Report for more detailed descriptions of technologies and environmental impact associated with geothermal energy utilization.

# 2 TECHNOLOGY STATUS AND DEVELOPMENT

## 2.1 Power Production

The world average geothermal power plant's annual capacity factor (CF) is estimated at 70-80%. Even higher values up to 97-98 % might be achieved, but with increased maintenance costs; which might be compensated by higher-priced electricity.

### 2.1.1 Heat to power conversion cycles

The efficiency of the heat to power conversion cycle and the parasitic load and pump demand play an important role when estimating the economic factors under different conditions and the terms of reference should be established when collecting and comparing data from different authors. Dry steam power plants have the highest efficiency among all geothermal power plants, reaching values of 50-70 % [DiPippo 2012]. 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 hot water since the conversion factor in a heat exchanger is far greater than converting heat to electricity. The ORC binary plants can reach efficiencies between 25 % and 45 % [Emerging Energy Research 2009]. The kalina binary cycle can, under certain design conditions, operate at higher cycle efficiencies of between 30 % and 65 % [Emerging Energy Research 2009]. Efficiency is largely determined by the reservoir temperature but R&D efforts that enable efficiency of the conversion process include better heat exchangers and the nozzles. Efficiency enhancements are not a priority of the sector.

### 2.1.2 Drilling methods

Drilling represents 30 % to 50 % of the cost of a hydrothermal geothermal electricity project and more than half of the total cost of EGS. Lowering drilling costs is therefore a key issue for reducing the capital investment and operation costs of geothermal power plants. The established deep drilling technique is the rotary drilling. Tri-cone rotary bits were introduced in 1909 and supplemented in the 1970s by the polycrystalline diamond bit which has until now not been widely adopted by the geothermal industry.

Geothermal drilling benefits from on-going industry improvements. Examples are the placement of casings while drilling in the 1950s; top drive power swivels, air/foam balanced drilling, and polycrystalline diamond compact (PDC) bits in the 1970s; micro drill and coiled tubing in the 1980s; and horizontal drilling, reverse circulation cementing, logging while drilling, and environmentally safe fluid formulations since the 1990s.

Despite these improvements, drilling costs continue to be high and therefore considerable emphasis has been placed on the development of new drilling technologies [Dumas et al. 2013]. The development of new drilling methods is ongoing. They include: jetting (high performance/mud jet bits), thermal drilling (spallation, molten ion penetration, plasma bit), direct stream, millimetre wave, high voltage electro impulses. Many of those new methods have been demonstrated in the laboratory but not under field conditions at significant depths.

Currently, two projects focusing on deep drilling are operating within the Horizon 2020 framework. The DESCRAMBLE project[1] drills into super-critical conditions and studies drilling components as well as well completion materials, design and control. The Thermodrill project combines conventional rotary drilling with water jetting with the aim of achieving 50 % faster drilling in

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[1] www.descramble-h2020.eu

hard rock in addition to reduce costs by 30 % as well as reducing induced seismicity risks. Both projects started in 2015.

### 2.1.3 Drilling technologies and completion

High mass flows and therefore high volume flows necessitate large diameter wells for geothermal energy production. High temperatures in geothermal reservoirs also call for alternate equipment to that routinely used in the oil and gas industry. As geothermal wells, particularly those for EGS systems tend to be several km deep the need for technologies minimising tripping times are necessary to keep costs down. Casing drilling minimises tripping times due to pulling and running of the drill string and has been applied when problems are expected but does not offer faster rate of penetration (ROP) than conventional drilling. Coil tubing drilling offer fast drilling process with shorter tripping times but is limited by depth. The current challenges facing the drilling industry are not technical but commercial. Drilling days have been reduced towards lowering costs but completion costs are still expensive and can be lowered by decreasing complexity and more standardisation of well components. A more thorough description of this highly important aspect of geothermal plants may be found in Section 6.3.2 and Section 6.3.3.

Developments are ongoing towards fully automated drill rigs leading to less personnel risk and decreased drilling duration. Finally, it is anticipated that geothermal drilling will start using rotary steerable systems (RSS) adopted from the Oil and Gas industry in facilitating extended reach drilling and/or deeper directional wells.

### 2.1.4 Heat exchangers

In geothermal power plants, a range of heat exchangers can be installed, fulfilling various tasks such as pre-heating, and superheating and serving as evaporator or condenser.

Heat exchangers frequently come in contact with corrosive fluids at high temperatures in geothermal plants. The development of heat exchangers from new materials is mentioned as a key action that may benefit several technologies (solar thermal and hybrid plants, CHP, fuel cells) in the Integrated Roadmap of the SET-Plan.

### 2.1.5 Emission abatement systems

Gases that do not condense with the steam in the power plant's condensers are referred to as non-condensable gases (NCG). The main NCG species in geothermal steam are carbon dioxide ($CO_2$) and hydrogen sulphide ($H_2S$). Ammonia ($NH_4$) is often absent but may be up to 10 vol. % in the steam. Smaller amounts of $H_2$, $N_2$, Ar, $CH_4$, CO and Hg may exist among the emitted gases.

Of these gases, $H_2S$ is the gas of highest concern due to its toxic nature and therefore emphasis will be made on $H_2S$ abatement systems. Depending on site specific factors, a specific process may have to be incorporated into the plant process to remove $H_2S$ from the emissions stream.

Many technologies exist for removing $H_2S$ from gases and the selection of technology depends on gas amount and composition and the level of $H_2S$ removal required. These include liquid redox sulphur recovery processes (e.g. Stretford, LO-CAT), the modified Claus process (gas phase oxidation), burn/scrub processes, burn/vent processes, amines and physical solvents, scrubbing $H_2S$ with caustic soda, scrubbing with other alkaline earth minerals, wet sulphuric acid process (WSA), AMIS (Mercury and $H_2S$ removal), direct acid gas injection, Paques/thiopac, ThioSolv, Biox and water adsorption and injection. These technologies are of different maturity, some have been developed for other industries and modified for the geothermal industry and others are developed within the geothermal industry. Recently ENEL Green Power completed the installation their patented AMIS system to all its geothermal power plants in Tuscany reducing $H_2S$ and Hg emissions with efficiency exceeding 95%.

The development emphasis is on process optimisation to minimize chemical additions (primarily for pH adjustments) and to treat gas streams to minimize the degrading of adsorbents.

### 2.1.6 Re-injection

Geothermal energy is regarded a renewable resource. However, the resource may be overexploited if there is no balance between production and inflow into the resource. The optimum level of long-term sustainable production depends on the resource characteristics. The production and re-injection may have to be amended during the production history and new wells (both production and re-injection wells) are often drilled in strategic locations as better understanding is gained on the geothermal resource behaviour. The production and re-injection rate is then controlled to prevent the adverse effects of premature pressure and temperature declines. The resource behaviour should therefore be monitored by the operators. The resource is frequently monitored by geochemical tracers, seismicity, reservoir pressure and temperature as well as micro-gravity. Results from these monitoring tools are then fed into reservoir simulation models which aid in planning the exploitation of the resource and predicting its behaviour in the future.

Research efforts concentrate on maintaining continuous flow rate without the need of maintaining abnormally high wellhead pressures. Prevention of mineral scaling in the reservoir immediately adjacent to re-injection wells is important. Temperature adjustment (for thermal fracture stimulation and control of the fluid chemistry have to be studied in conjunction to the overall reservoir characteristics (thermal sweep area, active reservoir volume) to enable optimal management of the reservoir.

### 2.1.7 Flexible generation of electricity

The large scale deployment of intermittent power sources such as wind and solar PV calls for measures to stabilise electricity grids. Geothermal EGS-ORC power plants offer the possibility to provide such stabilisation.

EGS are not weather dependent such as other renewable energy sources and can therefore provide base load to the system. In Hawaii, there exists a hydrothermal plant that can be adjusted from 22-38 MW [GEA 2015] although the flexibility of combined heat and power plants can be tested further [JRC 2014]. EGS plants rely on pumps to circulate fluids mining heat from the ground and ORC is always used for power conversion. In ORC plants, the ramp rate may be as high as 30 % of nominal power per minute. Currently, nearly all geothermal plants are operated as base load plants [GEA 2015] since a) sufficient economic considerations have not been offered to ensure acceptable return on investment according to industry survey and b) more research and development is needed to couple geothermal power production with energy storage technology (in other words store heat in the underground for later usage). For dispatchable power, future contracts need to encourage geothermal operators to offer flexibility in power delivery, enabling it to compete with natural gas power plants [GEA 2015].

## 2.2 Direct use

Direct use applications of geothermal fluids range in temperatures from few degrees C to 150 °C. Different categories of direct use exist, for example: space and district heating, greenhouse heating, aquaculture pond heating, agricultural drying, industrial uses, cooling, snow melting, bathing and swimming [Lund 2011]. The main applications worldwide are bathing & swimming and space/district heating.

For heating, direct use applications depend on technical advances of heat exchangers in other sectors as the geothermal fluids are often not suitable to be distributed to district heating networks.

Concerning the development of the technology, already in 1984, Gudmundsson stated

”the technology of direct applications is available and should not be a barrier to further developments” [Gudmundsson 1985]. Standard equipment is being used for direct use projects. Recently, [Blanco Ilzarbe et al. 2013] found that there are not many new patents in the area of direct use besides some developments regarding integration of geothermal energy use in buildings.

At the moment, district heating systems is the geothermal sector with the most dynamic development [EGEC 2013a]. Newer developments include concepts to extend lifetime of doublet design projects by drilling a third production well and converting the former two wells into injection wells (triplet system). This concept, mainly applied in France, can allow for 30 additional years of use of the geothermal resource [EGEC 2013a]. Concerning new space/district heating systems, more and more triplet systems are installed. Also smaller systems are becoming more common with shallower resources, sometimes used in combination with large heat pump systems [EGEC 2013a]. More recently, geothermal resources of low to medium temperature are now used for combined heat and power production with a binary cycle power plant first and subsequent direct use, which also improves the economics of geothermal projects [Lund 2011].

## 2.3 Shallow geothermal

Ground source heat pumps (GSHP) use shallow geothermal energy which is available almost everywhere. They convert the low temperature geothermal energy to thermal energy at a higher temperature which can be used for space or water heating [Ochsner 2008]. Usually, a refrigerant is used as the working fluid in a closed cycle [Self et al. 2013]. 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) [Ochsner 2008, Vellei 2014].

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

Despite the successes in the past and continuous growth, RD&D in GSHP is focussing on further increasing the efficiency of GSHP systems and reducing costs [Angelone & Labini 2014a]. The main development areas include ease of maintenance and repair, improved control systems, more efficient working fluids, and increased efficiency of auxiliaries such as pumps and fans [Angelone & Labini 2014a]. Ground collectors should be improved by optimisation of design and grouting material [RHC 2014]. Currently mainly plastic tubes are used for ground collectors which offer low cost and corrosion resistance but show low thermal conductivity [Angelone & Labini 2014b].

The Geothermal Energy Roadmap of the European Technology Platform on Renewable Heating & Cooling recommends the development of new antifreeze fluids that are environmentally benign, and offer better thermal characteristics than current fluids [RHC 2014]. It is anticipated these above-mentioned advances can increase the efficiency of GSHP systems. The borehole thermal resistance (Rb) Performance Indicator has been reduced by more than 40 % over the last ten years. The overall impact of this value to a defined shallow geothermal system is given by the Hellström-efficiency, which increased from below 60 % to about 75 % in state-of-the-art installations over the past 10 years. There is still room for improvement, so provided the technology progress is continued, efficiencies of about 80 % in 2020 seem achievable [JRC 2014].

# 3 MARKET STATUS AND DEVELOPMENT

## 3.1 Deployment trends

The capacity of all geothermal energy installations worldwide amounted to about 82 GW in 2015 (Figure 1). Deployment of GSHP is greatest, followed by direct use, and power generation (Figure 1). Lead markets for geothermal energy are the Americas, Europe, and Asia.

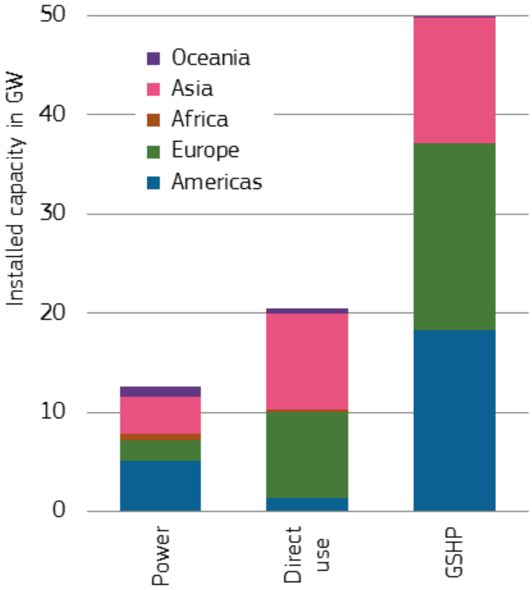

*Figure 1 Global installed geothermal capacity in 2015*
*Sources:* [Bertani 2015, Lund & Boyd 2015], *own analysis*

The deployment of the individual sub-technologies differs considerable between countries (Figure 2). In some countries such as the United States, China and Sweden, GSHP dominate the geothermal energy market. In other countries, power generation leads deployment.

The highest total installed capacity of geothermal energy is in the United States (about 21 GW), followed by China (about 18 GW), and Sweden (about 5.6 GW). The ten countries that have the highest installed capacity account for about 75 % and the 15 countries that have the highest installed capacity account for about 85 % of total installed capacity worldwide.

In recent years, the capacity of geothermal energy increased steadily. Capacity for power production has increased by 16 %, direct use by 45 % and installed capacity of GSHP has even increased by more than 50 % between 2010 and 2015.

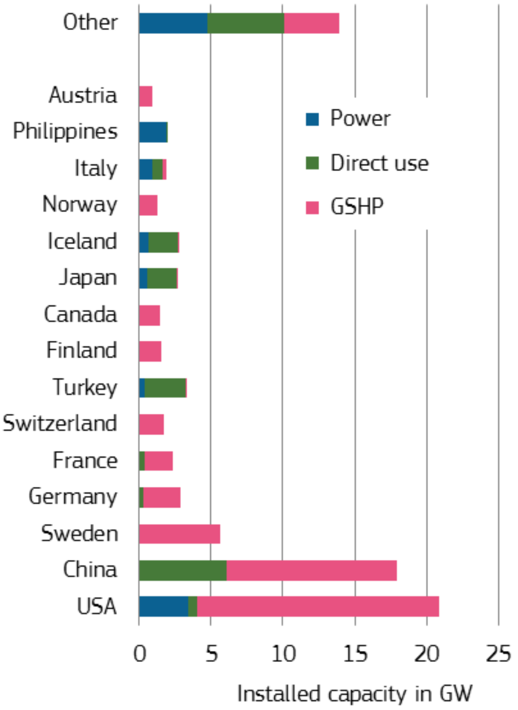

*Figure 2 Global installed geothermal capacity in top 15 countries in 2015 according to country*
*Sources:* [Bertani 2015, Lund & Boyd 2015], *own analysis*

## 3.2 Geothermal power

### 3.2.1 Power turbines

The global market in geothermal power is dominated by four major manufacturers (Toshiba, Mitsubishi, Ormat, Fuji) accounting for about 80 % of the installed capacity [BNEF 2015]. In Europe, Ansaldo-Tosi leads the market with about 30 % of capacity [EGEC 2014]. Other prominent players in Europe are Mitsubishi, Fuji, Ormat, and GE/Nuovo Pignone (Figure 3). Ansaldo-Tosi and GE/Nuovo Pignone are mainly active in

Italy with capacity installed in hydrothermal power plants existing since a very long time. Other European players such as Siemens or Alstom do not play a major role.

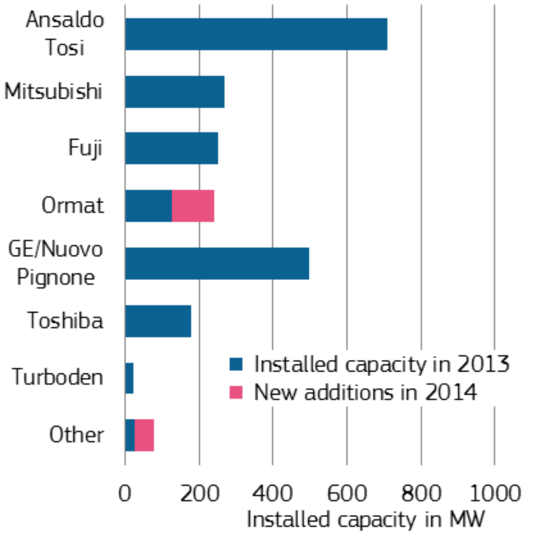

*Figure 3 Installed capacity for power generation and new additions in Europe according to turbine manufacturer*
*Sources:* [EGEC 2013a, EGEC 2014]

Capacity additions in Europe in 2014 took place in Turkey only with about 170 MWe of additional installed capacity in 2014. A majority of the new power plants (115 MWe) were supplied by Ormat. When we look at the different sub-technologies of power production, we see that all new installations in 2014 were ORC plants (Figure 4).

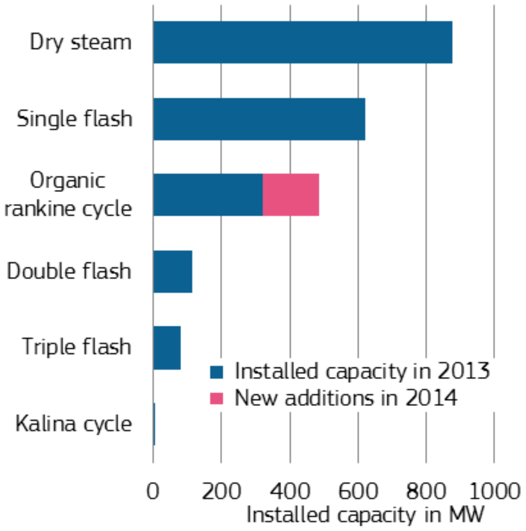

*Figure 4 Installed capacity for power generation and new additions in Europe according to technology*
*Source:* [EGEC 2013a, EGEC 2014]

This development is consistent with developers moving into the more widespread medium enthalpy regions where flash and direct steam cycles (suitable for high enthalpy regions) are not suitable. Still, the major share of installed capacity is by conventional (dry steam and flash) power plants.

### 3.2.2 Power production

In 2015, about 12 GWe of geothermal power plants were installed worldwide and of these, 770 MWe have been added in 2014, again a record in annual installations [JRC 2015]. The main growth took place in Africa with additions of 375 MWe, followed by Europe (about 210 MWe), and Australasia (about 170 MWe). Geothermal electricity generation has continuously increased and in 2014, about 74 TWh have been produced (Figure 5) which is about 0.3 % of global electricity production.

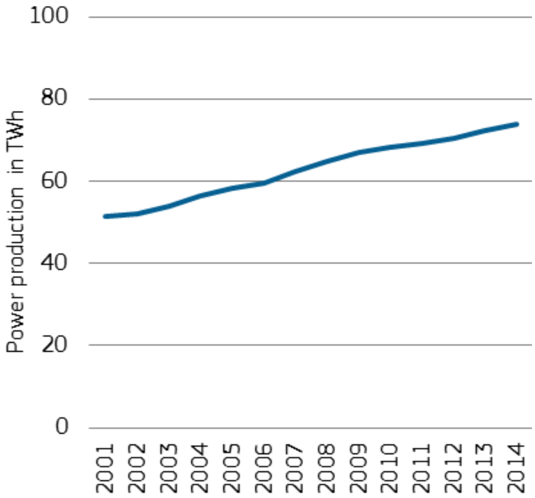

*Figure 5 Global geothermal power production between 2005 and 2014*
*Sources: Own calculations, based on* [Observ'ER 2013, OECD/IEA 2013, REN21 2015]

The 51 geothermal power plants in the EU-28 account for about 0.95 GWe capacity. No additional capacity has been added in 2014. In terms of power plant technology, dry steam and single flash technology dominate the European market, with shares of 40 % and 42 %, respectively [EGEC 2014].

The production of electricity from geothermal in Europe reached about 12 TWh in

2014 and 5.6 TWh in the EU according to [EGEC 2014]. Figure 6 shows that annual electricity production from geothermal energy in the EU did not significantly increase during the past years. In 2013, geothermal energy provided about 0.2 % of the total final electricity demand (in total about 2800 TWh) and 0.8 % of the electricity generated by renewable sources in the EU. The capacity factor of the geothermal power plants in Europe was about 76 %, which is comparable to the past years since again some commissioning and maintenance took place in 2014 [EGEC 2013a, EGEC 2014].

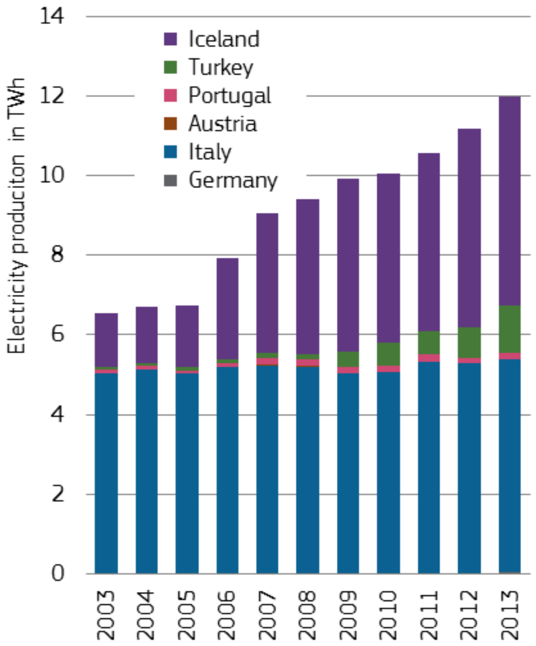

*Figure 6 Electricity generation from geothermal energy in Europe*
*Sources:* [Eurostat 2015], *own analysis*

### 3.2.3 Power production targets

According to Directive 2009/28/EC, each Member State of the European Union must adopt a National Renewable Energy Action Plans (NREAP) that details how it will reach their binding target for the share of energy from renewable sources in gross final energy consumption in 2020 [EU 2009].

19 EU countries have included geothermal energy in their NREAP [Sigfusson & Uihlein 2015]. Latest data available shows that in 2014, EU targets were reached for shallow geothermal (mainly GSHP) while the targets for geothermal power and deep geothermal (mainly direct use) were slightly missed (Table 1).

*Table 1 Geothermal energy in the EU: NREAP targets and progress*

| | Shallow geothermal | Deep geothermal | Geothermal power |
|---|---:|---:|---:|
| | GWhth | GWhth | MWe |
| 2014 actual[a] | 43930 | 10120 | 947 |
| 2014 target | 24410 | 13976 | 987 |
| 2020 target | 49340 | 30590 | 1612 |

Sources: [ECN 2011, EurObserv'ER 2013, EGEC 2014, EurObserv'ER 2015], own analysis

In total, 12 EU Member States have set NREAP targets for geothermal power (Table 2). Current deployment is about 95 % of the 2014 and about 61 % of the 2020 target for the EU.

*Table 2 Installed geothermal power production capacity in the EU in MW: NREAP targets and progress*

| Country | 2014 actual | 2014 target | 2020 target |
|---|---:|---:|---:|
| Austria | 1.8 | 1 | 1 |
| Belgium | | 0 | 3.5 |
| Czech Republic | | 4.4 | 4.4 |
| Germany | 28.4 | 57 | 298 |
| Greece | | 20 | 120 |
| Spain | | 0 | 50 |
| France | 13.1 | 47 | 80 |
| Hungary | | 4 | 57 |
| Italy | 875.5 | 820 | 920 |
| Portugal | 23 | 30 | 75 |
| Romania | 0.05 | 0 | 0 |
| Slovakia | | 4 | 4 |
| EU | 947 | 987 | 1613 |

Sources: [ECN 2011, EGEC 2014], own analysis

The main reason for this development is due to the slow growth of geothermal power production in France and Germany, where targets have not been reached in 2014. In France, no geothermal power development has occurred for the last 10 years except the EGS of Soultz-sous-Forêts and targets will not be reached. In Germany, a number of projects are under construction. In total, another 670 MWe of geothermal power have to be installed in the EU in order to reach the 2020 target, an increase of 70 % compared to current capacity.

### 3.2.4 Market projections and outlook

The net geothermal electricity production in the EU 28 was about 5.6 TWh in 2014 (0.8 % of total renewable electricity production 0.2 % of total electricity consumption) and the absolute generation value has been relatively stable since 2004. The net electricity production in Germany, the main growing market has increased from 12 GWh in 2008 to 67 GWh in 2013. Production in the largest market Italy has remained relatively stable at around 5200 GWh. Currently the utilisation of geothermal resources in the EU is about 3 % of the economic potential of 174 TWh in 2030 [van Wees et al. 2013] indicating a large scope of growth in the sector.

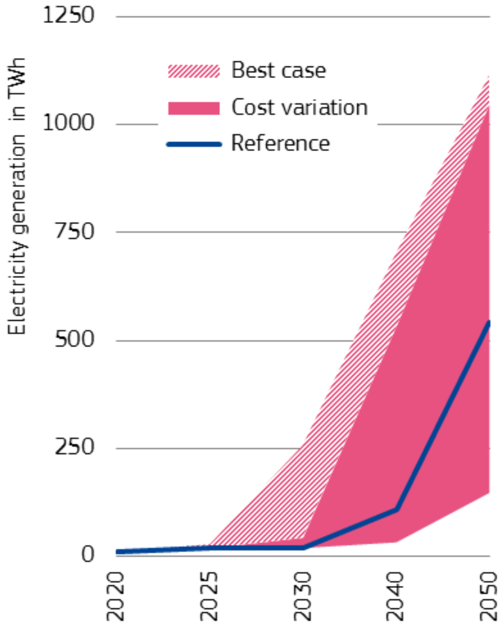

*Figure 7 Expected geothermal electricity production in the EU28 from 2020 to 2050*

We used the JRC-EU-TIMES model to calculate the contribution of geothermal to the EU energy system [Simoes et al. 2013] in the future. For the reference scenario, values in Section 0 based on the same methodology as in [Carlsson et al. 2014] were used. Three additional scenarios were modelled. First, a low cost scenario which assumes a reduction of 6 % of CAPEX and OPEX for hydrothermal organic rankine cycle (ORC) systems and a reduction of 21 % for ORC plants with an enhanced geothermal system (EGS). The high cost scenario assumes higher CAPEX and OPEX (15 % for hydrothermal and 24 % for ORC-EGS). A best-case scenario with 50 % reduction of drilling and power plant costs compared to the reference was also modelled.

Under the reference scenario, annual electricity generation will increase from 5.6 TWh in 2020 to about 540 TWh in 2050 (Figure 7). Installed capacity will increase from 0.9 GW to about 72 GW (Figure 8).

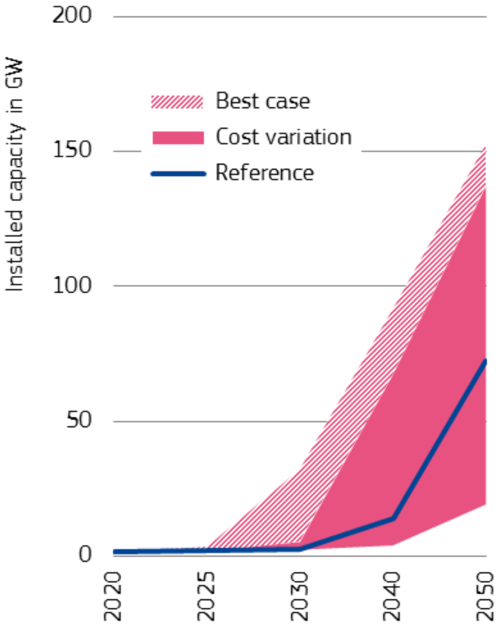

*Figure 8 Expected installed geothermal power capacity in the EU28 from 2020 to 2050*

In the case of the high cost scenario, the difference to the reference scenario is small until 2030 but can reach a reduction of two thirds in 2050. Installed capacity and power production are greater under the low cost scenario, compared to the reference scenario already in 2030. In 2050, installed capacity and power generation are almost 50 % greater than in the reference scenario.

The most optimistic scenario shows twofold capacity and power generation in 2050 compared to the reference (up to 1100 TWh electricity generation and 150 GW installed capacity). This means that achievements in the area of drilling technologies leading to lower drilling costs can have big impacts on the deployment of geothermal energy in the future.

In the reference scenario, the EU potential for geothermal power production is only exploited to 21 % in 2050 (Figure 9).

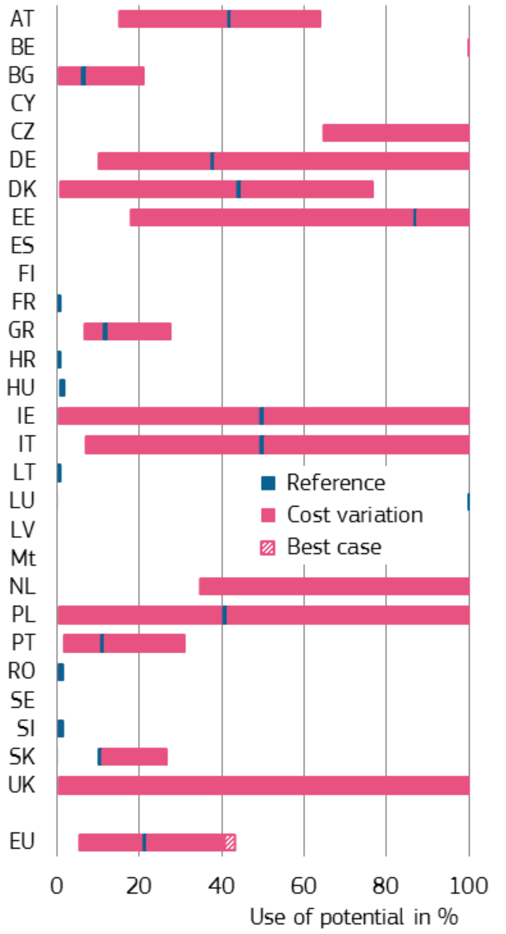

*Figure 9 Use of geothermal potential in the EU28 in 2050*

In the base case scenario, the potential is used to 43 % in the EU; while in the high cost scenario, the potential is only used to 6 %. In five countries, the potential is fully used in 2050 in the reference scenario (Belgium, Czech Republic, Luxembourg, Netherlands, United Kingdom) and in five more countries in the low cost scenario (Germany, Estonia, Ireland, Italy and Poland).

A great barrier towards large scale uptake of geothermal energy is financing [Sigfusson & Uihlein 2015]. Since the resource is only confirmed after drilling, high risk is involved in geothermal finance. Risk insurance funds aim at alleviating the shortage of insurance policies for the resource risk. The introduction of a risk insurance fund cannot be modelled directly in the JRC-EU-TIMES model. However, the interest rate for financing geothermal projects could be used as a proxy since reduction of risks might offer the opportunity to get capital at lower interest rates. A low risk and very low risk scenario (10 % and 8 % interest rate, compared to 12 % in the reference scenario) were modelled. Both scenarios lead to higher deployment of geothermal compared to the reference scenario (53 % and 96 % higher electricity generation in 2050). Compared to the low cost scenario, deployment will still be smaller for low risk scenario but very similar for the very low risk scenario (Figure 10). This shows that R&D investments to lower technology costs are of higher importance compared to risk mitigation via a risk insurance fund in the long term.

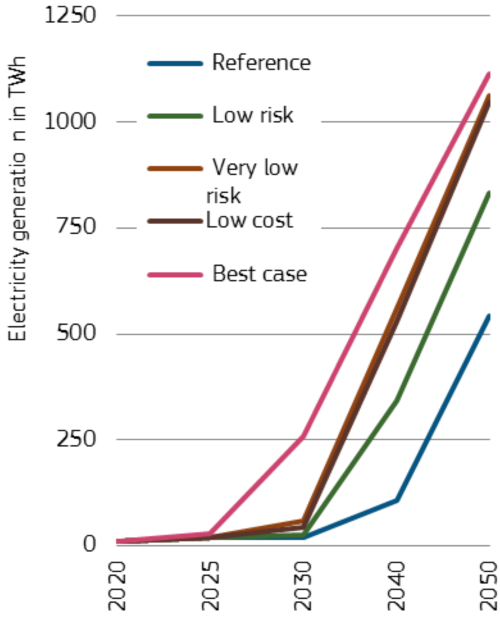

*Figure 10 Scenario analysis of perceived risk*

## 3.3 Direct use

Statistics on installed capacity and heat production from direct heat systems is difficult to obtain and often not reliable. Data for this report was taken mainly from [Lund & Boyd 2015] which refers to installed capacity and production in 2014.

The commissioning rate of new installations in the past was low leading to heat production of about 10120 GWh$_{th}$ in 2014 which is an increase of 720 GWh$_{th}$ or 8 % compared to 2012 (9400 GWh$_{th}$). The most dynamic sector of direct use is still district heating systems where almost 80 MW$_{th}$ have been installed in Europe in the last year and total production reached about 4260 GW$_{th}$ [EGEC 2014] which is already about 40 % of total heat production from direct use systems.

Compared to geothermal power, more countries have included direct use in their NREAP (17 Member States). When we look at 2014 targets, only five countries (Austria, Bulgaria, Spain, Hungary and Slovakia) have reached their 2014 NREAP target. In terms of absolute distance to target, France (about 1760 GWh), Germany (about 1330 GWh), and the Netherlands (910 GWh) are furthest away from the 2014 target.

*Table 3 Geothermal direct use in the EU in GWh: NREAP targets and progress*

| Country | 2014 actual | 2014 target | 2020 target |
|---|---|---|---|
| Austria | 430 | 291 | 465 |
| Belgium | 30 | 45 | 66 |
| Bulgaria | 327 | 35 | 105 |
| Czech Republic | 25 | 174 | 174 |
| Germany | 925 | 2256 | 7978 |
| Greece | 188 | 256 | 593 |
| Spain | 62 | 44 | 110 |
| France | 1380 | 3140 | 5815 |
| Hungary | 2659 | 1663 | 4152 |
| Italy | 1995 | 2942 | 3489 |
| Lithuania | 9 | 47 | 58 |
| Netherlands | 396 | 1303 | 3012 |
| Poland | 206 | 500 | 2070 |
| Portugal | 108 | 186 | 291 |
| Romania | 490 | 547 | 930 |
| Sweden | 0 | 0 | 0 |
| Slovenia | 177 | 221 | 233 |
| Slovakia | 682 | 326 | 1047 |
| United Kingdom | 30 | 0 | 0 |
| EU | 10120 | 13976 | 30589 |

Sources: [ECN 2011, Lund & Boyd 2015], own analysis

For the EU as whole, 3800 GWh more have to be produced in order to reach the 2014 NREAP target, which is about 34 % of current production. In order to reach the 2020 target, current production of heat from geothermal direct use has to more than triple.

## 3.4 Ground Source Heat Pumps (GSHP)

The European heat pump and also the GSHP market is now a market dominated by major manufacturers [Sigfusson & Uihlein 2015]. The countries of origin of those manufacturers mirror the main markets for GSHP with many big producers being located on Germany and Sweden (e.g. BDR, Bosch, Danfoss, Nibe and Stiebel Eltron).

In total, 15 EU Member States have set NREAP targets for ground source heat pumps (Table 4).

*Table 4 Heat production from GSHP in the EU in GWh: NREAP targets and progress*

| Country | 2014 actual | 2014 target | 2020 target |
|---|---|---|---|
| Austria | 1440 | 140 | 302 |
| Belgium | 335 | 647 | 1710 |
| Germany | 4200 | 4350 | 6059 |
| Denmark | 695 | 1849 | 2314 |
| Greece | 135 | 174 | 582 |
| Spain | 210 | 247 | 471 |
| France | 2775 | 4652 | 6629 |
| Hungary | 110 | 186 | 1244 |
| Italy | 472 | 1303 | 6071 |
| Netherlands | 880 | 1698 | 2814 |
| Romania | 32 | 23 | 93 |
| Sweden | 15200 | 5687 | 9478 |
| Slovenia | 96 | 256 | 442 |
| Slovakia |  | 23 | 47 |
| United Kingdom | 500 | 3175 | 11083 |
| EU | 27080 | 24409 | 49340 |

Sources: [ECN 2011], own analysis

Heat production from GSHP in 2014 was not available directly from statistics. Instead, we estimated it using the heat production according to [ECN 2011] for 2012 and extrapolating it to 2014 using information on the number of GSHP installed from [EurObserv'ER 2013, EurObserv'ER 2015]. According to this estimate, heat production from GSHP in the EU surpassed the NREAP target in 2014 and reached about 89 % of the 2020 target already (Table 4).

More than half of all countries have reached their target; Austria and Sweden have even reached the 2020 target already. Slovakia and the UK are furthest from reaching their 2014 NREAP targets in relative terms. In absolute terms, about additional 5 400 GWh have to be produced annually in order to reach the 2020 NREAP target, which corresponds to an increase of current production by about 11 %

# 4 ECONOMIC ASPECTS AND COST COMPONENTS

The JRC performs techno-economic assessments of renewable energies for different current and future technologies on a regular basis [Carlsson et al. 2014]. The assessment includes the quantification of cost as well as the breakdown of capital expenditure. In the current contribution the CAPEX has been broken down in more suitable manner for geothermal power plants. For geothermal energy, three reference power plant types are assessed:

- Flash power plant extracting fluid from a hydrothermal system at 2.5 km depth;
- ORC power plant extracting fluid from a hydrothermal system at 2.5 km depth;
- ORC power plant extracting 165 °C fluid at 100 kg s$^{-1}$ from EGS at 5.5 km depth.

The following sections provide the CAPEX breakdown for the power plant types. Assumptions for cost variations of ORC plants (both hydrothermal and EGS) for sensitivity analysis of energy system modelling are furthermore provided.

### 4.1.1 Flash power plants from a hydrothermal reservoir

The CAPEX breakdown for a flash power plant is given in Figure 11. Mechanical equipment costs represent more than 51 % of CAPEX, followed by owner's development cost and project indirect costs.

Table 5 summarises the economic indicators for the flash power plant. The upper CAPEX range assumes that wells are 3.5 km deep instead of 2.5 km.

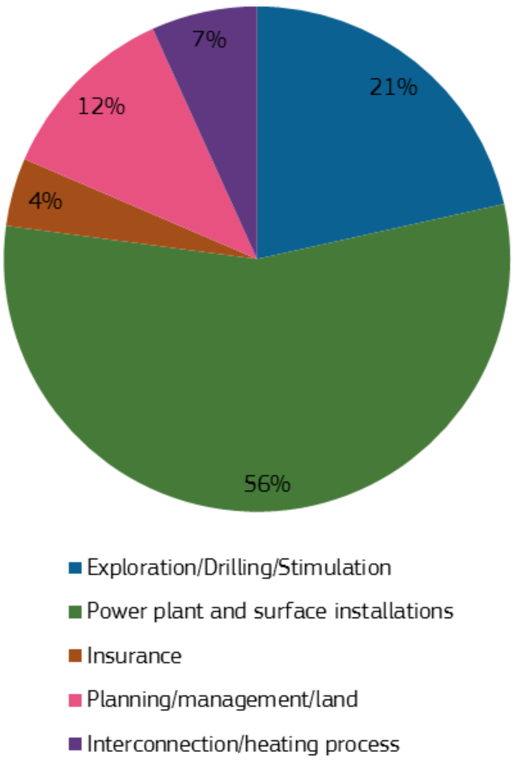

*Figure 11 CAPEX breakdown of a hydrothermal flash power plant*

*Table 5 Indicators for a flash power plant extracting fluid from hydrothermal system at 2.5 km depth*

| **Parameter** | **Unit** | **2010** | **2020** | **2030** | **2040** | **2050** |
|---|---|---|---|---|---|---|
| Net electrical power | MW | 45 | 45 | 45 | 45 | 47 |
| Gross electrical power | MW | 47 | 47 | 47 | 47 | 47 |
| Thermal power | MW | 196 | 191 | 188 | 184 | 189 |
| Net efficiency | % | 23 | 23.5 | 23.9 | 24.4 | 24.9 |
| Max. capacity factor | % | 95 | 95 | 95 | 95 | 95 |
| Avg. capacity factor | % | 95 | 95 | 95 | 95 | 95 |
| Technical lifetime | years | 30 | 30 | 30 | 30 | 30 |
| CAPEX ref | €$_{2013}$/kW$_e$ | 5530 | 4970 | 4470 | 4020 | 3610 |
| CAPEX low | €$_{2013}$/kW$_e$ | 2500 | 2500 | 2500 | 2500 | 2500 |
| CAPEX high | €$_{2013}$/kW$_e$ | 5930 | 5370 | 4870 | 4420 | 4010 |
| CAPEX floor | €$_{2013}$/kW$_e$ | 2000 | 2000 | 2000 | 2000 | 2000 |
| CAPEX learning rate | % | - | - | - | - | - |
| FOM | % of CAPEX ref. | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 |

### 4.1.2 ORC hydrothermal power plant

A reference power plant for the year 2013 was constructed with the aid of Geoelec's software [Dauenhauer 2014]. The power plant is an ORC plant receiving 100 kg $s^{-1}$ of 165 °C water from a single production well and delivering 60 °C water into a single injection well. The gross capacity of the plant is 5.1 MW and net capacity is 4.4 MW. The total CAPEX of the plant is $EUR_{2013}$ 37.3 million ($EUR_{2013}$ 7.3 million per MW) and brakes down as shown in Figure 12. All cost aspects within the ETRI are accounted for.

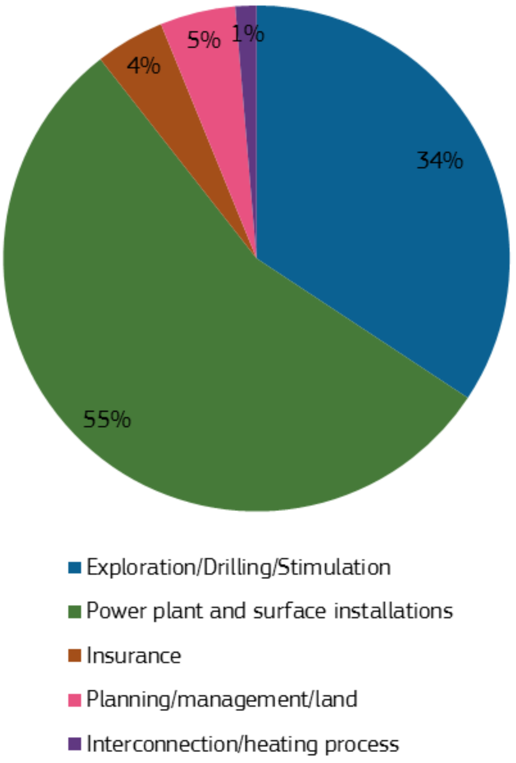

*Figure 12 CAPEX break down for ORC hydrothermal power plant*

### Net efficiency of power plant

The development of efficiency of the ORC hydrothermal power plant was assumed to increase linearly from the current value of 10.6% (net power as a percentage of energy contained in the geothermal source fluid) to the value of the Otake pilot binary plant in Japan of 12.9 % in 2050 [DiPippo 2015]. Pumps and auxiliary systems are assumed to consume 15 % of gross power output.

### Learning curves

The estimated cost of the ORC hydrothermal power plant was adjusted to the learning curves for flash power plant of [Schröder et al. 2013] in the following manner: First, a linear cost reduction was assumed between 2010 and 2020. Then the cost in 2013 according to the curve could be estimated at EUR 4.344 million per MW. Second, the ratio between the cost of the reference plant ($EUR_{2013}$ 7.3 million per MW) and the learning curve plant ($EUR_{2013}$ 4.344 million per MW) was calculated (1.67) and the costs could be predicted (Table 6).

*Table 6 Learning curve for CAPEX of ORC hydrothermal power plant*

| Year | [Schröder et al. 2013] $EUR_{2010}$ $kW^{-1}$ | CAPEX reference $EUR_{2013}$ $kW^{-1}$ |
|---|---|---|
| 2010 | 4200 | 7483 |
| 2020 | 3775 | 6726 |
| 2030 | 3392 | 6043 |
| 2040 | 3049 | 5432 |
| 2050 | 2740 | 4882 |

### Variations in cost estimations

A high CAPEX was established by adding one extra production or injection well. The low value for CAPEX was achieved by lowering drilling cost by half. The cost of insurance also altered as the premium is proportional to the costs associated with drilling and reservoir stimulations. The very low cost scenario includes lowering drilling cost by half and lowering the cost of all surface installations from EUR 4 million to EUR 2 million per MW (Table 7).

*Table 7 CAPEX shares in % for ORC hydrothermal power plant*

| CAPEX item | Reference | Low cost | High cost | Very low cost |
|---|---|---|---|---|
| Exploration/Drilling/ Stimulation | 34 | 41 | 22 | 32 |
| Power plant & surface installations | 55 | 48 | 59 | 42 |
| Insurance | 4 | 5 | 12 | 17 |
| Planning/ management/ land | 5 | 4 | 5 | 7 |
| Interconnection/ heating process | 1 | 1 | 1 | 2 |

### Summary of ORC hydrothermal data

Table 8 gives an overview of the data used in the JRC-EU-TIMES model for the ORC hydrothermal power plant. The FOM was maintained as 2 % of CAPEX for the years 2010 to 2050 as assumed in [Carlsson et al. 2014].

*Table 8 Overview of CAPEX and OPEX values for the ORC hydrothermal power plant*

| | Unit | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Technical | | | | | | |
| Net electrical power | MW | 4.4 | 4.6 | 4.9 | 5.1 | 5.3 |
| Gross electrical power | MW | 5.5 | 5.8 | 6.1 | 6.3 | 6.7 |
| Thermal power | MW | 41 | 41 | 41 | 41 | 41 |
| Net efficiency | % | 10.6 | 11.2 | 11.8 | 12.3 | 12.9 |
| Max capacity factor | % | 95 | 95 | 95 | 95 | 95 |
| Avg. capacity factor | % | 95 | 95 | 95 | 95 | 95 |
| Costs | | | | | | |
| Overnight corrected CAPEX ref | €$_{2013}$ kW$^{-1}$ | 7483 | 6726 | 6043 | 5432 | 4882 |
| Overnight corrected CAPEX low | €$_{2013}$ kW$^{-1}$ | 7009 | 6300 | 5660 | 5088 | 4572 |
| Overnight corrected CAPEX high | €$_{2013}$ kW$^{-1}$ | 8614 | 7743 | 6957 | 6253 | 5620 |
| Overnight corrected CAPEX floor | €$_{2013}$ kW$^{-1}$ | 4946 | 4446 | 3995 | 3591 | 3227 |
| FOM | % Capex ref | 2 | 2 | 2 | 2 | 2 |

## 4.1.3 ORC EGS Power plant

### Reference cost and cost breakdown

A reference EGS power plant for the year 2013 was constructed with the aid of Geoelec's software [Dauenhauer 2014]. The power plant is an ORC plant receiving 100 kg s$^{-1}$ of 165 °C water from a single production well and delivering 60°C water into a single injection well. The gross capacity of the plant is 5.5 MW and net capacity is 4.4 MW. The total CAPEX of the plant is EUR$_{2013}$ 59.8 million (EUR$_{2013}$ 10.9 million per MW) and brakes down as shown in Table 10. All cost aspects within the ETRI are accounted for.

### Net efficiency of power plant

The development of efficiency of the ORC EGS power plant was assumed to increase linearly from the current value of 10.6% (net power as a percentage of energy contained in the geothermal source fluid) to the value of the Otake pilot binary plant in Japan of 12.9 % in 2050 [DiPippo 2015]. Pumps and auxiliary systems are assumed to consume 15 % of the gross power output.

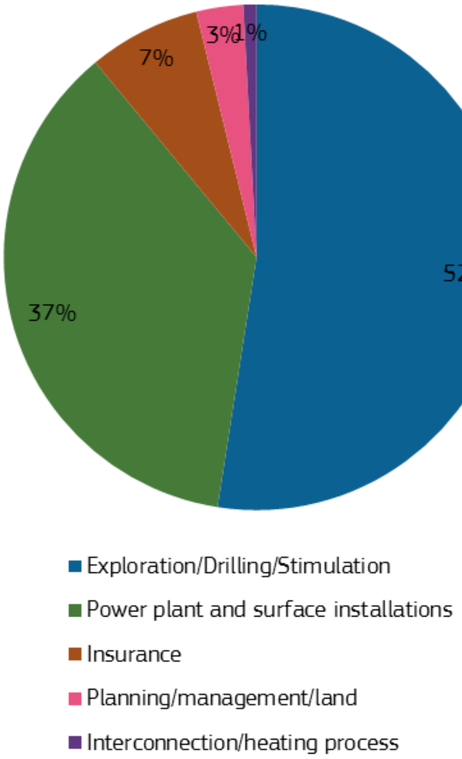

*Figure 13 CAPEX break down for ORC EGS power plant*

## Learning curves

The estimated cost of the ORC EGS power plant was adjusted to the learning curves for flash power plant of [Schröder et al. 2013] in the same manner as shown above (Table 9).

*Table 9 Learning curve for CAPEX of ORC EGS power plant*

| Year | [Schröder et al. 2013] EUR$_{2010}$ kW$^{-1}$ | CAPEX reference EUR$_{2013}$ kW$^{-1}$ |
|---|---|---|
| 2010 | 22014 | 11585 |
| 2020 | 17985 | 9465 |
| 2030 | 15688 | 8256 |
| 2040 | 14999 | 7894 |
| 2050 | 14339 | 7546 |

## Variations in cost estimations

A high CAPEX was established by increasing the cost of reservoir stimulation from EUR 6 million to EUR 8 million and adding one extra production or injection well. The low value for CAPEX was achieved by lowering drilling cost by half. The cost of insurance also altered as the premium is proportional to the costs associated with drilling and reservoir stimulations. The very low cost scenario includes lowering drilling cost by half and lowering the cost of all surface installations from EUR 4 million to EUR 2 million per MW (Table 10).

*Table 10 CAPEX shares in % for ORC EGS power plant*

| CAPEX item | Reference | Low cost | High cost | Very low cost |
|---|---|---|---|---|
| Exploration/Drilling/ Stimulation | 52 | 43 | 60 | 56 |
| Power plant & surface installations | 37 | 46 | 29 | 30 |
| Insurance | 7 | 6 | 8 | 7 |
| Planning/ management/ land | 3 | 4 | 2 | 5 |
| Interconnection/ heating process | 1 | 1 | 1 | 1 |

## Summary of ORC EGS data

Table 11 gives an overview of the data used in the JRC-EU-TIMES model for the ORC EGS power plant. The FOM was maintained as 1.8 % of CAPEX for the years 2010 to 2050 as assumed in [Carlsson et al. 2014].

*Table 11 Overview of CAPEX and OPEX values for the ORC hydrothermal power plant*

| | **Unit** | **2010** | **2020** | **2030** | **2040** | **2050** |
|---|---|---|---|---|---|---|
| Technical | | | | | | |
| Net electrical power | MW | 4.4 | 4.6 | 4.9 | 5.1 | 5.3 |
| Gross electrical power | MW | 5.5 | 5.8 | 6.1 | 6.3 | 6.7 |
| Thermal power | MW | 41 | 41 | 41 | 41 | 41 |
| Net efficiency | % | 10.6 | 11.2 | 11.8 | 12.3 | 12.9 |
| Max capacity factor | % | 95 | 95 | 95 | 95 | 95 |
| Avg. capacity factor | % | 95 | 95 | 95 | 95 | 95 |
| Costs | | | | | | |
| Overnight corrected CAPEX ref | €$_{2013}$ kW$^{-1}$ | 11585 | 9465 | 8256 | 7894 | 7546 |
| Overnight corrected CAPEX low | €$_{2013}$ kW$^{-1}$ | 9135 | 7463 | 6510 | 6224 | 5950 |
| Overnight corrected CAPEX high | €$_{2013}$ kW$^{-1}$ | 14379 | 11748 | 10247 | 9797 | 9366 |
| Overnight corrected CAPEX floor | €$_{2013}$ kW$^{-1}$ | 7019 | 5734 | 5002 | 4782 | 4572 |
| FOM | % Capex ref | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |

# 5 POLICY SUPPORT AND POLICY FRAMEWORK

Policy support can take various forms and a number of support schemes exist within the EU. Policy support mechanisms differ between Member States but they are also different regarding the technology (power production, direct use, GSHP).

### 5.1.1 Geothermal power

Geothermal project development for power production has high upfront cost and can take as little as 3 years but average development time is about five to seven years. In general, EU legislation requires that dispatch priority is given to renewable electricity insofar as the operation of the national electricity system permits [EU 2009]. However, still, market barriers in terms of regulations and market transparency exist [EGEC 2012]. Policy support instruments for geothermal power production include both push and pull mechanisms such as risk insurance funds, feed-in-tariffs (FIT), feed-in-premiums (FIP), tradable certificates, tendering, and soft loans [Sigfusson & Uihlein 2015].

Table 12 gives an overview current of feed-in-tariffs (FIT) and feed-in-premiums (FIP) for geothermal electricity in the EU. FIT show ranges between 5 ct/kWh and 30 ct/kWh and FIP range between about 5 ct/kWh and 13.5 ct/kWh. Quota systems are in place in Belgium, Romania, and the United Kingdom. Revenues from those systems are in the range of 9 ct/kWh to 11 ct/kWh [EGEC 2013b].

As can be seen, a limited number of countries offer support to geothermal electricity. Market-based mechanisms such as feed-in-tariffs are in general dedicated at a large range of renewable energy technologies and probably not ideally suited to support geothermal power projects. [EGEC 2013b] states that " ... as only a handful of geothermal projects have received operational aid over the last five years, it seems therefore premature to talk about the need for more market-based mechanisms ..." The importance of risk insurance funds that cover or alleviate the geological risks (not finding an adequate resource, resource declines over time) is evident and some countries such as France, Germany, Iceland, The Netherlands and Switzerland have set-up risk insurance funds for geothermal energy. EGEC argues for an European geothermal risk insurance to be put in place in the EU in order to pool the risk amongst all projects in the EU [EGEC 2013b].

*Table 12 FIT and FIP for geothermal electricity in the EU*

| Country | Rate and eligibility |
|---|---|
| FIT | |
| Austria | 7.4 ct/kWh, 13 years eligibility |
| Croatia | 15 ct/kWh, 14 years eligibility, extra bonus of up to 15 % can be provided |
| France | 20 ct/kWh plus 8 ct/kWh efficiency bonus, 15 years eligibility |
| Germany | 25 ct/kWh plus 5 ct/kWh bonus for petrothermal systems, 20 years |
| Greece | 9.5 ct/kWh (above 90 °C), 20 % more if no other support received |
| Hungary | Up to 3.9 ct/kWh, depending on time of day, area, period of year and capacity |
| Portugal | 8.4 ct/kWh, Azores only |
| Slovakia | 19 ct/kWh, Tariff decrease if co-funding by government |
| Slovenia | 15.25 ct/kWh, 15 years, limited to 5 MW |
| FIP | |
| Estonia | 5.37 ct/kWh, 12 years eligibility |
| Italy | 9.9 ct/kWh > 1 MW, 13.5 ct/kWh < 1MW, depending on zonal hourly price |
| Slovenia | 10.4 ct/kWh for FIP |
| Netherlands | 6.8 ct/kWh , Values for 2012 |

Sources: [EGEC 2013b, EGEC 2014], own analysis

### 5.1.2 Direct use and GSHP

EGEC provides an overview of financial support schemes for geothermal heat in the EU including incentives for GSHP [EGEC 2013a, EGEC 2013b]. In many countries, financial support for GSHP have been phased out since the technology is considered competitive on the market but is still required in emerging markets [EGEC 2013a].

For GSHP, special focus must also be put on support to remove barriers on awareness but no information on support schemes was available.

[EGEC 2013b] sees geothermal heating technologies (with the exception of EGS) becoming cost competitive with fossil fuel heating which allows a phasing out of subsidies for geothermal direct use and GSHP. Barriers towards high upfront costs still may hinder the sector from progress, and some innovative financing instruments are suggested, such as Energy Service Companies (ESCO) or discounts on electricity consumed by GSHP.

*Table 13 Support schemes for geothermal heat in the EU*

| Country | Invest-ment grant | Tax re-duction | Carbon tax | Other | Country | Invest-ment grant | Tax re-duction | Carbon tax | Other |
|---|---|---|---|---|---|---|---|---|---|
| Austria | X | | | | Ireland | | | X | X[d] |
| Belgium | X | X | | X[a] | Italy | | X | | X[c] |
| Bulgaria | X | | | | Lithuania | X | | | X[d] |
| Cyprus | X | | | | Luxembourg | X | | | |
| Czech Republic | X | X | | | Netherlands | | X | | X[d] |
| Denmark | X | X | X | | Poland | X | | | |
| Estonia | X | | | | Romania | X | | | |
| Finland | X | | X | | Slovenia | X | | | X[c] |
| France | X | X | X | X[b] | Spain | X | | | |
| Germany | | | | X[b,c] | Sweden | | | X | |
| Greece | X | X | | | UK | X | | X | X[c,d] |
| Hungary | X | | | | | | | | |

a) Subsidy; b) Insurance scheme; c) Low interest loan; d) Feed-in-scheme
Sources:: [EGEC 2013a, EGEC 2013b]

# 6 ENGINEERED GEOTHERMAL SYSTEMS

High enthalpy resources have limited occurrence in Europe with Italy (916 MWe) and the Azores (29 MWe) being the only EU member states currently producing electricity from high enthalpy resources. However medium and low enthalpy hydrothermal resources are more widespread giving opportunities to widespread direct heat use and in some cases power plants have been commissioned (Austria, 1.2 MWe, Germany, 27 MWe and Romania, 0.1 MW) and more countries have projects in different stages of development (Czech Republic, Hungary, Latvia, Netherlands, Poland, Slovakia and UK) [Bertani 2015].

In addition to these hydrothermal power plants, the first 1.5 $MW_e$ EGS petrothermal pilot plant at Soultz-sous-Forêts in France is fully operative. An EGS plant relies either on a stimulation of a hot dry reservoir with limited occurrence of open faults and cracks (often termed petrothermal system) or on a stimulation of deep sedimentary aquifers where convection is absent (often termed Hot Sedimentary Aquifer, HSA).

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.

The economic potential of geothermal electricity including EGS for the year 2050 has been estimated at 2570 TWh in the EU covering up to 50 % of its demand [van Wees et al. 2013] However, due to the much more widespread occurrence of hot dry rocks than hydrothermal systems within the EU, there is a need to fully develop and demonstrate the EGS petrothermal technology under various geological conditions if the share of geothermal energy within the EU power mix is to increase from its current 0.2 % of final electricity demand.

This chapter gives an overview of previous and existing EGS projects, evaluates the current state of the art of EGS systems, identifies and analyses the bottlenecks preventing large scale deployment and gives recommendations on the policy and incentives needed to facilitate the advances of the technology.

## 6.1 Overview of EGS projects

A comprehensive overview of EGS projects is provided by [Breede et al. 2013, Breede et al. 2015]. Currently, 14 EGS projects are ongoing worldwide (Figure 14). The majority of them take place in the EU (10 projects).

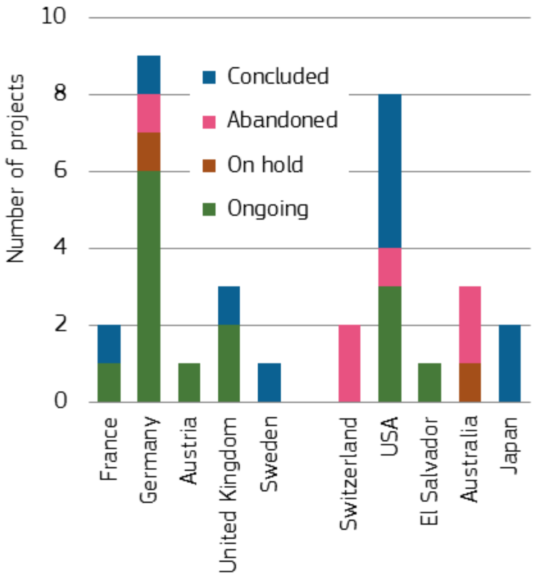

*Figure 14 Number of EGS projects according to country*

In total, 32 EGS projects have been identified worldwide Table 14. In addition to these projects the GEOSTRAS and South Hungarian EGS demonstration projects are in preparation. The majority of them are petrothermal systems (22 projects) while 9 projects are HSA systems. Interestingly, although most projects were conducted as research facilities, a large number (14 projects) were/are commercial developments.

*Table 14 EGS project overview*

| Country | Project | Status | System | Type |
|---|---|---|---|---|
| France | Le-Mayet-de-Montagne | Concluded | Petrothermal | Research facility |
| | Soultz-sous-Forêts | Ongoing | Petrothermal | Research facility |
| Germany | Bruchsal | Ongoing | Hydrothermal | Commercial plant |
| | Bad Urach | Abandoned | Petrothermal | Pilot plant |
| | Landau | On hold | HSA | Commercial plant |
| | Groß-Schönebeck | Ongoing | Petrothermal | Research facility |
| | GeneSys Hannover | Ongoing | Petrothermal | Research facility |
| | Insheim | Ongoing | HSA | Commercial plant |
| | Mauerstetten | Ongoing | Petrothermal | Research facility |
| | Unterhaching | Ongoing | HSA | Commercial plant |
| | Falkenberg | Concluded | Petrothermal | Research facility |
| Switzerland | Basel | Abandoned | Petrothermal | Commercial plant |
| | St. Gallen | Abandoned | HSA | Commercial plant |
| Austria | Altheim | Ongoing | HSA | Commercial plant |
| United Kingdom | Eden | Ongoing | Petrothermal | Commercial plant |
| | Redruth | Ongoing | Petrothermal | Commercial plant |
| | Rosemanowes | Concluded | Petrothermal | Research facility |
| Sweden | Fjällbacka | Concluded | Petrothermal | Research facility |
| USA | Southeast Geysers | Abandoned | HSA | Pilot plant |
| | Fenton Hill | Concluded | Petrothermal | Research facility |
| | Newberry Volcano | Ongoing | Petrothermal | Research facility |
| | Northwest Geysers | Ongoing | Petrothermal | Research facility |
| | Raft river | Ongoing | HSA | Research facility |
| | Bradys | Concluded | HSA | Commercial plant |
| | Desert Peak | Concluded | HSA | Commercial plant |
| | Coso | Concluded | Petrothermal | Commercial plant |
| El Salvador | Berlín | Ongoing | Petrothermal | Commercial plant |
| Australia | Hunter valley | Abandoned | Petrothermal | Research facility |
| | Paralana | On hold | Petrothermal | Commercial plant |
| | Copper Basin | Abandoned | Petrothermal | Pilot plant |
| Japan | Hijori | Concluded | Petrothermal | Research facility |
| | Ogachi | Concluded | Petrothermal | Research facility |

## 6.2 EGS projects

### 6.2.1 France

### Le Mayet

The Mayet project, starting in 1978 performed various hydraulic fracturing stimulation tests and was concluded in 1986 (Table 15).

*Table 15 Project overview of Le Mayet*

| Project name | Le Mayet |
|---|---|
| Location | Le-Mayet-de-Montagne |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1978 |
| End date | 1986 |
| Rock | Igneous, Granite |
| Wells | Phase 1: three vertical wells, 200 m deep (1978-1981)<br>Phase 2: 2 vertical boreholes, 800 m deep, 100 m apart (1982-1986) |
| Stimulation | Various hydraulic fracturing tests performed (up to 250 bar wellhead pressure) |
| Reservoir | Flow rate of 7 L/s (planned), Temperature measured 22 °C |
| Seismicity | Microseismicity, not felt on surface |
| Funding | Agence Française pour la Maîtrise de l'Energie & Centre National de la Recherche Scientifique |
| Capacity | n.a. |
| Operator | n.a. |
| Status | Concluded |

Sources: [Cornet 1987, Cornet, F 1987, Breede et al. 2013, Bauer et al. 2015]

### Soultz-sous-Forêts

The project at Soultz-sous-Forêts involves partners from several EU Member States. A feasibility study was performed from 1987 to 1992 and two boreholes (GPK 1 and GPK 2) were drilled between 1993 to 1997 to about 3500 m depth [BINE 2008]. In 1998, GPK 2 was deepened to about 5000 m and two additional boreholes (GPK 3, GPK4 ) were drilled to 5000 m until 2005 [BINE 2008]. The project involves two different reservoirs, the upper one (about 3000 m) in a fractured granite formation (higher permeability) and the lower one (about 5000 m) in a granite with lower permeability [Breede et al. 2015].

*Table 16 Project overview of Soultz-sous-Forêts*

| Project name | European EGS project |
|---|---|
| Location | Soultz-sous-Forêts |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1984 |
| End date | Ongoing |
| Rock | Granite |
| Wells | One well was drilled to about 3600 m, three wells (one injection and 2production), to about 5000 m |
| Stimulation | Hydraulic and chemical fracturing |
| Reservoir | 165 °C, 30 l/s |
| Seismicity | Microseismicity |
| Funding | EUR 80 million total costs (30 from EU, 25 from Germany, 25 from France) |
| Capacity | 1.5 MWe, ORC, entered into operation in 2008 |
| Operator | EEIG Exploitation Minière de la Chaleur |
| Status | Ongoing |

Sources: [BINE 2008, Portier et al. 2009, Breede et al. 2013, Géothermie Perspectives 2015]

### 6.2.2 France/Germany

### GEOSTRAS

The GEOSTRAS project is a continuation of the Franco-German partnership launched in the Soultz-sous-Forêts project. It is one of two EGS projects receiving funds from the NER 300 programme. The geothermal installations are planned to be installed at the harbour of Strasbourg whereas the installations for heat transfer and conversion will be on the German side of the border with the cooling units providing heat to the industrial port area of Kehl where demand is high.

*Table 17 Project overview: Geostras*

| Project name | GEOSTRAS |
|---|---|
| Location | Strasburg (FR) / Kehl (DE) |
| Type | Demonstration plant |
| Class | Petrothermal |
| Start date | Funding decision 2012. Planned operation 2020. |
| End date | NER300 funding ends 2025 |
| Rock | Not known |

| Project name | GEOSTRAS |
|---|---|
| Wells | Not known |
| Stimulation | Not known |
| Reservoir | >150 °C |
| Seismicity | Not known |
| Funding | Total investment costs not known, EUR 16.8 million from NER300. |
| Capacity | 6.7 MWe and 35 MWth |
| Operator | Fonroche |
| Status | Ongoing |
| Sources: [EC 2014, EC 2015] | |

### 6.2.3 Germany

#### Bruchsal

Although classified as an EGS by [Breede et al. 2015] the geothermal power plant project in Bruchsal is a conventional hydrothermal system, there exists a convective heat transfer (Table 18).

*Table 18 Project overview: Bruchsal*

| Project name | Bruchsal |
|---|---|
| Location | Bruchsal |
| Type | Commercial plant |
| Class | Hydrothermal doublet system |
| Start date | 1983 |
| End date | Ongoing |
| Rock | Middel Bunter |
| Wells | GB I (1930 m)and GB II (2540 m) |
| Stimulation | No |
| Reservoir | About 120 °C to 130 °C, 24 l/s |
| Seismicity | No |
| Funding | EUR 8.1 million total investment costs (drilling only), EUR 2.5 million from EU, EUR 2.7 million from Germany |
| Capacity | 5.5 MWth, 0.55 MWe |
| Operator | EnBW |
| Status | Ongoing |
| Sources: [Herzberger et al. 2010, Breede et al. 2013, Tiefe Geothermie 2015a] | |

#### Bad Urach

Bad Urach was one of the first EGS projects on pilot scale worldwide started in 1977 [Breede et al. 2013].

*Table 19 Project overview: Bad Urach*

| Project name | Geothermie-Pilotprojekt Bad Urach |
|---|---|
| Location | Bad Urach |
| Type | Pilot plant |
| Class | Petrothermal |
| Start date | 1977 |
| End date | 2008 |
| Rock | Metamorphic, Gneiss |
| Wells | Urach 3, research well, 1977, 4445 m<br>Urach 4, 2004, 4300 m (planned) but only drilled until 2793 m (geological difficulties, loss of drilling fluid, financial difficulties) |
| Stimulation | Hydraulic fracturing tests performed (1979 - 2003), up to 340 bar |
| Reservoir | In Urach 3, 170 °C was measured at 4445 m<br>Pump rates up to 50 L/s achieved during fracturing tests |
| Seismicity | Microseismicity occurred |
| Funding | 6.5 mio. EUR from BMU |
| Capacity | 1 MWe (planned) |
| Operator | Forschungskollegium Physik des Erdkörpers (FKPE) |
| Status | Abandoned<br>In Urach 3: torn off bore rod in 3234 m, Urach 4 could not be drilled to final depth. Attempts to create a shallow reservoir to be used for direct heat was also proven not to be economically viable (less heat users, unsufficient flow rate, high costs for restoring bore holes) |
| Sources: [Cammerer & Michel 2009, Breede et al. 2013] | |

#### Landau

Similarly to Bruchsal, it is not easy to decide whether Landau is an EGS or not (Table 20). According to [Häring 2007] Landau shows characteristics of EGS but also conventional hydrothermal systems since stimulation was performed to increase the already existing permeability. [Breede et al. 2015] consider Landau a hot sedimentary aquifer (HAS).

Seismic events of 2.4 to 2.7 M occurred in 2009. Most probably due to a leakage, heaving and horizontal movements of the ground occurred in 2013 and subsequently the power plant was shut down. Reopening plans are currently being discussed.

*Table 20 Project overview: Landau*

| Project name | Landau |
|---|---|
| Location | Landau (Pfalz) |
| Type | Commercial plant |
| Class | Hot Sedimentary Aquifer (HSA) |
| Start date | 2003 |
| End date | Ongoing |
| Rock | Muschelkalk (Sedimentary) |
| Wells | 3170 m to 3300 m |
| Stimulation | No stimulation for producer, hydraulic stimulation for injector |
| Reservoir | 70-80 l/s, 159 °C |
| Seismicity | 2.7 M |
| Funding | State of Rhineland-Palatia and Federal German Ministry for the Environment |
| Capacity | 3 MWe, 3-6 MWth |
| Operator | Geo x |
| Status | Ongoing |
| Sources: [Breede et al. 2013] | |

## Groß-Schönebeck

The research facility in Groß-Schönebeck aims at developing techniques for the exploration and usage of geothermal energy [GFZ 2015]. The research facility hosts a number of projects ranging from stimulation experiments to studies on corrosion and material resistance, thermodynamic modelling, and power production (Table 21).

*Table 21 Project overview: Groß-Schönebeck*

| Project name | Groß-Schönebeck |
|---|---|
| Location | Groß-Schönebeck |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 2000 |
| End date | ongoing |
| Rock | Sandstone and andesitic volcanic rocks |
| Wells | 2001: borehole E GrSk 3/90 an abandoned borehole from unsuccessful natural gas exploration was reopened (4309 m)<br>2006: drilling of second hole (Gt GrSk 4/05) to 4400 m |
| Project name | Groß-Schönebeck |
| Stimulation | Hydraulic gel proppant and fracturing; chemical fracturing |
| Reservoir | 145 °C borehole, flow rate 20 l/s |
| Seismicity | Negligible |
| Funding | Not known |
| Capacity | 10 MW$_{th}$ 1 MW$_{e}$ planned (ORC) |
| Operator | GFZ |
| Status | Ongoing |
| Sources: [Breede et al. 2013] | |

## GeneSys Hannover

The GeneSys project consists of 2 parts (Table 22). The first part, a research project in Horstberg is already concluded and aimed at testing the single well concept while a subsequent demonstration project in Hannover is still ongoing [MIT 2006, BGR 2015a, BGR 2015b, BGR 2015c]. The project is intended to "investigate concepts that allow the use of the widespread low-permeability sediments for geothermal energy extraction" [MIT 2006]. It is also the first project to test a single well concept which means lower drilling costs but higher risks due to salt deposition [Breede et al. 2013].

*Table 22 Project overview: GeneSys*

| Project name | GeneSys |
|---|---|
| Location | Horstberg & Hannover |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 2003 |
| End date | 2007 |
| Rock | Sedimentary (Bunter sandstone) |
| Wells | Horstberg Z1: 3800 m, Hannover (Groß-Buchholz, GT-1): 2900 m |
| Stimulation | Hydraulic fracturing<br>20.000 m³ freshwater have been injected (up to 80 l/s) |
| Reservoir | Horstberg: Reservoir temperature Z1: 150 °C, flow rate 10 to 20 l/s<br>Hannover: Reservoir temperature Z1: 160 °C, flow rate 7 l/s (planned) |
| Seismicity | No measured event at Horstberg<br>Microseismicity in Hannover (1. 8M) |
| Funding | GeneSys Hannover was/is funded by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU) and the Federal Ministry for Economic Affairs and Energy (BMWi) with EUR 15 million. |

| Project name | GeneSys |
|---|---|
| Capacity | Aim: providing heat for the Geozentrum Hannover (2 MWth needed with 25 m³/h at 130 °C) |
| Operator | Federal Ministry of Economics and Technology |
| Status | Project Hannover is ongoing<br>The freshwater injected dissolved high amounts of salt in depths of 3500 to 3800 m. Heavy salt deposition occurred during pumping up the hot water, first in the annular space, then in the production string. Re-extraction of water has been stopped. Currently salt depositions have been removed and further analyses are ongoing |
| Sources: [Jung et al. 2006, MIT 2006, Breede et al. 2013, BGR 2015b] | |

## Insheim

Similarly to Landau, Insheim is an existing hydrothermal resource where hydraulic stimulation was applied to enhance well productivity/injectivity [Bauer et al. 2015]. Planning started in 2007 and the power plant entered into operation in 2012 (Table 23).

*Table 23 Project overview: Insheim*

| Project name | Insheim |
|---|---|
| Location | Insheim |
| Type | Commercial plant |
| Class | Hot Sedimentary Aquifer (HSA) |
| Start date | 2007 |
| End date | Ongoing |
| Rock | Keuper, Perm, Bunter sandstone |
| Wells | 3600 m to 3800 m |
| Stimulation | Hydraulic stimulation |
| Reservoir | 165 °C, 50-80 l/s |
| Seismicity | 2 M to 2.4 M and microseismicity |
| Funding | EUR 0.6 million (BESTEC) for tests |
| Capacity | 4.8 MWe, 6-10 MWth (planned) |
| Operator | Geofuture |
| Status | Ongoing |
| Sources: [Breede et al. 2013] | |

## Mauerstetten

In 2008, a borehole was drilled to 4000 m depth but porosity was too small for geothermal use. The commercial project was abandoned (Table 24). Currently, a research project is ongoing in order to analyse if hydraulic fracturing could be used to further develop the project [Kreisbote 2013].

*Table 24 Project overview: Mauerstetten*

| Project name | Mauerstetten |
|---|---|
| Location | Mauerstetten |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 2011 |
| End date | 2012 |
| Rock | Limestone |
| Wells | Depth of GT1 4080 m (unsuccessful well) and the side-track GT1a also showed very small productivity |
| Stimulation | Chemical and hydraulic fracturing (planned) |
| Reservoir | 130 °C, flow rate unknown yet |
| Seismicity | Unknown |
| Funding | Bundesumweltministerium (EUR 2.45 million) |
| Capacity | Unknown |
| Operator | Exorka (planned) |
| Status | Ongoing |
| Sources: [BMU 2012, Schrage et al. 2012, Breede et al. 2013] | |

## Unterhaching

According to [Breede et al. 2015], Unterhaching could be classified as a HSA project (Table 25). It is the only HSA project applying chemical stimulation. This was needed since natural flow rates that were encountered were not satisfactory [BMU 2011].

*Table 25 Project overview: Unterhaching*

| Project name | Unterhaching |
|---|---|
| Location | Unterhaching |
| Type | Hot Sedimentary Aquifer (HSA) |
| Class | Hydrothermal |
| Start date | 2004 |
| End date | Ongoing |
| Rock | Limestone |
| Wells | 3350 m to 3380 m |
| Stimulation | Acid stimulation |
| Reservoir | 150 l/s, 123 °C |
| Seismicity | ≤ 2.2 M |
| Funding | About EUR 40.9 million, total investment EUR 90 million (EUR 16 million for Kalina plant) |
| Capacity | 3.4 MWe, 38 MWth (max.) |
| Operator | Geothermie Unterhaching |
| Status | Ongoing |
| Sources: [Kohl et al. 2009, BMU 2011, Breede et al. 2013, Geothermie Unterhaching 2015] | |

### Falkenberg

The project at Falkenberg (Table 26) is an EGS feasibility study at shallow depths to understand mechanical and hydraulic properties of fractures [Breede et al. 2013].

*Table 26 Project overview: Falkenberg*

| Project name | Falkenberg |
|---|---|
| Location | Falkenberg |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1977 |
| End date | 1986 |
| Rock | Granite |
| Wells | 500 m |
| Stimulation | Hydraulic fracturing<br>Injection of 6 m$^3$ water into borehole HB4a at 3.5 kg/s, with a breakdown pressure of 18 MPa |
| Reservoir | 13.5 °C, flow rates 0.2 to 7 l/s |
| Seismicity | Microseismicity |
| Funding | |
| Capacity | Not applicable (never planned) |
| Operator | |
| Status | Concluded |
| Sources: [MIT 2006, Breede et al. 2013] | |

## 6.2.4 Hungary

### Szeged

The project will drill a doublet down to 4 km depth into a variegated crystalline rock formation at located in a compressional stress field. Drilling and stimulation of the wells will commence in 2016 followed by testing of the reservoir capacity. The aim is then to construct a 5 MWe power plant.

*Table 27 Project overview: Szeged*

| Project name | South Hungarian EGS Demonstration Project |
|---|---|
| Location | Szeged |
| Type | Commercial plant |
| Class | Petrothermal |
| Start date | Funding decision 2012. Exploration started in 2014. |
| End date | Ongoing |
| Rock | Igneous, Granite |
| Wells | 2016: One production well and one injection well, both deviated, planned. The target zone to be stimulated ranges from 2900-3500 m depth. |
| Stimulation | Hydraulic stimulation relying primarily on shearing deformation. There, pressure up to 350 bar, will be applied and the aim is to stimulate multiple fracture zones using a temporary sealant from Altarock Energy (US 20130075089 A1). Once the weakest fracture zone has been stimulated, the sealant will be injected to fill the zone before the second weakest fracture zone is stimulated. The process will then be repeated until sufficient stimulation has been achieved. The sealant will then disintegrate with time due to warming up of the system. |
| Reservoir | Expected formation temperature: 175°C, 280 kg/s (expected) |
| Seismicity | Project not started |
| Funding | EUR 56 mio. project costs, EUR 39 mio. EUR funding from NER300. |
| Capacity | 8.9 MWe (planned) |
| Operator | EU-FIRE, Mannvit |
| Status | Ongoing |
| Sources: Sigurður Lárus Hólm, Steinar Þór Guðlaugsson, (pers. comm.) | |

## 6.2.5 Switzerland

### Basel

The Basel project (Table 28) was one of the few projects worldwide drilling to depths of 5000 m and more [Häring 2007].

*Table 28 Project overview: Basel*

| Project name | Deep Heat Mining (DHM) Project |
|---|---|
| Location | Basel |
| Type | Commercial plant |
| Class | Petrothermal |
| Start date | 2005 |
| End date | 2009 |
| Rock | Igneous, Granite |
| Wells | 2005: first exploratory drill of 2700m in Otterbach<br>Basel 1, May-October 2006, 5003 m through 2.4 km of sedimentary rocks and 2.6 km of granitic basement |

| Project name | Deep Heat Mining (DHM) Project |
|---|---|
| Stimulation | Hydraulic fracturing<br>Granite in the open hole below 4629 m depth was hydraulically stimulated to enhance the permeability. High rates of microseismic activity built up during the first 6 days of fluid injection with event magnitudes of up to ML 2.6. In view of this, it was decided to stop the injection (stimulation was initially planned over a period of 21 days) |
| Reservoir | Expected formation temperature: 200°C, 70 kg/s (expected) |
| Seismicity | Frequent earthquakes, including 3.4 M |
| Funding | 56 mio. CHF project costs, 28 mio. CHF from canton Basel |
| Capacity | 3 MWe and 20 MWth (planned) |
| Operator | Geopower Basel |
| Status | Abandoned<br>Induced seismicity was exceeding acceptable levels |

Sources: [Häring et al. 2008, Giardini 2009, Breede et al. 2013]

### St. Gallen

The project in St. Gallen uses a conventional hydrothermal resource and only a very minor stimulation with hydrochloric acid took place [Bauer et al. 2015]. Drilling started in 2013 and was put on hold when induced seismicity events with a maximum altitude of 3.6 M occurred [Breede et al. 2013]. During drilling, unexpectedly, gas was encountered in the drilling hole which raised the pressure. The well was closed and water and drilling mud was pumped into the well [Wolfgramm et al. 2005]. On 20th of July 2014, an earthquake of 3.6 M occurred followed by a number of micro-seismic events. Subsequently, the well was secured and production testing started. However, flow rates of about 6l/s were much lower than expected (50 l/s). After evaluating the results of the production testing and taking into account gas inflow, and the increased risk of seismicity, the project was closed.

Several possible alternative usage scenarios have been developed, including the drilling of a second well with the aim to establish a doublet system or placing a deep heat pump for heat generation but finally those options have been rejected due to economic considerations. The option to use the natural gas is still explored but would need long-term production testing for which financing could not be secured until now [Stadt St. Gallen 2015a].

*Table 29 Project overview: St. Gallen*

| Project name | Geothermie-Projekt St. Gallen |
|---|---|
| Location | St. Gallen |
| Type | Commercial plant |
| Class | Hot Sedimentary Aquifer (HSA) |
| Start date | 2009 |
| End date | 2014 |
| Rock | Malm, shell limestone |
| Wells | 4450 m |
| Stimulation | Chemical stimulation (2 times injection of 75 $m^3$ hydrochloric acid) |
| Reservoir | 130 to 150 °C (estimated) |
| Seismicity | 3.6 M |
| Funding | CHF 44 million spent so far, St. Gallen will receive CHF 18.2 million from risk insurance fond |
| Capacity | 30 $\text{MW}_{\text{th}}$ (expected) |
| Operator | n.a. |
| Status | Abandoned |

Sources: [Wolfgramm et al. 2005, Breede et al. 2013, Bauer et al. 2015, Stadt St. Gallen 2015a, Stadt St. Gallen 2015b]

## 6.2.6 Austria

### Altheim

The project in Altheim is a commercial HSA project with acid stimulation performed (Table 30).

*Table 30 Project overview: Altheim*

| Project name | Altheim |
|---|---|
| Location | Altheim |
| Type | Commercial plant |
| Class | Hot Sedimentary Aquifer (HSA) |
| Start date | 1989 |
| End date | Ongoing |
| Rock | Limestone |
| Wells | 2165 m to 2306 m |
| Stimulation | Acid stimulation |
| Reservoir | Temperature about 105 °C, 70 l/s |
| Seismicity | Unknown |
| Funding | 35 % of total investment costs (EUR 5.8 million) funded by EU (Joule-Thermie) |
| Capacity | 1 MWe, 14.4 MWth, ORC, district |

| Project name | Altheim |
|---|---|
| | heating since 1990, power plant installed in 2001 |
| Operator | Terrawat |
| Status | Ongoing |
| Sources: [Breede et al. 2013, Energiesparverband Oberösterreich 2015, Tiefe Geothermie 2015b] | |

### 6.2.7 United Kingdom

#### Eden project

Currently, a petrothermal EGS project is being planned in Cornwall (Table 31). Due to a reduction of DECC's funding towards geothermal energy, the future of the project is not clear.

*Table 31 Project overview: Eden*

| Project name | Eden project |
|---|---|
| Location | St Austell, Cornwall |
| Type | Commercial plant |
| Class | Petrothermal |
| Start date | 2010 |
| End date | Ongoing |
| Rock | Granite |
| Wells | Target depth 4000 m |
| Stimulation | Hydraulic fracturing |
| Reservoir | 180 to 190 °C (estimated), 55 l/s (estimated) |
| Seismicity | Unknown |
| Funding | GBP 2 million from DECC geothermal fund |
| Capacity | 4 MWe |
| Operator | EGS Energy Limited |
| Status | Ongoing, planning permission obtained |
| Sources: [Eden Project 2009, Breede et al. 2015, EGS Energy 2015] | |

#### Redruth

A commercial plant is planned in Redruth by Geothermal Engineering Limited (Table 32). In 2013, a grant of GBP 6 million was withdrawn since the project did not find private finance [West Briton 2015].

*Table 32 Project overview: Redruth*

| Project name | United Downs project |
|---|---|
| Location | Redruth |
| Type | Commercial plant |
| Class | Petrothermal |
| Start date | 2009 |
| End date | Ongoing |
| Rock | Granite |
| Wells | 3 wells planned, 1 injection and 2 production |
| Stimulation | Hydraulic fracturing planned |
| Reservoir | 190 °C |
| Seismicity | n.a. |
| Funding | GBP 6 million granted from Regional Growth Fund but grant was withdrawn since private funding was not found |
| Capacity | 10 MWe, 55 MWth |
| Operator | n.a. |
| Status | Ongoing |
| Sources: [Law 2011, Halper 2012, West Briton 2015] | |

#### Rosemanowes

The Rosemanowes project conducted one of the first EGS experiments worldwide (Table 33). Experiments in a granite rock to study the fracturing of crystalline rocks were performed [Häring 2007]. The research was a significant contribution to further develop EGS and showed the feasibility to create an artificial geothermal reservoir [Parker 1999]

*Table 33 Project overview: Rosemanowes*

| Project name | Rosemanowes |
|---|---|
| Location | Rosemanowes |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1984 |
| End date | 1992 |
| Rock | Granite |
| Wells | 2600 m depth |
| Stimulation | Hydraulic fracturing, viscous gel stimulation, placements of proppants in joints |
| Reservoir | Temperature 79 to 100 °C, flow rate 4 to 25 l/s |
| Seismicity | Maximum magnitude 3.1 |
| Funding | Not known |
| Capacity | n.a. |
| Operator | n.a. |
| Status | Concluded |
| Sources: [Häring 2007, Breede et al. 2013] | |

## 6.2.8 Sweden

### Fjällbacka

The Petrothermal EGS project at Fjällbacka was running from 1984 to 1995 and was one of the first EGS experiments worldwide (Table 34).

*Table 34 Project overview: Fjällbacka*

| Project name | Fjällbacka |
|---|---|
| Location | Fjällbacka |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1984 |
| End date | 1995 |
| Rock | Granite |
| Wells | 70 to 500 m |
| Stimulation | Hydraulic fracturing and acid stimulation with HCl-HF |
| Reservoir | Temperature 16 °C, flow rates between 0.8 to 1.8 l/s |
| Seismicity | Microseismicity |
| Funding | Not known |
| Capacity | Not known |
| Operator | Not known |
| Status | Concluded |
| Sources: [Portier et al. 2007, Breede et al. 2013] | |

## 6.2.9 United States

### Southeast Geysers

A more recent project at the southeast Geysers had to be abandoned due to a collapse of the wellbore (Table 35).

*Table 35 Project overview: Southeast Geysers*

| Project name | Southeast Geysers |
|---|---|
| Location | The Geysers |
| Type | Pilot plant |
| Class | Hot Sedimentary Aquifer (HSA) |
| Start date | 2008 |
| End date | 2009 |
| Rock | Sedimentary, greywacke |
| Wells | Re-drilling of well (NCPA E-7) for EGS tests, (2008-2009, 12000 ft. (3660 m) planned, 1341 m reached |
| Stimulation | Not performed due to cancellation, the aim of the project was to create multiple fracture zones in one well |
| Reservoir | |
| Seismicity | Induced seismicity risk expected |
| Funding | DOE funding |
| Capacity | n.a. |
| Operator | Altarock Energy |
| Status | Abandoned<br>Wellbore was collapsing, drilling assembly became stuck due to the borehole collapsing in the unstable serpentine and mélange |
| Sources: [AltaRock 2009, Petty 2009, Breede et al. 2013] | |

### Fenton Hill

The first EGS tests in the world were performed at Fenton Hill in 1973 by scientists from the Los Alamos National Laboratories [Häring 2007]. Experiments were conducted between 1974 and 1992 (Table 36).

*Table 36 Project overview: Fenton Hill*

| Project name | Fenton Hill |
|---|---|
| Location | The Geysers |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1974 |
| End date | 1992 |
| Rock | Crystalline rock |
| Wells | 2932 to 4390 m<br>Phase I, 1974-1980, dealt with field development and associated research on a 3 km deep reservoir with a temperature of about 200°C.<br>Phase II followed in 1979, with the drilling of EE-2 into a deeper (4.4 km), hotter (300°C) reservoir. |
| Stimulation | Hydraulic fracturing |
| Reservoir | 200 to 327 °C, flow rates of 10 to 18.5 l/s achieved (26.9 and 30.3 MPa pressure on the injection wellhead). Fluid extracted reached about 190 °C |
| Seismicity | Microseismicity |
| Funding | Not known |
| Capacity | Not known |
| Operator | Not known |
| Status | Concluded |
| Sources: [MIT 2006, Häring 2007, Breede et al. 2013] | |

### Newberry Volcano

The Newberry Volcano site has been selected as one of five sites to be evaluated in Phase I of the Frontier Observatory in Geothermal Energy (FORGE) by the US DoE (Table 37).

*Table 37 Project overview: Newberry Volcano*

| Project name | Newberry Volcano EGS Demonstration |
|---|---|
| Location | Newberry |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 2010 |
| End date | ongoing |
| Rock | Volcanic rocks |
| Wells | 3066 m |
| Stimulation | Hydroshearing, multi-zone isolation techniques<br>Four million gallons of water over 32 days of pressurized pumping injected |
| Reservoir | Temperature 315 °C, flow rate unknown |
| Seismicity | Microseismicity |
| Funding | US Department of Energy funding received for Phase I |
| Capacity | 35 MW binary system possible |
| Operator | Altarock Energy |
| Status | Ongoing |
| Sources: [Cladouhos et al. 2012, Breede et al. 2013, AltaRock 2015a, AltaRock 2015b] | |

## Northwest Geysers

The aim of the Northwest Geysers EGS Demonstration Project is to "reopen and recomplete two of the abandoned exploratory wells and deepen them for injection and stimulation" [Rutqvist et al. 2013]. It was launched in 2009, and Phase I (pre-stimulation) and Phase II (Stimulation) have been completed. Currently, Phase III (Monitoring) is ongoing (Table 38).

*Table 38 Project overview: Northwest Geysers*

| Project name | Northwest Geysers |
|---|---|
| Location | The Geysers |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 2009 |
| End date | ongoing |
| Rock | Metasedimentary rocks (greywacke) |
| Wells | Prati 32 (P-32) as injection well and Prati State 31 (PS-31) as production well were reopened and deepened to 3058 m and 3396 m, respectively |
| Stimulation | Thermal fracturing<br>One year stimulation injection of cool water conducted (max. pressure 32 MPa) |
| Reservoir | About 400 ° C, flow rate 9.7 l/s |
| Seismicity | Microseismicity |
| Funding | DoE funding, total project funding: USD $8.5 million (DoE USD 5.2 million and Calpine USD 3.3 million) |
| Capacity | 5 MW$_e$ target capacity |
| Operator | Calpine Corporation |
| Status | Ongoing |
| Sources: [Walters 2010, Breede et al. 2013, Rutqvist et al. 2013, Walters 2013] | |

## Raft River

The raft river project in Idaho started in 2009 aiming at developing and demonstrating EGS technology (Table 39). The well has been prepared for stimulation and stimulation has most probably been performed. Unfortunately, no up-to-date information about the project was found.

*Table 39 Project overview: Raft River*

| Project name | Raft river |
|---|---|
| Location | Raft river |
| Type | Research facility |
| Class | Hot Sedimentary Aquifer (HSA) |
| Start date | 2009 |
| End date | Ongoing |
| Rock | Quartzite, Schist |
| Wells | 5 production wells and 4 injection wells at the site. Well RRG-9 to be used for the stimulation |
| Stimulation | Thermal and hydraulic fracturing<br>Phase I: 60 °C water, Phase II: 12 °C cold water, Phase III: Hydraulic |
| Reservoir | Maximum 150 ° C |
| Seismicity | Not known |
| Funding | USD 7.4 million (DoE), USD 2.8 million University of Utah, total project cost USD 10.2 million |
| Capacity | Currently 10.5-11.5 MW$_e$ |
| Operator | University of Utah |
| Status | Ongoing |
| Sources: [Moore & McLennan 2013, DoE EERE 2015a, DoE EERE 2015b] | |

## Bradys

At Bradys, the project tried to increase well injectivity and hydraulic connection between well and producing field [DoE EERE 2015a]. According to [Snyder & Zemach 2013], hydraulic and chemical stimulation was performed (Table 40).

*Table 40 Project overview: Bradys*

| | |
|---|---|
| Project name | Bradys |
| Location | Bradys |
| Type | Commercial plant |
| Class | Hot Sedimentary Aquifer (HSA) |
| Start date | 2008 |
| End date | 2015 |
| Rock | Rhyolite & altered tuff |
| Wells | Well 15-12 ST-1, 1320 m |
| Stimulation | Hydraulic fracturing |
| Reservoir | About 200 °C |
| Seismicity | Microseismicity |
| Funding | USD 4.5 million (DoE) |
| Capacity | Not known |
| Operator | Ormat |
| Status | Concluded |

Sources: [Snyder & Zemach 2013, DoE EERE 2015a, Drakos & Akerley 2015, DoE EERE 2015c]

### Desert Peak

Similarly to the Bradys project, at Desert Peak, Ormat tried to extend the life of unproductive wells by means of hydraulic and chemical fracturing (Table 41). The project has been successfully completed [Kelkar 2015].

*Table 41 Project overview: Desert Peak*

| | |
|---|---|
| Project name | Desert Peak |
| Location | Desert Peak |
| Type | Commercial plant |
| Class | Hot Sedimentary Aquifer (HSA) |
| Start date | 2002 |
| End date | 2013 |
| Rock | Rhyolite |
| Wells | Well 27-15, about 1000 m |
| Stimulation | Hydraulic and chemical fracturing |
| Reservoir | About 210 °C |
| Seismicity | Microseismicity |
| Funding | USD 5.4 million (DoE) |
| Capacity | Capacity of Desert Peak 2 power plant (12.5 $MW_e$) increased by 1.7 $MW_e$ |
| Operator | Ormat |
| Status | Concluded |

Sources: [Faulds et al. 2010, Chabora et al. 2012, Chabora & Zemach 2013, Benato et al. 2015, DoE EERE 2015a, Kelkar 2015]

### Coso

The Coso project received USD 4.5 million funding to study the feasibility of hydraulic fracturing (Table 42). According to [Rose 2012, OpenEI 2015], a first stimulation at well 34-9RD2 failed since a large natural fracture was encountered during the deepening of the well [Foulger et al. 2008]. Also the recompletion of another well (46A-19RD2) failed since the well liner could not be removed to the total well depth. Subsequently, the project was stopped.

*Table 42 Project overview: Coso*

| | |
|---|---|
| Project name | Coso |
| Location | Coso |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 2002 |
| End date | 2012 |
| Rock | Diorite, granodiorite, granite |
| Wells | 2430 to 2956 m |
| Stimulation | Hydraulic, thermal and chemical fracturing |
| Reservoir | Temperature > 300 °C |
| Seismicity | Seismicity ≤ 2.8 M |
| Funding | USD 4.5 million |
| Capacity | About 200 $MW_e$ (Navy I and II)<br>Increase of production by 5 $MW_e$ envisaged |
| Operator | Coso Operating Company |
| Status | Concluded |

Sources: [Chopra 2000, Wyborn et al. 2000, Rose et al. 2005, Rose et al. 2006, Breede et al. 2013, OpenEI 2015]

## 6.2.10 El Salvador

### Berlín

An EGS project in El Salvador was performed by Shell International (Table 43). The aim was to stimulate an existing dry well "to create an extensive network of fractures occupying a volume of 0.1–1.0 km$^3$ at a depth of 2000 m$^3$.

*Table 43 Project overview: Berlín*

| | |
|---|---|
| Project name | Berlín |
| Location | Berlín |
| Type | Commercial plant |
| Class | Petrothermal |
| Start date | 2001 |
| End date | Ongoing |
| Rock | Volcanic rocks |
| Wells | 2000 m to 2380 m |

| Project name | Berlín |
|---|---|
| Stimulation | Hydraulic and chemical fracturing (HCl and HF) |
| Reservoir | 179 °C to 196 °C |
| Seismicity | ≤ 4.4 M |
| Funding | Not known |
| Capacity | 185 MW |
| Operator | LaGeo |
| Status | Ongoing |
| Sources: [Breede et al. 2013] | |

### 6.2.11 Australia

#### Hunter valley

The Hunter valley project investigated a gravity anomaly in the south east of Australia and measured temperature in several boreholes (Table 44). In the centre of the anomaly, a deeper hole (1946 m) was drilled confirming the geothermal anomaly.

Subsequently, Geodynamics received a funding offer of AUD 7 million for drilling a deep well by round 2 of the Geothermal Drilling Program. The aim of the project was to drill two 4500 m holes followed by stimulation and flow testing [Gurgenci 2015]. The project was abandoned in 2015 due to lack of political support [Think GeoEnergy 2015a, ABC 2015].

*Table 44 Project overview: Hunter valley*

| Project name | Hunter valley |
|---|---|
| Location | Hunter valley |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1999 |
| End date | 2015 |
| Rock | Granite |
| Wells | In a first phase in the early 2000s, several shallow boreholes (300 – 920 m) and then PPHR1 drilled to 1946 m |
| Stimulation | n.a. |
| Reservoir | Estimated at 275 °C at 5 km, 14000 PJ in total |
| Seismicity | n.a. |
| Funding | AUD 7 million |
| Capacity | n.a. |
| Operator | Geodynamics |
| Status | Abandoned |
| Sources: [MIT 2006, Think GeoEnergy 2015a, ABC 2015] | |

#### Paralana

The Paralana project aimed at developing a 3.75 MWe commercial power project in the Mt Painter region (Table 45). So far, the drilling and stimulation have been completed. The next stage would be the drilling and completion of Paralana 3 (production well) to complete the fluid circulation loop, followed by a second hydraulic stimulation to increase the reservoir volume [Petratherm 2015]. In 2014, Petratherm announced that it could not secure AUD 5 million equity required to draw down on a AUD 13 million Emerging Renewables Program (ERP) Grant awarded by the Australian Renewable Energy Agency (ARENA) which lead to a cancellation of the ERP grant and subsequently of AUD24.5 million from the Renewable Energy Development Program (REDP). From publicly available information, it is not fully clear if the project is put on hold or cancelled.

*Table 45 Project overview: Paralana*

| Project name | Paralana Geothermal Energy Project |
|---|---|
| Location | Flinders Ranges |
| Type | Commercial plant |
| Class | Petrothermal |
| Start date | 2005 |
| End date | Ongoing |
| Rock | Metasediments, granite |
| Wells | Paralana 1, shallow evaluation drilling, 500 m, high temperature gradient (76 °C/km), subsequently deepened to 1807 m<br>Paralana 2, drilled in 2009 to 4003 m, designed to be injection well |
| Stimulation | Hydraulic fracturing and acid stimulation<br>Injection test in 2011 with 1.3 to 5.3 l/s<br>Main fracturing with 3.1 million litres of fracturing fluid (over 5 days) with pressures up to about 62 MPa. Initial injection rates of 3 l/s with steady improvement (due to several acid treatments). At the end of the injection period, 27 l/s were reached |

| Project name | Paralana Geothermal Energy Project |
|---|---|
| Reservoir | About 170 °C temperature encountered in Paralana 2, flow rate up to 6 l/s<br>Measured resource estimate of 41 $\text{PJ}_{\text{th}}$ (sustains 5.4 $\text{MW}_{\text{e}}$ for 30 years)<br>Between 3500 to 4000 m (target zone), total estimated resources are 9300 $\text{PJ}_{\text{th}}$ (520 $\text{MW}_{\text{e}}$) |
| Seismicity | Microseismicity, < 2.6M |
| Funding | AUD 62.8 million Federal Government's Renewable Energy Demonstration Program (REDP), AUD 7 million from Geothermal Drilling Program |
| Capacity | 3.75 $\text{MW}_{\text{e}}$ |
| Operator | Petratherm |
| Status | On hold |

Sources: [Breede et al. 2013, Petratherm 2014, Petratherm 2015]

## Cooper Basin

The Cooper Basin project is one of the largest EGS projects worldwide [Breede et al. 2015]. Recently, Geodynamics wrote down the project and its assets due to investment hurdles [Think GeoEnergy 2015b].

*Table 46 Project overview: Cooper Basin*

| Project name | Cooper Basin |
|---|---|
| Location | Cooper Basin |
| Type | Pilot plant |
| Class | Petrothermal |
| Start date | 2003 |
| End date | 2013 |
| Rock | Granite |
| Wells | Habanero 1 (2003): 4421 m, 243 °C<br>Habanero 2 (2004): 4459 m, 244 °C<br>Habanero 3 (2008): 4200 m, 242 °C<br>Jolokia 1 (2008): 4911 m, 278 °C<br>Savina 1 (2009): 3700 m, suspended<br>Habanero 4 (2012): 4204 m, 242 °C |
| Stimulation | Hydraulic fracturing<br>Stimulation of Habanero 1-4 (2.2-34 million L)<br>Stimulation of Habanero 1 with 16000 $m^3$ (600 bar) water created a reservoir of 0.7 km3 |
| Reservoir | 242 °C to 278 °, total reservoir estimated at 59200 PJ, 700 PJ end user energy, flow rate estimated at 35 kg/s per well |
| Seismicity | ≤ 3.7 M |
| Funding | AUD 59 million from ARENA |
| Capacity | 1 $\text{MW}_{\text{e}}$ Habanero pilot plant |
| Operator | Geodynamics Ltd. |
| Status | Project abandoned due to lacking political support |

Sources: [Häring 2007, Breede et al. 2013, Geodynamics 2015]

### 6.2.12 Japan

## Hijiori

In Hijiori, stimulation experiments were conducted by the New Energy and Industrial Technology Organisation (NEDO) in a volcanic area (Table 47). The research project consisted of 4 wells at depths between 1800 and 2300 m [Häring 2007]. High water losses and scale deposits occurred during circulation tests [Matsunaga et al. 2005].

*Table 47 Project overview: Hijiori*

| Project name | Hijiori HDR Test Site |
|---|---|
| Location | Hijiori |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1985 |
| End date | 2002 |
| Rock | Granodiorite |
| Wells | One injection well (SKG-2, 1788 m)<br>Three production wells (HDR-1, HDR-2 and HDR-3, 2200-2300 m) |
| Stimulation | Hydraulic fracturing, 2100 t of water with 70 kg/s max |
| Reservoir | Two reservoirs, a shallow and a deep one.<br>Shallow reservoir: about 1800 m, 250 °C temperature, created 1985-1991<br>Deep reservoir: about 2200 m, 270 °C temperature, created 1992<br>Flow rate 17 l/s |
| Seismicity | Microseismicity |
| Funding | National Institute for Resources and Environment (NIRE) |
| Capacity | Binary power plant, 0.13 $\text{MW}_{\text{e}}$, 0.8 $\text{MW}_{\text{th}}$ |
| Operator | NEDO (New Energy and Industrial Technology Development Organization) |
| Status | Concluded |

Sources: [Yamaguchi et al. 1995, Tenma et al. 2000, Matsunaga et al. 2005, Breede et al. 2013]

### Ogachi

The Ogachi project, one of the first EGS projects, aimed at developing technology for HDR use in Japan (Table 48). It is a multiple production well system with 1 injection and 4 production wells. Several issues were studied including a new hydraulic fracturing method that can create multiple reservoirs at different depths from a well. [Kaieda et al. 2005]. The project had to be stopped due to financial problems.

*Table 48 Project overview: Ogachi*

| Project name | Ogachi |
|---|---|
| Location | Ogachi |
| Type | Research facility |
| Class | Petrothermal |
| Start date | 1989 |
| End date | 2002 |
| Rock | Granodiorite |
| Wells | 400 to 1100 m |
| Stimulation | Multiple wells with multiple fracture zones and hydraulic fracturing |
| Reservoir | Temperature 60 to 228 °C, 6.7 to 20 l/s flow rate |
| Seismicity | Microseismicity |
| Funding | Not known |
| Capacity | Not known |
| Operator | Not known |
| Status | Concluded |

Sources: [Kaieda et al. 2005, Häring 2007, Breede et al. 2013]

## 6.3 Current challenges and possible bottlenecks of EGS

The key issue facing the geothermal power sector is the deployment of EGS technology. To date, the technology has been demonstrated on small scale in few locations and the Soultz-sus-Forêts is the only operational petrothermal system feeding electricity to the grid. However, for an adequate proof of concept the technology needs to be demonstrated under different geological conditions where permeability can be produced and maintained without having to rely too heavily on pre-existing fractures in the reservoirs. Operators need to demonstrate the ability to adequately control reservoirs in different settings, both in terms of heat extraction and from chemical stimulants and seismic point of view. In the process of providing widely applicable proof of concept of petrothermal EGS, drilling technologies as well as reservoir management and monitoring technologies should be developed extensively.

The risk of failure and the high upfront costs associated with geothermal development (in particular EGS which requires deep wells) has been identified as a key bottleneck preventing large scale deployment. Due to the high risk, financing costs play a major role in the LCOE of geothermal projects. Figure 15 displays the cost components constituting the LCOE of a petrothermal EGS power plant a presented in chapter 4.1.3 Three scenarios are provided, a 7 % discount rate as it was used to compare energy technologies in [Sigfusson & Uihlein 2015, page 50], a 12 % discount rate as it is used for geothermal in the JRC-EU-TIMES model [Simoes et al. 2013] and a variable discount rate as it is done in the GETEM model of the US Department of Energy Geothermal Technologies Office (DOE-GTO) [Nathwani & Mines 2015]. The variable discount model is suitable for geothermal as the highest discount rates are applied when risk of failure is high at the onset of a project but decreases from 30 % during exploration to 15 % during drilling down to the final 7 % during the construction phase of the power plant that should not start until the a commercial viability of the discovered resource has been confirmed.

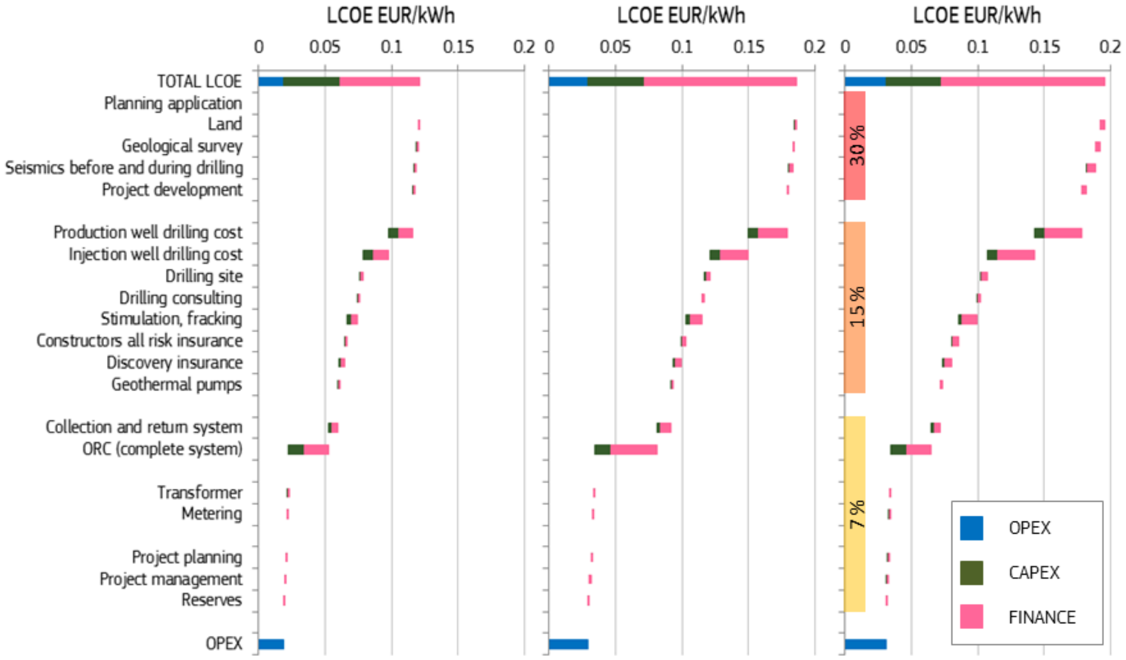

*Figure 15 Levelised costs of electricity of EGS systems according to components. Left: 7 % discount rate, middle: 12 % discount rate, right: variable discount rates*

Regardless of the discount scheme it may be observed that financing costs always dominate the LCOE and emphasis therefore has to be placed on lowering the risks that may in turn grant access to cheaper capital. In addition to financing costs, the cost of wells, the ORC system and the OPEX constitute the largest cost components whereas the cost of stimulation, an activity that determines largely the success or failure of the EGS project, is smaller. Ganz [Ganz 2015] reviewed expert reports on exploration risks of geothermal projects in hydrothermal karst and sandstone aquifers in Germany. There the thermal power of a geothermal well is the proxy for probability of project success. Thermal power is the product of flow rate and temperature, two factors that can be estimated and measured separately. Therefore two probabilities have to be established, the probability of high enough temperature, and probability of high enough flow rate. In 12 out of 13 wells, expert reports predicted aquifer temperature correctly. Similarly the probability of flow rates were predicted in 11 out of 13 wells. Lessons learned from [Ganz 2015] can to some extent be applied to the EGS systems although data to predict flow rates is more scarce than for the hydrothermal aquifers. The intensified use of 3D seismics to define geothermal resources and regional variations can possibly aid towards providing more accurate estimation of exploration risks. However, a systematic evaluation of the correlation between probability of success predictions based on 3D seismics and the actual success rate of geothermal wells has not been carried out yet and should be done as more data is collected [Ganz 2015].

### 6.3.1 Estimate of resource potential

It is well known that the heat stored in the Earth's crust is very high. However, the estimation of heat in place would benefit from more direct measurements. An extensive drilling campaign has been proposed by the European Geothermal Energy Council (EGEC) and would bring benefits to the geothermal sector in two ways: first, it would facilitate a more accurate estimate of the resource potential in Europe by establishing temperature gradients and heat flows in the crust and provide a better picture of the geology in the area. Second, due to increased drilling activities in the sector, knowledge and experience would be accumulated quicker.  These factors both lead to lower overall capital costs lower risk of failure which in turn may lead to lower financing cost of the project.

### 6.3.2 Drilling risks and costs

Today, drilling costs often constitute more than half of the cost associated with construction and commissioning of a geothermal power plant. Drilling into hydrothermal reservoirs includes drilling into highly heterogeneous materials where hard rocks may alternate with fractures where complete loss of circulation and collapsing geological formations may be experienced. Loss of circulation can lead to extensive losses of drill muds and cements. Collapsing formations may prevent movement of casings and in worst cases lead to the necessity of cutting the drill string causing the bottom hole assembly, collars and parts of the drill string to be left in the well [Sveinbjornsson & Thorhallsson 2014]. The main reason for higher drilling costs of EGS systems compared to hydrothermal resources is the depth of wells. The elevated depth requires longer non-productive times during replacement of drill bits and equipment and more energy to rotate the drill string.  An intensive drilling campaign as mentioned in the chapter above provides the opportunity to develop and test novel drilling technologies in a reasonably short period of time and better direct resource potential and drilling development projects are therefore highly complementary.

### 6.3.3 Reservoir stimulation and management

Reservoir stimulation is the single most critical research enabling the development of the EGS technology. Circulation of fluids must occur at sufficient rates to ensure sufficient commercial return, preferably with as small injection pressure as possible to lower pumping costs. At the same time, the volume of the reservoir has to be large enough to prevent premature breakthrough of injected waters with associated temperature decrease in production wells. Early thermal breakthrough has been observed where distance between injector and producer were less than 200 m [Roegiers et al. 2012] and references therein. The distance between the injectors and producers is not the only factor preventing thermal breakthrough and ensuring adequate thermal sweep from the reservoir. The key issue is making sure the fluids come in contact with sufficient reservoir volume.

Directional drilling and horizontal wells have become cheaper due to technical developments in the oil and gas industry for enhanced oil recovery and fracking. It can be of high value for geothermal operators to observe developments in this larger sector with the aim of more widespread implementation for geothermal reservoir production. Fracture networks propagate from the wellbores in specific orientation that is related to the existing stresses in the geothermal reservoir. At several km depths the orientation of the fractures with the lowest fracture initiation pressure tend not to be horizontal (and therefore perpendicular to traditionally vertically drilled wells) but rather near vertical, depending on the regional tectonics. Hence, horizontal drilling increases the change of intersecting several fracture zones that can be stimulated. The elevated change of intersecting several potential fracture zones increases the change of commercially feasible power plant as experience has shown a single fracture zones only tend to sustain approximately 1-2 MW final production on the surface and furthermore increasing the sweeping volume of geothermal reservoirs is always of high priority of geothermal operators to prevent premature thermal drawdown at the production wells.

Stimulation of a geothermal reservoir may be carried out in four principal ways or combination of these [Roegiers et al. 2012, Schumacher & Schulz 2013]

1. Hydraulic stimulation is the process of injecting fluid into a rock mass at, or below the fracture opening pressure (Also known as matrix stimulation). The stimulation seeks to induce shear deformation

on favourably oriented natural fractures in the rock mass.

2. Hydraulic fracturing is the process of injecting fluid into a rock mass at a rate and pressure sufficient to form and propagate opening mode fractures. Shear deformation may also occur around the main opening fracture where the pressure seizes to exceed the minimum principal stress.
3. Thermal stimulation is the process where permeability is increased by cold water injection.
4. Chemical stimulation is the process where complexation agents and or acids are injected into a well to increase the solubility of minerals which in turn increases the permeability immediately surrounding wells.

### Physical stimulation

Today, natural permeability of hydrothermal reservoirs mainly determines the productivity of geothermal wells. For petrothermal EGS systems, hydraulic fracturing is always needed whereas chemical stimulation may be the most effective treatment to remove skin in wells preventing adequate contact between the well and reservoir.

In the petroleum industry, treatment procedures are used routinely to create fractures in sedimentary rocks but these procedures have not been transferred with uniform results to the geothermal industry.

In the past, hydraulic fracturing has been tried at several hydrothermal and EGS reservoirs with mixed results where site conditions have detrimental effect on the end results. During hydraulic fracturing, single, opening mode hydraulic fractures tend to be formed. A series of these fractures should be produced by isolating short interval and pressurized at the wellbore. This procedure promotes:

1. The formation of multiple fractures to ensure sufficient heat extraction rates from the rock body.
2. Slower fluid velocities minimising scaling risk (scaling rates increase considerably as turbulence increases) and
3. Decreases differential pressure across the aquifer resulting in decreased pumping demand with associated parasitic loads within the power plant.

An overview of isolating practices applied in the geothermal industry is provided by [Walters et al. 2012]. The stimulation can either be done after total depth (TD) has been achieved or as viable fracture zones are encountered. These options include:

1. Drilling to TD, then stimulating fractures from bottom up with the aid of an inflatable packer that is elevated to next fracture zone after each simulation step.
2. Drilling to TD and identify all viable fracture zones before using cemented or sand liners after each fracture zone has been identified. This option tends to impair permeability and is not recommended.
3. Drilling to TD and identify all viable fracture zones before using liners with cementing stage collars or external and/or swellable packers.
4. Drilling to uppermost fracture zone, insert packer above the zone and stimulate before isolate with expandable liner or swell packers (plug and go).
5. Drilling a pilot hole to TD and then bore lateral bores or side tracks into previously identified fracture zones. These options are more costly than drilling a single borehole.

Examples of packer technologies are detailed in [Walters et al. 2012]. Often these packers are not rated for the temperatures found in high enthalpy hydrothermal systems (e.g. >300 °C) but may be suitable for the temperatures expected in EGS systems (150-200 °C).

For multiple zone stimulation Halliburton provide the RapidStage$^{TM}$ system. There a series of fracture zones can by stimulated by dropping a ball from the surface that hits a sleeve closing the well at a designated zone. The process is then repeated towards the wellhead. No removal of the balls is required afterwards as they degrade after operations.

Altarock have developed a method (US Patent 8272437) where the fracture zone with the lowest fracture pressure is stimulated by hydraulic shearing. Once adequate stimulation of this single fracture zone has been achieved, a temporary fracture sealant is injected into the well. The sealant enters the newly stimulated zone and blocks it. Thereafter, more water is pumped to the well to stimulate a new fracture zone with the weakest fracture pressure. The process is then repeated until sufficient number of fracture zones have been stimulated. The sealant is thermally unstable and therefore degrades as the well warms up after drilling and stimulation activities have seized.

## Chemical stimulation

Chemical stimulation procedures are typically carried out to remove skin in geothermal wells, in other words, promoting enhanced connection between the well and reservoir. Chemical stimulation further serves to remove drill muds that may clog fractures and pores near the well. Chemical stimulation methods may be applied to limestone reservoirs to create fracture networks (wormholes) but they have not been shown to enhance matrix permeability [Kalfayan 2008] except immediately near the well [Flores-Armenta 2010]. The dissolution rate of reservoir minerals differs by several orders of magnitude with carbonates dissolving much faster than silicates and generally mineral dissolution rate is higher under acidic conditions than neutral or slightly alkaline conditions. Hydrochloric acid (HCl) is frequently used to dissolve carbonates near wells whereas fluoric acid (HF), usually combined with HCl, is needed to dissolve silicates. Carbonate minerals, being mainly calcite and dolomite frequently precipitate in fractures under elevated temperatures and calcite precipitation surrounding of hydrothermal systems is a common phenomenon. Schumacher and Schulz [Schumacher & Schulz 2013] studied the effectiveness of acidizing geothermal well in the South German molasses basin (carbonate reservoirs) and reported the largest effect of initial acid treatments while subsequent treatments improved the wells only marginally. The main feed zones enabling fluid flow between wells of the Soultz-sus Forêts EGS system contain 3.3 % calcite and 0.8 % dolomite which have been shown to the most impact on porosity and in turn permeability of the reservoir [Fritz et al. 2010]. Although the carbonate minerals in reservoirs may best be treated with HCl, the HF is often added to dissolve drilling muds and chips that may clog pores and fractures near the well since these cannot be dissolved by HCl.

## Scaling prevention

Scaling prevention plays an important role during stimulation and subsequent operation of geothermal reservoirs. The issue is particularly relevant for EGS systems were re-injected fluids are far from equilibrium following the heat extraction process on the surface. As an example the circulating fluids in the Soultz-sus-Forêts project [Fritz et al. 2010] are supersaturated with regards to pyrite, a rapidly crystallising mineral as well as galena, potassium feldspar, quarts and smectite all leading to risk of scaling immediately adjacent to the well bore. On the contrary the cooled waters are undersaturated with regards to the fast dissolving calcite and dolomite and a series of slower dissolving silicates and sulphates. These will dissolve immediately adjacent to the well. The challenge is therefore to ensure continuous flow rates through the reservoir by preventing immediate precipitation of pyrite around the well and at the same time preventing the formation of calcite further from the well.

Calcite reactions in reservoirs such as Soultz-sous-Forêts may be represented by the following equation:

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^-$$

Where the equilibrium constant is determined by the reservoir temperature. Considering this reaction the overall process of an

EGS system can be simplified and described at 5 areas in the process (Figure 16)

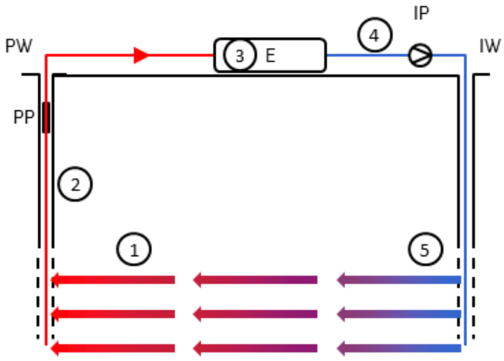

*Figure 16 The flow path of geothermal fluid during operation of an EGS system. See text for explanations.*

1. Fluid as is at mineral equilibrium with rocks at reservoir conditions. A production pump (PP) at depth in the production well (PW) extracts fluid from the reservoir towards the heat exchangers (E).
2. It is important to maintain high pressure towards the heat exchanger to prevent boiling of $CO_2$ from the fluid as removal of $CO_2$ shifts the equilibrium to the left leading to calcite scaling in pipes and the pump. If high pressure maintenance is somehow unfeasible small amount of acid may be added to lower pH thus preventing calcite formation.
3. Once the fluid enters the heat exchanger, it is rapidly cooled down leading to undersaturation of calcite but at the cost of increased precipitation risk of silica and pyrite as their solubility decreases at low temperature.
4. Calcite is undersaturated at this low temperature but there is still a silica and pyrite scaling risk.
5. Once the cold fluid enters the reservoir, calcite is dissolved adjacent to the well releasing calcium ion ($Ca^{2+}$) but as the fluids move from the well and are heated up the calcite soon becomes oversaturated in the fluid. A complexing agent such as acetic acid might be added to the solution to complex $Ca^{2+}$ thus preventing it forming calcite. Contrary to calcite, there exists a considerable risk of silica and pyrite precipitation next to immediately adjacent to the well, a risk that decreases as the water is heated up in the reservoir.

Calibration of these geochemical processes is under reservoir conditions somehow difficult due to a number of assumptions that need to be made.

### 6.3.4 Recommendations on EGS

The potential placement of facilities relying on hydrothermal resources is by far more limited than those of HSA-EGS which in turn is much smaller than petrothermal EGS. However these potentials remain inversely correlated with the associated risks of failure engaging in these projects once a potential resource has been identified.

It is paramount to develop and apply technologies to increase the probability of success of geothermal wells tapping into deep petrothermal systems.

### Reservoir stimulation

So far it has proved difficult to create petrothermal reservoirs will sufficiently low impedance to allow for commercial flow rates. More efforts have to be made in creating multiple fracture networks between two wells enabling sufficient thermal sweep of the reservoirs without the need of drilling multiple wells.

Methods for stimulation and maintenance of permeability need to be applicable under variety of geological conditions to enable large scale deployment.

Although fracturing costs are much smaller than drilling costs, development of effective stimulation methods is a fundamental issue for EGS. Without a successfully stimulated reservoir, a 4-5 km deep well doublet has limited commercial value from power production point of view. Furthermore, increasing the mass flow through a system can be much more beneficial than drilling into warmer reservoirs [Sigfusson & Uihlein 2015].

### Drilling

The geothermal industry will benefit from advances in directional drilling, fracking and blocking developed within the oil and gas industry. These advances need to be applied under conditions relevant for geothermal reservoirs.

A large emphasis should be made on lowering drilling costs by new methods that can increase rate of penetration and preferably technologies should evolve towards reduced tripping times primarily associated with replacement of drill bits.

### Risks

Induced seismicity constitutes the largest risk factor associated with EGS while at the same time being the tool for creating the geothermal reservoir. The risk assessment of induced seismicity of a particular reservoir should be a prerequisite to its inclusion of resource assessment. Therefore, the risk needs to be assessed under a variety of geological conditions in order to provide more relevant resource assessment on continental scale.

### Public opinion

Seismic events associated with stimulation and geothermal operations have led to public debate and negative perception on the geothermal industry.

Parallel to the technical developments to reduce induced seismicity risks, emphasis has to be made on increasing public awareness of the technology. Operators need to work according to general guidelines where the public is kept notified of operations, in particularly when stimulation is being carried out as well as when large changes are expected in the operation of the geothermal plants.

The understanding of the role of geothermal energy in futures energy mix may contribute to increased public tolerance towards EGS systems [Bauer et al. 2015].

# 7 CONCLUSIVE REMARKS

The geothermal industry operating within the EU is currently small but evidence exists that the potential for power and heat production is large with only a small fraction having been utilized so far.

Nineteen EU countries have included geothermal energy in their NREAP. Latest data available shows that in 2014, EU targets were reached for shallow geothermal (mainly ground source heat pumps) while the targets for deep geothermal (mainly direct use) and geothermal power were missed. In order to reach the 2020 target, current production (72 % of 2014 target) of heat from geothermal direct use has to more than triple. Concerning, geothermal electricity production, current deployment is about 95 % of the 2014 target and about 61 % of the 2020 target for the EU.

There are still some technical barriers preventing large scale geothermal electricity production. If EGS will be demonstrated in larger variety of geological conditions, the supply may grow from the current production of 5.6 TWh by a factor of hundred to 540 TWh in 2050 according to the JRC-EU-TIMES model. This prediction assumes that EGS will be a proven technology in the future but does not assume any major cost reductions. This growth corresponds to a change from current market share of 0.2 % to 12.6 % of total generated electricity in the EU assuming the baseline CAP scenario.

Cost reductions associated with drilling and surface installations might increase the market share to 24.5 % (1050-1100 TWh) of generated electricity in 2050 according to the JRC-EU-TIMES model.

Direct use of geothermal has been growing recently and this growth will continue as the risk is much lower when drilling depths do not exceed few kilometres as in the case of EGS. Of the geothermal technologies covered in this report, the EGS technology is the one that needs the highest public financial support as it is by far the least market ready and will need considerable political support in the form of funding as well as more transparent regulations will be needed to facilitate large scale deployment of the technology.

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