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A systematic review of enhanced (or engineered) geothermal systems: past, present and future

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Abstract

Enhanced (or engineered) geothermal systems (EGS) have evolved from the hot dry rock concept, implemented for the first time at Fenton Hill in 1977. This paper systematically reviews all of the EGS projects worldwide, based on the information available in the public domain. The projects are classified by country, reservoir type, depth, reservoir temperature, stimulation methods, associated seismicity, plant capacity and current status. Thirty five years on from the first EGS implementation, the geothermal community can benefit from the lessons learnt and take a more objective approach to the pros and cons of 'conventional' EGS systems.

Keywords: Enhanced geothermal system, Engineered geothermal system, Hot dry rock, Conventional EGS, EGS database worldwide

Review

The currently used term 'enhanced or engineered geothermal system' (EGS) has its roots in the early 1970s when a team from Los Alamos National Laboratories began the hot dry rock (HDR) project at Fenton Hill (Cummings and Morris 1979; Tester et al. 1989; Brown 1997; Duchane 1998). The concept is described in Potter et al. (1974). HDR was also known as hot fractured rock because of either the need to fracture the virtually impermeable formations or the presence of natural fractures in the hot reservoir (Wyborn et al. 2005; Goldstein et al. 2011) or as hot wet rock (HWR) when it was established that the formations were not completely dry but contained some fluids. The European EGS project at Soultz-sous-Forêts in France is an example of a HWR reservoir (Duchane 1998). Further nomenclature encountered in the literature include stimulated geothermal system, deep heat mining (Häring and Hopkirk 2002; Häring 2007) and deep earth geothermal. All of the above usually imply the use of petrothermal systems (Ilyasov et al. 2010; Gebo NDS 2012a).

Schulte et al. (2010) defined the typical geological settings for EGS, varying from igneous (e.g. Iceland), metamorphic (e.g. Lardarello, Italy), magmatic (e.g. Soultz, France) and sedimentary (e.g. Groß Schönebeck and Horstberg, Germany).

According to Potter et al. (1974), the most suitable rock type for HDR is granite or other crystalline basement rock; temperatures should vary from 150°C to 500°C at depths in the order of 5 to 6 km, with an average flow rate over a 10-year reservoir lifetime of 265 l/s, with hydraulic fracturing achieving a contact surface area of approximately 16 km^2, an average thermal capacity of 250 MW_{th} that could be obtained from the surface heat exchanger, and with pressurized water entering at 280°C and leaving at 65°C. Based on these criteria, the potential electrical power that could be generated might amount to 50 MW_e at a net efficiency of 20%.

Over the years, different definitions of EGS have been proposed, covering a broad variety of rock types, depth, temperature, reservoir permeability and porosity, type of stimulation technique involved, etc. Below are four examples of recent EGS definitions in the public domain.

1. The Massachusetts Institute of Technology (MIT) led an interdisciplinary panel which defined EGS as 'engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources. For this assessment, this definition has been adapted to include all geothermal resources that are currently not in commercial production and require stimulation or enhancement. EGS would exclude high-grade hydrothermal but include conduction dominated, low permeability resources in sedimentary and basement formations, as well as geopressured, magma and low grade, unproductive hydrothermal resources. Co-produced hot water from oil and gas production is included as an unconventional EGS resource type that could be developed in the short term and possibly provide a first step to more classical EGS exploitation' (MIT et al. 2006a).
2. The Australian Geothermal Reporting Code Committee considered EGS as 'a body of rock containing useful energy, the recoverability of which has been increased by artificial means such as fracturing' (AGRCC 2010).
3. Williams et al. (2011) proposed that 'EGS comprise the portion of a geothermal resource for which a measureable increase in production over its natural state is or can be attained through mechanical, thermal, and/or chemical stimulation of the reservoir rock. In this definition, there are no restrictions on temperature, rock type or pre-existing geothermal exploitation'.
4. The BMU (2011) defines enhanced geothermal systems as creating or enhancing a heat exchanger in deep and low permeable hot rocks using stimulation methods. Following BMU's definition, EGS embraces not only HDR but also deep heat mining, hot wet rock, hot fractured rock, stimulated geothermal systems, and stimulated hydrothermal systems.

Clearly, the geothermal community lacks a universal definition of EGS, which may simply be taken as 'unconventional geothermal systems', diverging significantly from the initial HDR concept. This lack of clarity may constitute a potential obstacle to the implementation of tailored subsidy programmes.

In this study, the MIT definition is adopted with the only difference that geopressured and magmatic systems and also co-produced hot water from hydrocarbon wells are excluded. The reasons for this particular choice are that the MIT report was (and still is) regarded as a milestone report towards the development of EGS; also, from an engineering point of view, it is perhaps one of the most comprehensive definitions. On the other hand, it does not enter into the details of the different stimulation approaches and associated consequences for different EGS systems. Recently, for example, Jung (2013) has reconstructed the background to contemporary EGS: from the original HDR concept based on multi-zone hydraulic fracturing in competent crystalline formations, through that of open-hole massive injection in naturally fractured crystalline formations and finally to the proposed multi-zone massive injection (with the objective of generating multiple wing cracks) in naturally fractured crystalline formations. As this review does not aim at a project-by-project evaluation of the geomechanics that occur during EGS stimulation, the modified MIT definition is considered to be suitable for generating the database proposed in this study.

Geopressured and magma systems were left out from this review because they typically have been excluded from past EGS cataloguing attempts, such as those proposed by European Geothermal Energy Council (EGEC) (2012) and GtV (2013).

EGS milestones

During the last four decades, there have been some key milestones towards the development of EGS for heat production and electricity generation. The information that follows is based on the report by Tenzer (2001), supplemented by additional information:

- 1970: Proposals for the first EGS worldwide in Fenton Hill, Los Alamos, USA.
- 1973: First EGS experiments in Fenton Hill.
- 1974 to 1977: Feasibility studies for EGS projects in Japan.
- 1975: Start of preparations for the first scientific EGS pilot plant in Bad Urach, Germany.
- Since 1977: EGS feasibility studies for shallow depths at Falkenberg, Germany, Camborne School of Mines, Cornwall in the UK and Le Mayet, France.
- 1977: EGS Bad Urach - drilling starts.
- 1980 to 1986: EGS Bad Urach - deepening of the borehole to 3,488 m at 147°C and hydraulic tests for single borehole system.
- 1984 to 1985: Start of EGS; Neustadt-Glewe, as a pilot project for low enthalpy energy; to date, this is the warmest accessed hot water reservoir in Northern Germany.
- 1986: Start of the German-French EGS project at Soultz-sous-Forêts, France, as a joint European research EGS pilot plant.
- 1986 to 1991: First EGS experiments in Hijori and other locations in Japan.
- 1987: EGS Soultz - began drilling the first borehole to 2,000 m at 140°C and started the investigation of the crystalline basement in the Rhine-Graben.
- 1989: EGS Soultz - UK joins the project; formation of an industrial consortium for organized planning and operation of an EGS project in Europe.
- 1990: EGS Soultz - drilling of a second 2,000-m deep borehole and deepening of the first borehole to 3,500 m depth (at 160°C); geothermal reservoir identification; the second borehole was used as seismic observation borehole.
- 1991 to 1996: EGS Bad Urach - deepening of the borehole to a depth of 4,445 m at a temperature of 172°C; also performed intense borehole measurement programme.
- 1994–1995: EGS Soultz - deepening of the second borehole to a depth of 3,876 m, followed by a production test which saw the first steam production in Middle Europe from crystalline rocks; using massive stimulation and circulation tests

with seismic monitoring and development of the downhole heat exchanger, a thermal power of 8 MW was achieved.
- 1996: Start of deep heat mining project in Basel, Switzerland - a pilot project for EGS in a modern urban environment.
- 1996 to 1997: EGS Bad Urach - development of a downhole heat exchanger by massive hydraulic fracturing; the largest EGS created worldwide; long-term (4 months) hydraulic circulation test; a thermal power of 11 MW was achieved.
- 1998 to 2000: EGS Soultz - deepening of the second borehole to 5,060 m at 201°C; hydraulic stimulation and seismic monitoring.
- 2001: Start of EGS Groß-Schönebeck, Germany, which was the first *in situ* geothermal laboratory for developing techniques for the exploration and usage of geothermal energy.
- 2003: Start of EGS Cooper Basin, Australia - the largest demonstration EGS project in the world.
- 2003: Test of new single well concept in Genesys Horstberg, Germany.
- 2003: Start of EGS Landau - the first geothermal combined heat power plant to be connected to the grid; the one and only EGS project in a German town.
- 2004: Start of Unterhaching, Germany, the first geothermal project in the Bavarian Molasse Basin where, in addition to heat supply, electricity generation was also achieved; first Kalina power plant in Germany; first project worldwide with a private sector insurance for geological risk in deep boreholes.
- 2005: Start of EGS Paralana trying to implement an underground heat exchanger called 'heat exchanger within an insulator (HEWI)' concept (heat exchanger within the insulator) (Petratherm 2012).
- 2006/2007: Deep heat mining project in Basel stopped due to repeated severe induced seismicity events; the project was permanently abandoned in 2009.
- 2007: First binary geothermal plant in France at EGS Soultz (with ORC plant).
- 2009: New law for renewable energies in Germany - electricity generation and supply to the power net gets more financial support.
- 2009: Start of EGS GeneSys Hannover, Germany, as a single well concept.
- 2009: Start of EGS St. Gallen, Switzerland.
- 2010: Implementation of new 'side-leg' concept in the EGS project Insheim (Germany); forked injection well shall reduce induced seismicity (Insheim 2012).
- 2011: EGS GeneSys Hannover put on hold due to salt deposition in the single well.
- 2011: Guidelines for 'seismic surveillance' for Germany published by Bundesverband Geothermie.
- 2012: Switzerland decides to support deep geothermal projects.
- 2012: EGS Insheim connected to the power net.
- 2013: EGS Habanero successfully commissioned, with generation of 1 MW_e of power; first EGS project in Australia generating electricity.
- 2013: EGS St. Gallen drilling started.
- 2013: EGS St. Gallen put on hold due to induced seismicity events with a maximum magnitude of 3.6 on the Richter Scale; green light to proceed given by City Council 5½ weeks later.

Systematic overview of past and present EGS projects worldwide

The following review should not be considered exhaustive as it is based exclusively on the information available in the public domain. Yet, to the authors' knowledge, this is the first public attempt to formally collate a large database of information on EGS worldwide, from the first HDR project at Fenton Hill in 1974 to date.

The objective of this review is to present key information on past and present EGS experience worldwide, from which key lessons can be learnt for the future.

The 31 EGS projects identified during this review are classified by country, reservoir type, depth, reservoir and wellhead temperature, stimulation methods, induced seismicity and radioactivity, plant capacity, flow rate and current status.

The 31 projects are divided into four different groups:

Table 1 comprises basic information about EGS projects that are still under development. It does not include pending commercial projects that are either at the status of raising funds (e.g. Munster in Germany and Eden in the UK) or still need governmental approval.

Tables 2 and 3 present projects that are already in the power generation phase.

Table 4 gives information about experimental projects that were developed to test single phase of an EGS project rather than the whole process to generate electricity.

Table 5 presents information on projects that are aimed for electricity generation but were abandoned due to various problems. Input information was drawn from different sources available in the public domain; all of which are cited in the titles of the tables.

This grouping criteria allow the reader to have an immediate overview of past vs. current vs. future EGS activities, better appreciate the challenges faced by EGS (technical, economic and related to public acceptance), develop a feeling for the level of research and development efforts put into EGS *vis-à-vis* the desire to achieve worldwide commercialisation of the concept.

Note that in the tables, 'microseismic' refers to seismic activity less than 3.5 on the Richter scale and is used for those cases when no further details on recorded seismicity could be found in the literature. See the following paragraphs for more discussions on induced seismicity in EGS projects.

When 'thermal capacity' is quoted next to 'installed electrical capacity', this implies a combined heat and power project.

Under 'stimulation methods', the terms 'hydraulic fracturing', 'hydraulic', 'hydroshearing', 'shear' and 'hydraulic stimulation' are taken directly as quoted by the cited sources. The authors of this manuscript have not performed an independent review or assessment of the specific stimulation methods implemented in or planned for each individual project, as this falls outwith the scope of this broader EGS review.

Overall, the tables above capture a detailed database of 31 EGS projects worldwide. Based on the tables, the following plots provide a way to extract trends and common characteristics of EGS.

As illustrated in Figure 1, most of the European EGS projects' reservoir/bottomhole temperatures are lower than 165°C, with the exception of Lardarello and Bouillante. Compared to Europe, the average EGS reservoir/bottomhole temperatures in America, Australia and Asia are higher although the well depths are comparable. Note that only 25 projects are displayed in Figure 1; the remaining 6

Table 1 EGS projects (R&D and commercial) still under development and not generating electricity

Project	Start date	Location	Well depth (m)	Stimulation methods	Description	Operator	Current status	Rock type	BHT (°C)	Seismic event	Flow rate (l/s)
Le Mayet[a]	1978 (Cornet 2012)	France (Cornet 2012)	200 to 800 (Cornet 2012)	Hydraulic fracturing with and without proppant (Cornet 2012; MIT et al. 2006b)	Research (Cornet 2012; MIT et al. 2006b)	Not known	Not known	Granite (Cornet 2012)	22 (Wyborn 2011)	Microseismic, not felt on surface (Cornet 2012)	5.2 (Wyborn 2011)
Genesys Hannover	2009 (Zimmermann et al. 2009)	Germany (Zimmermann et al. 2009)	3,900 (Zimmermann et al. 2009)	Hydraulic fracturing (Zimmermann et al. 2009)	Demonstrate single well concepts (Zimmermann et al. 2009)	Federal Ministry of Economics and Technology (Zimmermann et al. 2009)	Salt deposition has been removed (BGR 2013)	Bunter sandstone (Zimmermann et al. 2009)	160 (Blöscher et al. 2012)	Microseismic (1.8 M) (Huenges 2010)	7 (planned) (Zimmermann et al. 2009)
Groß Schönebeck	2000 (Zimmermann et al. 2009)	Germany (Zimmermann et al. 2009)	4,309 (Zimmermann et al. 2009; BINE 2012a) to 4,400 (BINE 2012a)	Hydraulic gel proppant and fracturing (Zimmermann et al. 2009; Blöscher et al. 2012; Huenges 2010) thermal (ENGINE 2008b), chemical (Henninges et al. 2012)	1st *in situ* geothermal laboratory, EGS research (Zimmermann et al. 2009)	GFZ, Schmidt + Clemens GmbH + Co. KG (BINE 2012a)	Production-injection experiment and data interpretation and modelling finished (Feldbusch et al. 2013)	Sandstone and andesitic volcanic rocks (Zimmermann et al. 2009; Blöscher et al. 2012)	145 (Blöscher et al. 2012)	Negligible (max, −1.8 to −1.0M) (Blöscher et al. 2012)	20 (Blöscher et al. 2012)
Mauerstetten	2011 (Schrage et al. 2012a)	Germany (Schrage et al. 2012a)	4,545 (Exorka 2013)	Chemical (Schrage et al. 2012b); hydraulic (Informationsportal Tiefe Geothermie 2013a)	Research (Schrage et al. 2012b)	Exorka GmbH, GFZ, TUBAF (Schrage et al. 2012a)	Seismic monitoring system installed (Informationsportal Tiefe Geothermie 2013a); next step, hydraulic stimulation (Informationsportal Tiefe Geothermie 2013a)	Limestone (Schrage et al. 2012a)	130 (Schrage et al. 2012a)	Unknown	Unknown
St. Gallen	2009 (Geothermie Stadt St. Gallen 2013a)	Switzerland (Geothermie Stadt St. Gallen 2013a)	4,450 (Geothermie Stadt St. Gallen 2013a)	Chemical and hydraulic (Geothermie Stadt St. Gallen 2013a)	Commercial: heat and power (Geothermie Stadt St. Gallen 2013a)	ITAG Tiefbohr GmbH (Geothermie Stadt St. Gallen 2013a)	Production test interrupted due to pump failure and resulting seismic event (Geothermie Stadt St. Gallen 2013a)	Malm, shell limestone (Geothermie Stadt St. Gallen 2013a)	130 to 150 (estimated) (Geothermie Stadt St. Gallen 2013a)	3.5 M (Geothermie Stadt St. Gallen 2013a)	(Geothermie Stadt St. Gallen 2013a)

Table 1 EGS projects (R&D and commercial) still under development and not generating electricity *(Continued)*

Newberry	2010 (Cladouhos et al. 2012)	USA (Cladouhos et al. 2012)	3,066 (BLM 2012)	Hydroshearing, multi-zone isolation techniques (Cladouhos et al. 2012)	Demonstration for EGS stimulation/ research (Cladouhos et al. 2012)	AltaRock Energy, Davenport Newberry (Cladouhos et al. 2012)	Stimulation started successfully (Informationsportal Tiefe Geothermie 2012)	Volcanic rocks (Fittermann 1988)	315 (Cladouhos et al. 2012)	Microseismic (Cladouhos et al. 2012)	Unknown
Northwest Geysers	In 1980s (Garcia et al. 2012)	USA (Romero et al. 1995)	3,396 (Garcia et al. 2012)	Thermal fracturing (Walters 2013)	Demonstration/ research (Garcia et al. 2012)	Calpine Corporation (Garcia et al. 2012)	Stimulation stage (5 MW of potential production) (Walters 2013)	Metasedimentary rocks (greywacke) (Romero et al. 1995; Garcia et al. 2012)	About 400 (Garcia et al. 2012)	Microseismic (0.9 to 2.87 M) (Garcia et al. 2012; Walters 2013)	9.70 (Garcia et al. 2012)
Paralana	2005 (Petratherm 2012)	Australia (Petratherm 2012)	4,003 (Petratherm 2012)	Hydraulic (Petratherm 2012)	Commercial power development (Petratherm 2012)	Petratherm, Beach Energy (Petratherm 2012)	Drilling of Paralana 3, submit funding application (Petratherm 2012)	Metasediments, granite (Petratherm 2012)	171 (Petratherm 2012)	Microseismic ≤2.6 M (Petratherm 2012)	Up to 6 (ENGINE 2008b)

GFZ, German Research Centre for Geosciences; TUBAF, Technische Universität und Bergakademie Freiberg (Germany); BHT, bottomhole temperature; [a]Note that little and contrasting information was found in the open domain concerning the project 'Le Mayet'. Some sources say that it was operational from 1984 till 1987 (Evans 2011). Others (MIT et al. 2006b) report that it was still ongoing as of 2006 and having a BHT of 33°C instead of the 22°C reported in the table.

Table 2 Ongoing EGS projects (R&D and commercial) generating electricity

Project	Start date	Location	Well depth (m)	Stimulation methods	Description	Operator	Rock type	Reservoir temperature (°C)	Seismic event
A.									
Bruchsal	1,983 (BMU2011)	Germany (BMU2011)	1,874 to 2,542 (BMU2011)	Unknown	Commercial (Enbw 2013)	EnBW, EWB (KIT 2013)	Bunter Sandstone (KIT 2013)	123 (Rettenmaier 2012)[a];	Microseismic (KIT 2013)
Landau	2003 (BINE 2012d)	Germany (Baumgärtner 2012)	3,170 to 3,300 (Baumgärtner 2012)	No stimulation for producer; hydraulic for injector (Baumgärtner 2012)	First implementation of EGS technology in Germany (BINE 2012d); first and only EGS in town in (D) (Baumgärtner 2012)	BESTEC, Geox (Baumgärtner 2012)	Granite (Lacirignola and Blanc 2012)	159 (Baumgärtner 2012)[a]	Microseismic (≤2.7 M) (Baumgärtner 2012), felt by residents
Insheim	2007 (Insheim 2012)	Germany (Insheim 2012)	3,600 to 3,800 (LGB-rlp 2012)	Yes (Baumgärtner 2012)	New concept, side-leg injection well (BINE 2012b)	Pfalzwerke geofuture GmbH (Pfalzwerke-geofuture 2012; BINE 2012b)	Keuper, perm, bunter sandstone, granite (Baumgärtner 2012)	165 (LGB-rlp 2012)	M: 2.0 to 2.4 and microseismic (Groos et al. 2012)
Neustadt-Glewe	1984 (BMU 2011)	Germany (Bracke 2012)	2,320 (Bracke 2012)	Unknown	Commercial, pilot plant for low enthalpy (BMU2011)	WEMAG AG, Stadt Neustadt-Glewe, Geothermie Neubrandenburg GmbH (BMU2011)	Sandstone (BMU 2011)	99 (GtV 2013)[a]	Unknown
Unterhaching	2004 (BMU2011)	Germany (Bracke 2012)	3,350 to 3,580 (Bracke 2012)	Acidizing (BMU2011)	First Kalina power plant in Germany (BINE 2012c)	Geothermie Unterhaching GmbH & Co. KG, Rödl & Partner GbR (BINE 2012c)	Limestone (Dumas 2010)	123 (Bracke 2012)[a]	Unknown
Soultz	1987 (MIT et al. 2006b)	France (Genter 2012)	5,093 (MIT et al. 2006d)	Hydraulic fracturing and acidizing (MIT et al. 2006d)	Research and demonstration (Genter 2012)	European cooperation project (MIT et al. 2006d)	Granite (MIT et al. 2006d)	165 (BMU 2011)	Microseismic (M = −2 to 2.9) (Genter 2012)
Bouillante	1963/1996 (Bertini et al. 2006)	France (Guadeloupe) (Bertini et al. 2006)	1,000 to 2,500 (Bertini et al. 2006)	Thermal cracking (Bertini et al. 2006)	Commercial (Bertini et al. 2006)	Geothermie Bouillante, CFG-Services, BRGM, ORKUSTOFNUN, COFOR (Bertini et al. 2006)	Volcanic lavas and tuffs (Bertini et al. 2006)	250 to 260 (Bertini et al. 2006)	Microseismic (Sanjuan et al. 2010)

Table 2 Ongoing EGS projects (R&D and commercial) generating electricity *(Continued)*

Altheim	1989 (Pernecker 1999)	Austria (Bloomquist 2012)	2,165 to 2,306 (Bayerisches Landesamt für Wasserwirtschaft 2011)	Acidizing (Pernecker 1999), hydraulic stimulation (ENGINE 2008b)	Commercial (Pernecker 1999)	Municipality of Altheim, Terrawat (Pernecker 1999)	Limestone (Bayerisches Landesamt für Wasserwirtschaft 2011)	106 (Bloomquist 2012)	Unknown
Lardarello	1970 (Cappetti 2006) (1904)	Italy (ENGINE 2008b)	2,500 to 4,000 (Bertini et al. 2006)	Hydraulic and thermal stimulation (ENGINE 2008b)	Research and demonstration (Cappetti 2006) and commercial	ENEL Green Power (Lazzarotto and Sabatelli 2005)	Metamorphic rocks (ENGINE 2008b)	300 to 350 (ENGINE 2008a)[a]	≤3.0 M (Bromley 2012)
Coso	2002 (Häring 2007)	USA (Häring 2007)	2,430 to 2,956 (Julian et al. 2009)	Hydraulic, thermal and chemical (Rose et al. 2004)	Research and development (Häring 2007)	Coso Operating Company (EGS Coso 2013)	Diorite, granodiorite, granite (Rose et al. 2004)	≥300 (EGS Coso 2013)	≤2.8 M (Julian et al. 2009)
Desert Peak	2002 (MIT 2006c)	USA (MIT et al. 2006c)	About 1,067 (Chabora et al. 2012)	Shear, chemical, hydraulic (Davatzes et al. 2012)	Research and development (Davatzes et al. 2012)	Ormat, GeothermEx (Val Pierce 2011)	Volcanic and metamorphic rocks (Chabora et al. 2012)	179 to 196 (Chabora et al. 2012)	Microseismic: −0.03 to 1.7 (Chabora and Zemach 2013)
Berlín	2001 (Bommer et al. 2006)	El Salvador (Rodríguez 2003)	2,000 to 2,380 (Rodríguez 2008)	Hydraulic fracturing and chemical (Rodríguez 2003)	Developing EGS project in a geothermal field (Rodríguez 2003)	Shell International (Rodríguez 2003), LaGeo (Bommer et al. 2006)	Volcanic rocks (Häring 2007)	183 (Bommer et al. 2006)	≤4.4 M (Bommer et al. 2006)
Cooper Basin	2003 (Majer et al. 2007)	Australia (Majer et al. 2007)	4,421 (Majer et al. 2007)	Hydraulic (Majer et al. 2007; Holl 2012)	Largest demonstration project in the world (Stephens and Jiusto 2010)	Geodynamics Ltd. (Majer et al. 2007; Geodynamics 2013)	Granite (Majer et al. 2007)	242 to 278 (Geodynamics 2013)	≤3.7M (Majer et al. 2007)
Hijiori	1985 (Sasaki 1998)	Japan (Sasaki 1998)	1,805 to 1,910 (Sasaki 1998)	Hydraulic fracturing (Sasaki 1998)	Developing EGS technologies (Sasaki 1998)	Japan's new energy (DiPippo 2012a), NEDO (Sasaki 1998)	Granodiorite (Sasaki 1998)	190 (DiPippo 2012a)	Microseismic (Sasaki 1998)

[a]Reservoir temperature not available, BHT is used instead.

Table 3 Ongoing EGS projects (R&D and commercial) generating electricity

Project	Type of power plant	Flow rate (l/s)	Distance between producer and injector (km)	Installed electrical capacity (MW_e)	Thermal capacity (MW_{th})	Flow assurance problem
B.						
Bruchsal	Kalina cycle (BMU2011)	28.5 (BMU2011)	1.4 (BMU2011)	0.55 (BMU2011)	5.5 (GtV 2013)	High salt contents (100 g/l); high CO_2 concentration (BMU 2011)
Landau	Organic Rankine Cycle (BINE 2012d)	70 to 80 (Baumgärtner 2012)	1.5 (Bracke 2012)	Up to 3.6 (Baumgärtner 2012)	2 to 5 (Baumgärtner 2012)	Unknown
Insheim	Organic Rankine Cycle (Informationsportal Tiefe Geothermie 2013b)	65 to 85 (planned) (Pfalzwerke-geofuture 2012)	Unknown	4.8 (Pfalzwerke-geofuture 2012)	6 to 10 (Pfalzwerke-geofuture 2012)	Unknown
Neustadt-Glewe	Organic Rankine Cycle (Bracke 2012)	35 (Bracke 2012)	1.5 (BMU2011)	0.21 (Bracke 2012)	4 (Bracke 2012)	High salt content, high gas concentration (Bracke 2012)
Unterhaching	Kalina cycle (BMU 2011)	150 (Bracke 2012)	4.5 (Bracke 2012)	3.36 (Bracke 2012)	38 (Bracke 2012)	Unknown
Soultz	Organic Rankine Cycle (BMU 2011)	30 (BMU 2011)	0.6 (BMU 2011)	1.5 (BMU 2011)	Non-scheduled (Dumas 2010)	Corrosion due to high salt contents (BMU 2011)
Bouillante	Double and single flash (Bertini et al. 2006)	150 (Bertini et al. 2006)	0.5 (Bertini et al. 2006)	15 (Bertini et al. 2006)	Unknown	Unknown
Altheim	Organic Rankine cycle (Bayerisches Landesamt für Wasserwirtschaft 2011)	81.7 (Bayerisches Landesamt für Wasserwirtschaft 2011)	1.7 (Bayerisches Landesamt für Wasserwirtschaft 2011)	1.0 (Bloomquist 2012)	12.4 (Bayerisches Landesamt für Wasserwirtschaft 2011)	Clogging by a mixture consisting of stone material and bentonite (Pernecker 1999)
Lardarello	Not known	100 (Cappetti 2006)	Variable: generally > 0.5 (ENGINE 2008a)	700 (ENGINE 2008b)	Not known	Highly corrosive, total loss of circulation when very high permeability fracture zones are encountered (ENGINE 2008b)
Coso	Unknown	Unknown	1.4 (Julian et al. 2009)	240 (Karner 2005)	Unknown	Unknown
Desert Peak	Unknown	100 (Chabora and Zemach 2013)	Unknown	1.7 (additional) (Chabora and Zemach 2013)	Unknown	Wellbore instability due to chemical stimulation (Chabora et al. 2012)
Berlín	Binary power plant (Prevost 2004)	Unknown	Unknown	54 (Bommer et al. 2006)	56 (Rodríguez 2000)	Unknown
Cooper Basin	Unknown	30 (Holl 2012)	Unknown	1 (Geodynamics 2013)	Unknown	Unknown
Hijiori	Binary Power Plant (DiPippo 2012a)	17 (Sasaki 1998)	0.038 to 0.063 (DiPippo 2012a)	0.13 (DiPippo 2012a)	8 (DiPippo 2012a)	High water losses (Johansson et al. 1993), precipitation of anhydrite (DiPippo 2012a)

projects (St. Gallen, Fjällbacka, Falkenberg, The Southeast Geysers, Basel and Bad Urach) are excluded because reservoir/bottomhole temperature data could not be found in the public domain or are only estimated in the case of St. Gallen.

The relationship shown in Figure 2 points out that most EGS activities are operated at flow rates lower than 40 l/s. Note that only 20 projects are displayed in Figure 2; the remaining 11 projects (Genesys Hannover, Insheim, Mauerstetten, Newberry, Coso, Berlín, Falkenberg, The Southeast Geysers, Basel, Bad Urach and St. Gallen) are excluded because flow rate data could not be found in the public domain.

Figure 3 displays EGS projects classified on the basis of rock types. Although it appears that EGS activities can be implemented in any of the three major groups of rocks on earth, most projects are developed in igneous rocks, following the original HDR concept.

The recorded maximum magnitudes of induced seismic events associated with the development of EGS projects worldwide are shown in Figure 4. Originally, the Richter scale was developed as a mathematical device to compare local earthquake sizes. The magnitude is defined as the logarithm of the wave amplitude recorded by seismographs. At that time, the smallest measurable earthquakes were assigned with values close to zero. However, due to the higher accuracy of modern seismographs, the Richter scale now measures earthquakes having negative magnitudes. Majer et al. (2007) reported that '…To date, the maximum observed earthquakes attributed to EGS operations have been magnitude 3.0 to 3.7 and the largest geothermal injection-related event was magnitude 4.6'. Later, Majer et al. (2013) also stated that for EGS, earthquakes are typically smaller than M 3.5 (M representing the momentum magnitude in this context). According to EGEC (2013), microseismic activity is less than 3.5 on the Richter scale. Only the projects with published induced seismic magnitude are displayed in Figure 4; the remaining 16 projects (Le Mayet, Mauerstetten, Newberry, Bruchsal, Neustadt-Glewe, Unterhaching, Bouillante, Altheim,, Hijiori, Genesys Horstberg, Fjällbacka, Fenton Hill, Ogachi, Bad Urach, Falkenberg and The Southeast Geysers), most of which have been reported to suffer from microseismicity, are omitted due to lack of explicit seismic data.

Stimulation methods that are applied in EGS developments are summarized in Figure 5, which reveals that hydraulic stimulation is the most commonly used method, independently of the rock type concerned. In addition, there are relatively few cases where chemical or thermal stimulation technologies are applied. This often leads to the assumption that the EGS definition only applies to hydraulically fractured systems.

The installed electrical and thermal capacity of EGS projects are summarized in Figure 6. Since EGS is still a developing concept, the database contains only 14 projects carried out with electricity generation. Note that the thermal capacities of Bouillante, Soultz, Lardarello, Desert Peak, Cooper Basin and Coso are missing as data could not be found in the public domain. The variation of production scale causes great capacity differences among the projects.

Figure 7 shows the rock type and well depth of all the studied EGS projects worldwide.

Results and discussions

From the information provided in the tables and the plots shown earlier, it appears that EGS projects currently under development are still on the learning curve, overcoming problems, gaining experience and trying to introduce advanced technology; the projects already concluded provide relevant history and analogy for upcoming developments and the projects that have been temporarily halted or abandoned give an insight into issues that must be avoided in the future.

Below are field cases where breakthrough methodologies were first implemented to validate the EGS concept. Unplanned events and issues that needed addressing in order to ensure feasibility and commerciality of EGS are discussed, and the corresponding lessons learnt are highlighted.

- The 'Paralana' project will use a new concept called the HEWI (Petratherm 2012).
- The 'Genesys' project was the first project worldwide testing a single well concept. Technical feasibility of the concept was proved by the 'Genesys Horstberg' project. The subsequent 'Genesys Hannover' aimed to use geothermal energy to heat the building complex of the Geozentrum Hannover (Tischner et al. 2010). The project has currently solved the problem of salt deposition, which has led to a suspension of the production test (Genesys 2012). This single well concept has the advantage of lower drilling costs as only one wellbore is needed to be drilled. However, since the circulating fluid moves through fractures, it is in direct contact with the rock formation, which leads to salt deposition risk. This experience has taught the geothermal community that flow assurance needs to be addressed ahead of time to prevent issues triggered by the chemical interaction between the injected fluid and the receiving rock, which can impair the overall success of an EGS project.
- The 'Groß Schönebeck' project is an important pilot for the development of geothermal technologies in Europe as an *in situ* laboratory was installed in one of the boreholes. The reservoir can be investigated by logging tools during production using a special Y-tool which is attached to the production string (Henninges et al. 2012). This system allows measurements with electrical tools and fibre-optic distributed temperature sensing. However, the data transfer to surface is problematic and can only be done discontinuously (Huenges 2013). This suggests that further technology advances are needed in the area of well logging for this type of applications. Using a newly developed fluid monitoring system, fluid physicochemical properties were measured online and *in situ* (Feldbusch et al. 2013). Worldwide, it is the only facility for the investigation of sedimentary large-scale structures under natural conditions. A 7-day long-term production-injection experiment between both boreholes to investigate the sustainability of the reservoir was completed in April 2012 (Feldbusch et al. 2013), and results, data interpretation and modelling of the experiments have been presented by Feldbusch et al. (2013), Cherubini et al. (2013) and Noack et al. (2013). A corrosion test will permit the verification of the long-term reliability of the system's components Bine 4 (2012). A thermal fluid loop as the initial phase of fluid production was established and continuously operated for 7 days (Feldbusch et al. 2013).

Table 4 Concluded experimental EGS projects (without power generation)

Project	Description	Start date	Location	Rock type	Reservoir temperature (°C)	Well depth (m)	Stimulation methods	Seismic event	Fluid temperature (°C)	End date	Flow rate (l/s)
Falkenberg	Investigation of hydraulic fracturing at shallow depth (Tenzer 2001)	1977 (Tenzer 2001)	Germany (Tenzer 2001)	Granite (MIT et al. 2006e)	13.5 (Kappelmeyer and Jung 1987)	500 (Tenzer 2001)	Hydraulic fracturing (Tenzer 2001)	Microseismic (MIT et al. 2006e)	Unknown	1986 (Tenzer 2001)	0.2 to 7 (Kappelmeyer and Jung 1987) (test)
Genesys Horstberg	Testing of new single well concepts at an abandoned gas well (BGR 2012a)	2003 (BGR 2012b)	Germany (BGR 2012a)	Sedimentary (BGR 2012a)	150 (ENGINE 2012)	3,800 (ENGINE 2012)	Hydraulic fracturing (BGR 2012a)	No measured event (Kreuter 2011)	115 (Tenzer 2001)	2007 (estimation) (BGR 2012b)	10 to 20 (Tischner et al. 2010)
Fjällbacka	Experimental project (Portier et al. 2007)	1984 (Jupe et al. 1992)	Sweden (Portier et al. 2007)	Granite (Portier et al. 2007)	16 (Wallroth et al. 1999)	70 to 500 (Jupe et al. 1992)	Hydraulic fracturing and acidizing (Portier et al. 2007)	Microseismic (Wallroth et al. 1999)	Unknown	1995 (Wallroth et al. 1999)	0.9 to 1.8 (Wallroth et al. 1999)
Rosemanowes	Experimental project (MIT 2006f)	1977 (MIT 2006f)	UK (MIT 2006f)	Granite (MIT 2006f)	79 to 100 (MIT 2006f)	2,000 to 2,600 (MIT 2006f)	Hydraulic fracturing (MIT 2006f), viscous gel stimulation (Parker 1999), placement of proppants in joints (Parker 1999)	Max. magnitude, 3.1 (Bromley and Mongillo 2008)	54.2 to 80 (Richards et al. 1992)	1992 (MIT 2006f)	4 to 25 (MIT 2006f)
Fenton Hill	First EGS in the world (MIT 2006g)	1974 (MIT 2006g)	USA (MIT 2006g)	Crystalline rock (Brown 2009)	200 to 327 (MIT 2006g)	2,932 to 4,390 (MIT 2006g)	Hydraulic fracturing (MIT 2006g)	Microseismic (Brown 1995)	180 to 192 (MIT 2006g)	1993 (MIT 2006g)	10.6 to 18.5 (MIT 2006g)
Ogachi	Test run EGS project in shallow depth (Kaieda et al. 2005)	1989 (Kaieda et al. 2005)	Japan (Kaieda et al. 2005)	Granodiorite (Kaieda et al. 2010)	60 to 228 (Kaieda et al. 2005)	400 to 1100 (Kaieda et al. 2005)	Multiple wells with multiple fracture zones (Kaieda et al. 2005); hydraulic (Kaieda et al. 2005)	Few microseismic (Kaieda et al. 2010)	160 (test result) (Kaieda et al. 2005)	2002 (Kaieda et al. 2005)	6.7 to 20 (Kaieda et al. 2005) (test)

- The Altheim project in Austria uses a special working fluid, which was never used before - a non-flammable, non-corrosive fluid with no ozone depletion activity (Bloomquist 2012).
- The 'Fenton Hill' project was the first attempt to extract geothermal energy form hot dry rocks with low permeability in the history of EGS (MIT et al. 2006g). One of the main lessons learnt from the Fenton Hill project is that an engineered hot reservoir should first be created from the preliminary borehole and then by connecting the enhanced reservoir and the injection borehole with the production boreholes (Brown 2009).
- The 'Rosemanowes Quarry' project in the UK stemmed directly from the positive results from Fenton Hill. One of the most significant lessons learnt from this project is that natural fractures and engineered fractures are almost unrelated. The natural fracture network plays a more important role compared with hydraulically enhanced fractures (MIT et al. 2006f). Also, as reported by Jung (2013), until then, the basement had been regarded as a competent rock mass, realizing that in reality, the basement contains open natural fractures even at great depth led to the abandonment of the HDR multi-fracture concept and the adoption of the hydraulic stimulation EGS concept.
- The 'Fjällbacka' project in Sweden gives similar conclusions to the Rosemanowes project, i.e. that naturally fractured systems dictate the results of reservoir stimulation (Wallroth et al. 1999).
- The 'Falkenberg' project began in 1976 and was planned as a test site for HDR at shallow depths to better understand the mechanical and hydraulic properties of fractures (Kappelmeyer and Jung 1987). A power generation phase was never intended.
- The 'Ogachi' project in Japan, a five-spot well pattern (four producers, one injector), was planned to be used for geothermal energy extraction from a shallow depth reservoir, but due to financial problems, the multiple production well system was not tried out. However, several basic technologies were successfully developed for general EGS activities through the project, which were later applied in another EGS programme in the Cooper Basin, South Australia in 2002 (Kaieda et al. 2005).
- The 'Basel' project in Switzerland saw induced seismic events - some exceeding 3.0 in magnitude - which led to its suspension (Ladner and Häring 2009). The Basel area has a history of natural seismic activity; the city was severely damaged by a 6.7 magnitude earthquake in 1356, the largest seismic event ever recorded in Central Europe (Giardini 2009). However, following a 3-year study after the seismic events recorded in connection with the geothermal project activities, the Basel project was cancelled. Induced seismicity associated with water injection and particularly hydraulic fracturing activities (due to changing stress patterns in reservoir rocks) has caused wide concern among the public (Majer et al. 2011).
- The 'Insheim' project has also had issues of induced seismicity. A so-called side-leg concept for the injection well was implemented to solve the problem (BINE 2012b). This concept enables pressure distribution during fluid injection over two separated ends of the injection well, thus minimizing the risk of induced seismicity. However, in 2013, another induced seismic event with a magnitude of 2.0 on the Richter scale

Table 5 Abandoned or on hold EGS projects

Project	Operator	Description	Start date	Location	Rock type	Stimulation methods	Seismic event	Well depth (m)	End date	Reasons of abandonment
Bad Urach	Forschungs-Kollegium Physik des Erdkörpers (MIT 2006h)	EGS pilot by one borehole only (Tenzer 2001)	1977 (Tenzer 2001), 2006 (Wyborn 2011)	Germany (Tenzer 2001)	Gneiss (Tenzer et al. 2000)	Hydraulic fracturing (Schanz et al. 2003)	Microseismicity (Schanz et al. 2003)	3,334 to 4,445 (Schanz et al. 2003)	1981 (MIT 2006i), 2008 (Wyborn 2011)	Torn off bore rods in borehole (Wyborn 2011)
Basel	Geopower Basel (Romano 2009)	Planning to develop EGS project (Ladner and Häring 2009)	1996 (Giardini 2009)	Switzerland (Romano 2009)	Granite (Ladner and Häring 2009)	Hydraulic fracturing (Ladner and Häring 2009)	Frequent earthquakes (including 3.4 M) (Romano 2009)	5,000 (Romano 2009)	2009 (Giardini 2009)	Induced seismicity exceeding acceptable levels (Giardini 2009)
The Southeast Geysers	AltaRock Energy (Romano 2009)	Redrill a well for EGS demonstration project (AltaRock Energy Inc. 2012)	2008 (Cotler 2009)	USA (Romano 2009)	Greywacke (AltaRock Energy Inc. 2012)	Multiple fractures zones in wells (planned) (AltaRock Energy Inc. 2012)	Induced seismicity risk (Romano 2009)	1,341 (AltaRock Energy Inc. 2012)	2009 (AltaRock Energy Inc. 2012)	Wellbore collapsing and induced seismicity risk (Romano 2009)

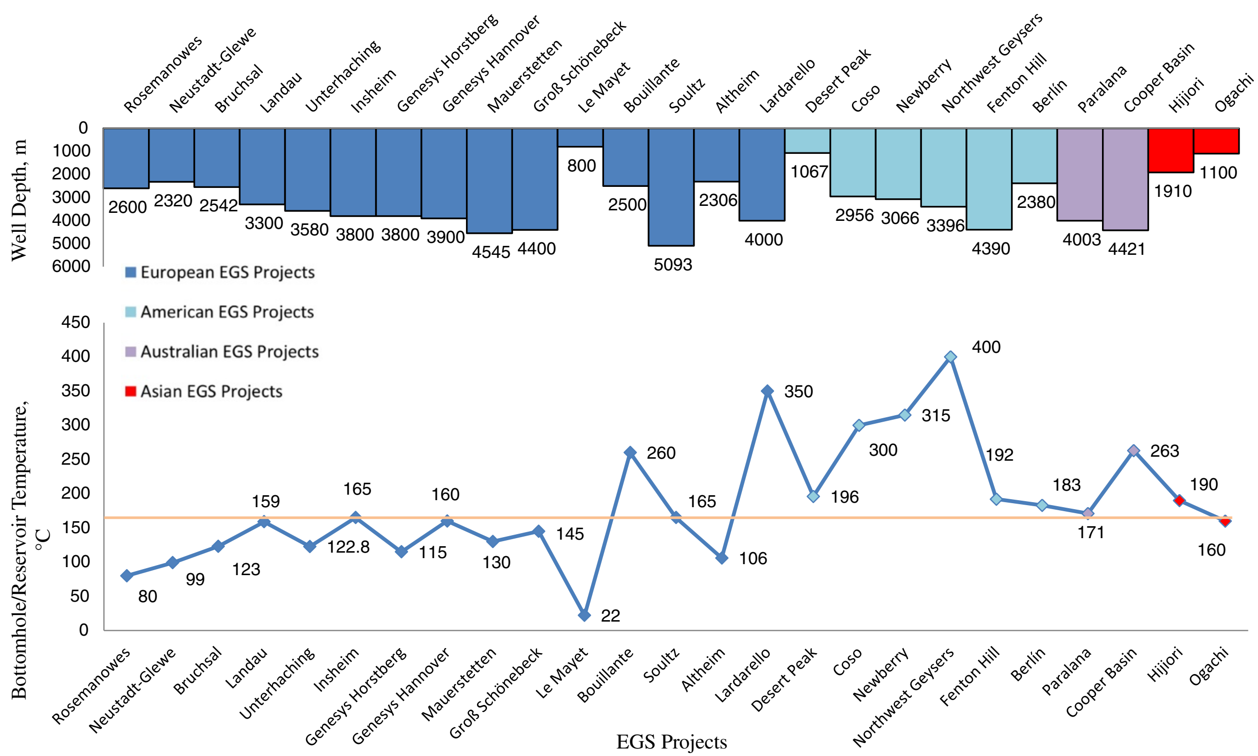

Figure 1 Worldwide EGS projects' reservoir/bottomhole temperature vs. depth.

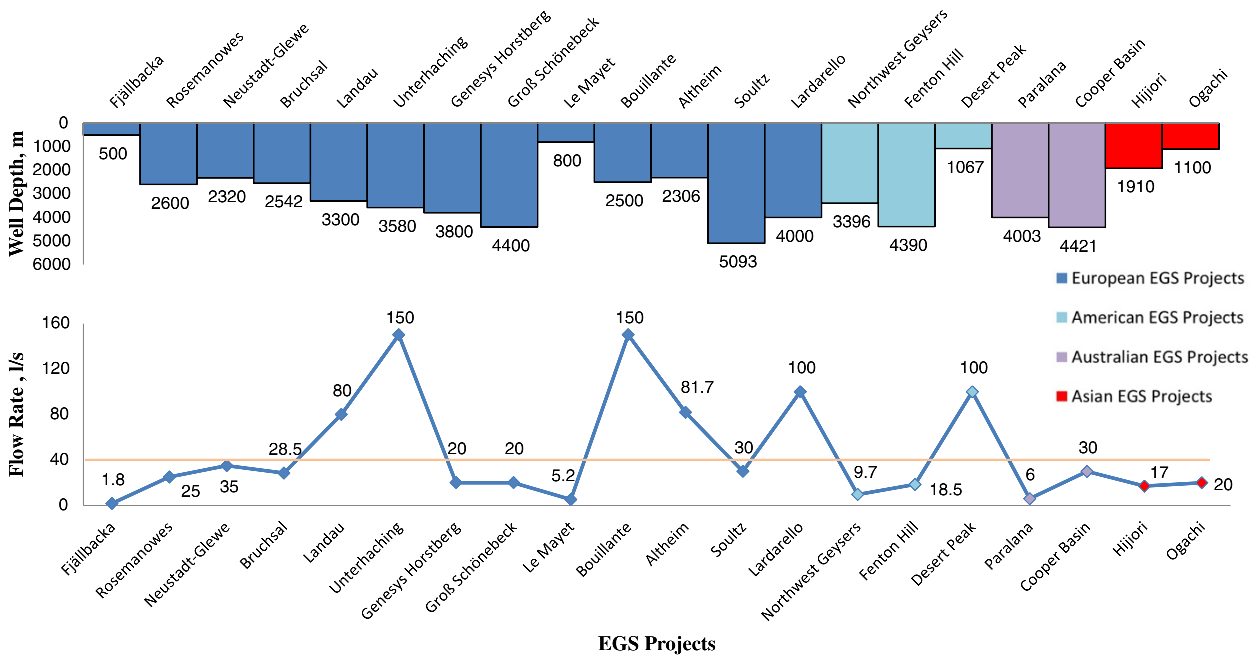

Figure 2 Worldwide EGS projects' flow rate vs. depth.

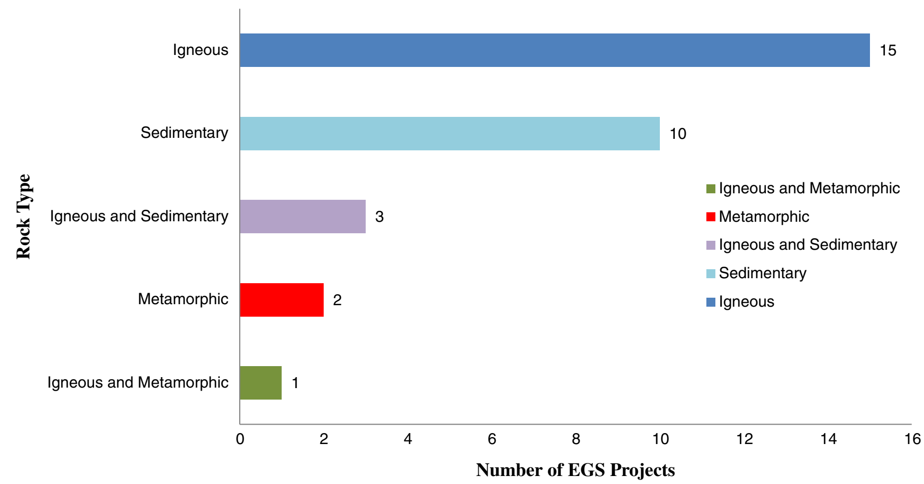

Figure 3 **EGS projects classified on the basis of rock types.**

occurred due to a water circulation stop during a reparation phase of the defective production pump (Geothermie-Pfalz 2013).

- The 'Landau' project is the first EGS project in a town in Germany, which is facing similar problems to Basel. Seismic events of 2.7 in magnitude took place in 2009, which resulted to the temporary suspension of the operations. The project was restarted after purchasing €50 million of annual liability insurance to cover potential seismic damages (DiPippo 2012b). As a consequence of these events, water has to be reinjected at a reduced pressure to avoid induced seismicity, resulting in reduced power generation. The problem is planned to be tackled by implementing in 2013 the same side-leg concept that was used in Insheim (BINE 2012b).
- The 'Soultz-sous-Fôrets' project in France has allowed significant experience to be gained by several countries who participated in this joint project. Many

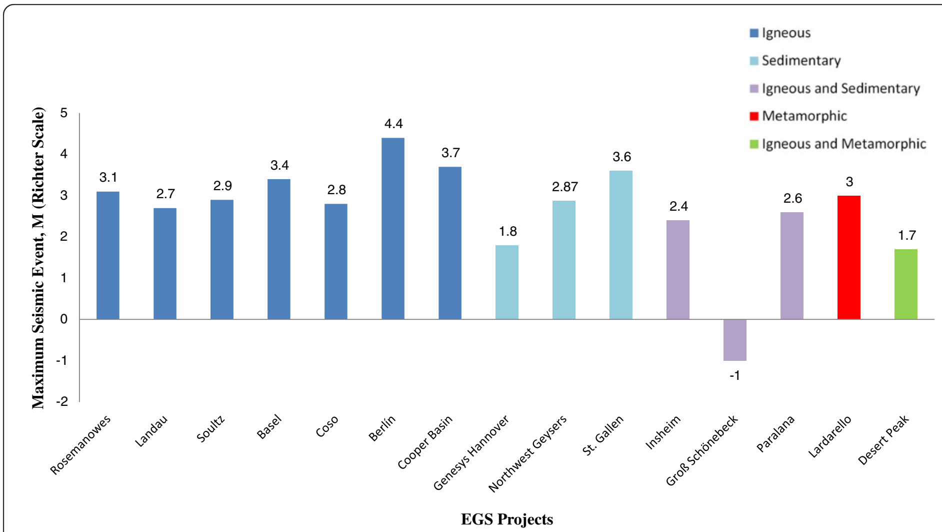

Figure 4 **Projects with published induced seismic magnitude.**

experiments were conducted during the first 21 years of the project's life before the power plant was built. Different stimulation techniques, such as hydraulic fracturing with and without proppants and chemical stimulation were applied. Chemical stimulation has resulted in less seismic activity than other methods. Change of hydraulic parameters due to fracturing has resulted in an instantaneous variation of seismic activity. Seismic events with magnitudes greater than 2 have occurred during the shut-in phase. Although minor damages were caused by this EGS project, it did generate concern among the local population.

Microseismic monitoring has become an indispensable technology for the acceptance of EGS developments as it is the case for other applications of hydraulic fracturing and high-pressure water circulation (e.g. the exploitation of unconventional oil and gas resources). The experience gained from preliminary projects has led to a common view that induced seismicity associated with EGS activities can halt further development of this concept particularly in densely populated areas. More recently, though, despite the 3.6 magnitude seismicity induced by well control operations during drilling in St. Gallen, the city council decided to continue with the project and complete the first drilling phase (Geothermie Stadt St. Gallen 2013b).

- The 'Bad Urach' project suspended operations because of financing problems arising from a 'difficult geologic situation' at the well site, which indicated that this project would be unprofitable (DiPippo 2012b).
- The 'Geysers' project was abandoned due to drilling difficulties and the risk of increasing seismic activity (AltaRock Energy Inc. 2012).

It is worth mentioning here that according to Gebo NDS (2012b), drilling expenditure is the highest component in the development costs of an EGS project and can vary from 42% to 90% of the overall capital costs.

As mentioned earlier, hydraulic stimulation is the most commonly used technique for improving the permeability of a geothermal reservoir. Some of the world's EGS projects

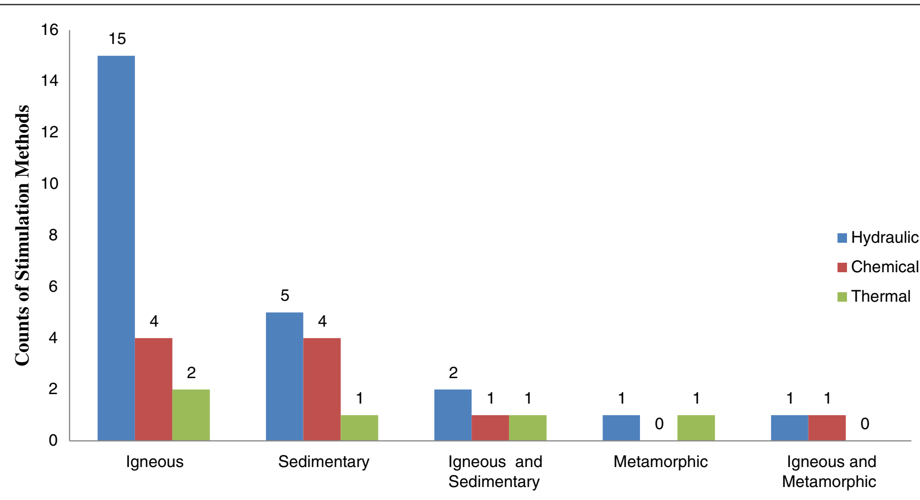

Figure 5 Stimulation methods applied to EGS projects worldwide.

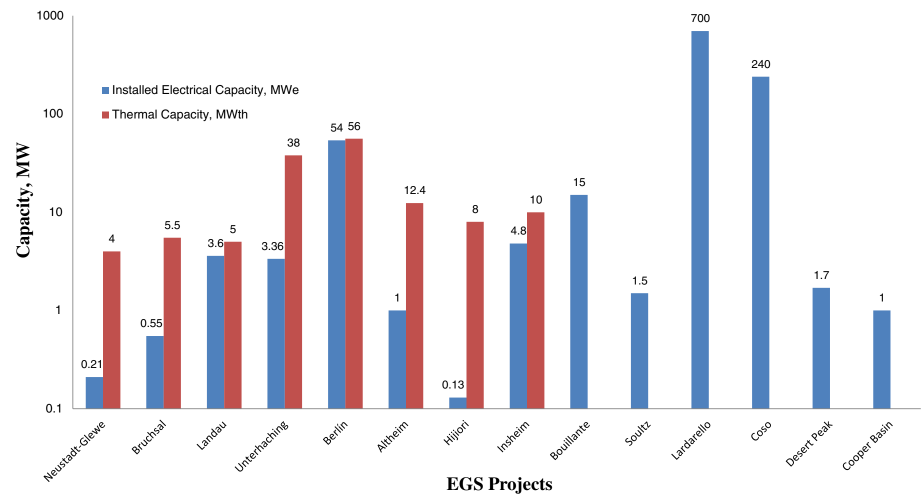

Figure 6 **Installed electrical and thermal capacity of worldwide EGS projects.**

can extract geothermal energy from naturally fractured reservoirs, such as Northwest Geysers, Landau, Insheim, Urach, Bruchsal, Soultz-sous-Fôrets, Fjällbacka, Hijiori, Rosemanowes, Falkenberg and Newberry. The pre-existing naturally fractured networks can be stimulated by low pressure that is just above the critical pressure of shear failure (hydraulic shearing). However, the process of hydraulic fracturing, which uses injected water at high pressure to crack the rocks, is also frequently used especially in granite. Compared with hydraulic fracturing with high injection pressure, hydraulic shearing can easily crack rocks with low pressure and keep the fractures open without requiring a propping agent. Chemical stimulation, which is most applicable in carbonate rocks or used to dissolve carbonate cement in sandstone formations, along with thermal stimulation has also proved to be effective in some cases. However, there is relatively little literature concerning the application of chemical and thermal stimulation technologies in EGS projects.

Other issues associated with EGS stimulation are related to the potentially harmful effects on the surrounding environment. There has been public concern for the

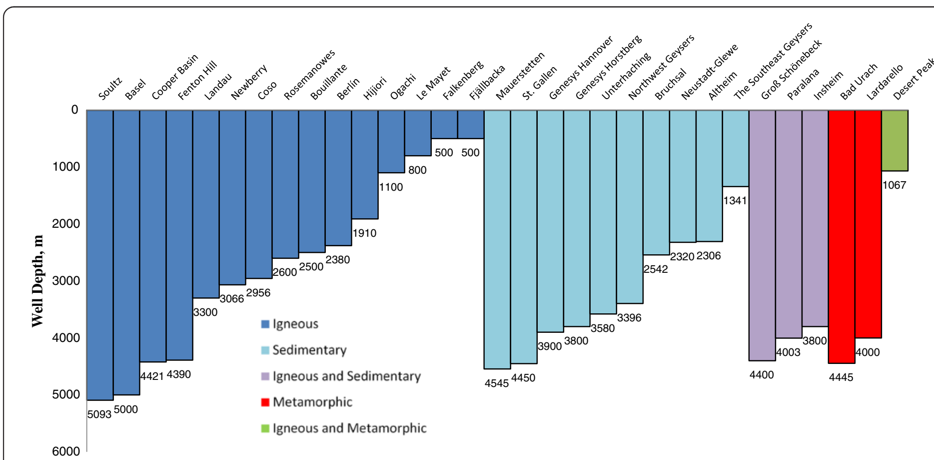

Figure 7 **Rock type and well depth of EGS projects worldwide.**

components of fracturing fluids that could represent a threat to drinking water sources. However, operators argue that EGS projects rarely require additives and chemicals (e.g. tracers, diverters, proppants) in fracturing fluids. When additives are necessary, then non-toxic chemicals are first considered. Also, deeply buried EGS reservoirs usually do not have a connection to near-surface groundwater aquifers, which would reduce the likelihood of contaminating drinking water (Regenspurg and Blöcher 2012).

Radioactivity is another problem emerging from EGS activities, which is caused by interaction between the geothermal fluid and certain formations containing radioactive elements. In general, the content of radionuclides in acidic magmatic rocks is higher compared to that in sedimentary rocks. Uranium and thorium are the most common radioactive elements found in granites. High reservoir temperature in EGS projects increases the solubility of radionuclides, which results in higher concentrations of these nuclides in the geothermal fluid. When the fluid is produced, the corresponding temperature reduction and pressure decrease in the surface facilities and causes deposition of scale, which leads to health, safety and environment problems. However, compared to other conventional energy production (e.g. oil and gas industry), the radioactivity occurring in EGS is likely to be very small (Battye and Ashman 2009). Radiation exposure of workers during the scale removal is avoided by using appropriate personal protection equipment. In general, the radiation exposure to the public is limited because long-lived natural radionuclides are not released during the operation of a geothermal power plant when the geothermal fluid is re-injected into the reservoir (Feige and Roloff 2012).

Almost all running EGS projects in the power generation phase utilize binary power plants. Binary systems use geothermal fluids with low temperature in the primary loop to vaporize working fluids with low boiling point that are used in the secondary loop to activate turbine-generator machine.

At present, two types of binary systems exist in the market: the organic Rankine cycle (ORC) which uses organic working fluids (e.g. propane or isobutane) and the Kalina Cycle which uses a mixture of two substances as the working fluid (e.g. water and ammonia). The advantage of the Kalina cycle over the ORC is that the abovementioned mixture boils at variable temperatures, which in turn creates higher efficiency at a certain inlet temperature, unlike the pure chemicals that are used in ORC (Clauser 2006). The disadvantages of the Kalina system are the challenge of fine tuning the plant operation and the tendency of the ammonia-water mixtures to prematurely condense during expansion. Hence, the majority of the EGS projects implemented so far tend to use ORC power plants.

The flow rate recovered with EGS projects is crucial in dictating the success of a project. It needs to be high to ensure the project's economic viability. Yet if the rate is too high, there may not be sufficient 'residence time' for the circulating medium in the reservoir to extract enough heat from the rock. Depending on reservoir permeability, fracture surface area, pumping pressure, etc., the flow rate varies significantly from project to project.

Along with the ongoing debate over the definition of EGS, it has also been reported that the output of EGS projects is far lower than the theoretical expectation. Sanyal and Butler (2005) built a number of simulation models as a starting point for estimating EGS reserves on the basis of conditions seen at a desert park in USA, which suggested a recovery factor greater than 40% for EGS. However, Grant and Garg (2012) later pointed out that the recovery factor for the Cooper Basin EGS system would be lower than 2%, according to the modelled performance.

Conclusions

Many publications provide eye-catching numbers about EGS potential, yet there is still much to do to tap this energy. However, from this review of EGS projects worldwide, it transpires that EGS is still on a learning curve. Success is not guaranteed, and this implies significant financial risks for any EGS project, which can lead to its abandonment in some cases (e.g. Bad Urach project).

This observation leads to the natural question of why success is not guaranteed. From the classification exercise performed in this work, it is possible to conclude that the 'typical' EGS system does not exist, so much that, as shown in the introduction, the geothermal community does not even have a universally accepted and unambiguous definition of EGS as yet.

The typical EGS system does not exist because - as shown in the tables and in the figures - there are several possible (and significantly different) geological, petrophysical, thermal, hydraulic and geomechanical environments where high temperature can be tapped underground. Even the depth where sufficiently high temperature can be encountered varies from region to region in the world, making it difficult to specify what 'deep geothermal energy' (another term often used within the geothermal community) really is and how it can be related to the EGS concept.

The problem is that of handling each particular EGS system in such a way that economic flow rates at the right temperature and over a sufficient time span can be obtained. It is commonly accepted that for an EGS doublet system to be of commercial size, assuming a depth greater than 3 km and a temperature greater than 150°C, the system should operate at flow rates between 50 and 100 l/s and produce an electric power of 3 to 10 MW_e over a life of at least 25 years (Jung 2013).

Based on the relatively limited EGS experience gathered to date and the extreme variety of natural occurrences and engineering solutions (including reservoir enhancement), it is therefore no surprise that EGS is still on a learning curve. This learning process must continue via more research and development, further technology advances and significantly more financial and political incentives before EGS will be commercially feasible, say in the next 10 to 20 years.

It is critical for EGS to ensure that relevant technologies are applied, having minimal risk of seismicity, and permitting the exploration of geothermal resource in a safe and environmentally friendly manner.

In the same vein, communities should be provided with regular, understandable and realistic information about EGS activities in order to gain public acceptance. Ongoing dialogue and interaction with communities are vital to achieve this.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
All: Systematic overview of past and present Egs projects worldwide + Results & Discussion. KB: Milestones + Tables. XL: Tables + Figures. KD: Review. GF: Conclusions. KB + GF: preparation of revised manuscript and rebuttal letter after referees' revision.

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