

# Economic feasibility assessment methodology

## CHPM2030 Deliverable D5.2

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CHPM2030



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**Author contact**

*Vojtěch Wertich*

*Minpol GmbH*

*Dundlerinweg 120/1*

*2753 Dreistetten*

*Austria*

*Email: [vojtech.wertich@minpol.com](mailto:vojtech.wertich@minpol.com)*

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*University of Miskolc*

*H-3515 Miskolc-Egyetemváros*

*Hungary*

*Email: [foldshe@uni-miskolc.hu](mailto:foldshe@uni-miskolc.hu)*





## CHPM2030 DELIVERABLE D5.2

# ECONOMIC FEASIBILITY ASSESSMENT METHODOLOGY

### *Summary:*

Deliverable is focused on the description of economic related issues of two levels of the CHPM (Combined Heat, Power and Metal extraction). Energy level, represented by enhanced geothermal system (EGS), is not a current rival to other conventional energy sources due to very high capital and operational costs. Simulations predict competitiveness of EGS in time framework of CHPM development. Extraction of metals from geothermal fluid is a commercially untested technology, which has no clearly defined operation costs. This makes the economic feasibility assessment difficult. Theoretical models suggest that positive economic feasibility can be achieved only on sites with higher concentrations of dissolved metals in brines and/or higher fluid flow.

### *Authors:*

Vojtěch Wertich, MinPol GmbH, economic geologist  
Lari Shanlang Tiewsoh, MinPol GmbH, energy policy specialist  
Günter Tiess, MinPol GmbH, executive director



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## List of abbreviations

ARENA – Australian Renewable Energy Agency  
ARRA – American Recovery and Reinvestment Act  
ASX – The Australian Stock Exchange  
BHP – Broken Hill Proprietary Company Limited  
BINE – German Information Service focusing on energy  
BP – British Petrol (company)  
CapEx – capital expenditures

¢/kWh – cents per kilowatt hour  
CRMs – The Critical Raw Materials for EU  
EGEC - the European Geothermal Energy Council  
EGS – enhanced geothermal system  
EIA – environmental impact assessment  
ENGINE – The Enhanced Geothermal Innovative Network for Europe  
FOA – Funding opportunity announcement  
GEISIR – The Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs  
GEOPIRES – software for economic simulation of geothermal projects  
GW<sub>e</sub> – gigawatt electrical  
GW<sub>th</sub> – gigawatt thermal  
GWh – gigawatt hour  
HDR – the hot dry rock  
IGCC – Integrated gasification combined cycle  
Inc. – incorporation – suffix indicating corporation  
ISL – in-situ leaching  
ISR – in-situ recovery  
KW<sub>e</sub> – kilowatt electrical  
KWh – kilowatt hour  
LCOE – levelized cost of energy / levelized cost of electricity  
LCOH – levelized cost of heat  
LLC – Limited liability company  
Ltd. – a private company limited by shares  
MIT - Massachusetts Institute of Technology  
MWe – megawatt electrical  
MWth – megawatt thermal  
MWh – megawatt hour  
NPV – net present value  
O&M – operational and maintenance cost  
OpenEI – Open Energy Information  
OpEx – operational expenditures  
PACE – Plan to Accelerate Exploration (South Australia)  
REDP – Renewable Energy Development Programme  
REE – rare earth elements  
REF – Renewable Energy Fund  
RFP – Request For Proposal  
R&D – research and development  
RMI – Raw Material Initiative 2008  
SA –The South Australia – a stat of the Commonwealth of Australia  
SD – System Dynamics  
TDS – Total Dissolved Solids  
TWh – terawatt hours  
US DOE – The United States Department of Energy  
USD – U.S. dollars  
VAT – Value Added Tax

USD exchange rate used in this study is set on average value from August 2018 (1 EUR = 1.14 USD)

## 1 Executive summary

CHPM technology aims at developing a technology of enhanced geothermal system (EGS) power plant combined with metal extraction facility which would extract raw materials from circulating fluid. The primary goal of the addition of the „metal extraction level“ (letter M in CHPM) to the EGS technology with installed both electrical ( $MW_e$ ) and direct-heat ( $MW_{th}$ ) producing capacity (CHP – combine heat and power), is to reduce high operational expenditures (OpEx) of EGS technology through the sale of the extracted products.

EGS technology, which is considered as unconventional geothermal energy, allows the exploitation of geothermal power plants outside of the conventional geothermal fields (e.g. Iceland). The future potential of EGS is enormous, when compared 982  $GW_e$  of 2015 installed capacity in EU-28 with a technical potential of EGS technology, which was calculated on 6560  $GW_e$ . On the other hand, the development of EGS is not economically feasible at the moment. All demonstration plants in the world were developed with significant governmental subsidy reaching 50-100% of the total investment required. Australian EGS projects were developed close to the commercial way, as the companies were trying to rise their capital for EGS development on the stock exchange, but they failed at securing additional investments from private sources.

The current levelized cost of electricity (LCOE, cost of electricity counting with both CapEx and OpEx) for EGS scenario with high thermal gradient above 70°C/km is still higher than the price of electricity for non-household consumers in EU-28. Currently, EGS is not economically competitive in comparison with conventional non-renewable, hydropower or in many cases also conventional geothermal power plants. Governmentally funded R&D programs in the U.S. and the EU are aiming at reducing cost for construction and operation of EGS power plants to a competitive level by 2030, which is in accordance with time framework of CHPM2030.

The extraction of metals from geothermal fluids at EGS power plant is a novel technology with untested feasibility. Only a few tests of extraction of metals from geothermal brines are in development for silica and lithium at conventional geothermal fields which differ from unconventional EGS especially by their much higher operation capacity (more wells, higher total fluid flow) in terms of possible metal extraction facility. Possible extracted quantities from a metal extraction plant connected to the EGS would be much smaller. It can be changed with the implementation of mild leaching reagents in order to increase concentrations of dissolved metals in producing geothermal brines.

Low technology readiness level (TRL) and lack of data from historical operations of metal extraction from geothermal brines are leading to ambiguously defined OpEx for such operations. Correct determination of OpEx is the main barrier for feasibility assessments of metal recovery from geothermal brines. Only a shift of the metal extraction technology on higher TRL based on new field demonstration and running operations can provide necessary data for the calculation of more accurate OpEx, and subsequently to determine exact economic feasibility assessments. Current models suggest that the economic feasibility of metal extraction from geothermal brines is being very site-specific dependent. Positive economic feasibility was theoretically assessed only for geothermal sites with a processing capacity of several hundred liters per second (>400 l/s) and/or brines rich in dissolved metals concentrations (e.g. lithium at >200 ppm or mg/kg).

## 2 Introduction

### 2.1 Objectives and role of the CHPM2030 project

The strategic objective of the CHPM2030 project is to develop a novel technological solution (Combined Heat, Power and Metal extraction from ultra-deep ore bodies), that will help reducing Europe's dependency on the import of metals and fossil fuels while, lowering the environmental impact of the energy supply.

In the envisioned technology, an Enhanced Geothermal System (EGS) is established on a metal-bearing geological formation, which will be manipulated in a manner enabling the co-production of energy and metals. On a laboratory scale, the project aims at proving the concept that the composition and structure of ore bodies have certain characteristics that could be used as an advantage when developing an EGS.

It is also planned to verify that metals can be leached from the ore bodies in high concentrations over a prolonged period of time and this may substantially increase the economics of the EGS. The project also aims at finding proof of the concept that continuous leaching of metals will increase the performance of the system over time in a controlled way without having to use high-pressure reservoir stimulation. According to our expectations, this will provide new impetus to geothermal development in Europe. Within the scope of the project, a Roadmap will also be developed to support the pilot implementation of CHPM systems before 2025, and full-scale commercial implementation before 2030.

### 2.2 Scope and structure of work package 5

The whole project is divided into 8 work packages; deliverable 5.2 is part of the fifth work package (WP5) called Integrated sustainability assessment. The objective of the WP5 is to assess expected environmental, social and economic impacts of each component of proposed CHPM infrastructure. CHPM technology is combining generation of power, both electric and heat, using a concept of the Enhanced Geothermal System (EGS) with extraction of metals utilizing a mining method very similar to in-situ leaching (ISL) or in-situ recovery. For these technologies, some partial impacts are already known and thus the assessment of CHPM project can benefit from these experiences. On the other hand, the proposed CHPM technology will be compared also with other, already established power plants and mining facilities to assess a possible sustainability of this novel technology.

The work package is composed of 5 tasks:

- a) Task 5.1 Integrated sustainability assessment framework introduced a structure of WP5 and role of individual tasks on the assessment of the CHPM technology.
- b) Task 5.2 Baseline economics for energy and mineral raw materials is focusing on the economic and financial issues of the CHPM technology. Gathered data will serve for the simulation of a modelling in D5.3 as well as for roadmap and preparing for pilots (WP6).
- c) Task 5.3 Decision support for economic feasibility assessment is about to develop a self-assessment tool which will be based on system dynamic approach, allowing to assess feasibility of different CHPM scenarios.



- d) Task 5.4 Social Impact Assessment and policy considerations will be considering possible impacts of proposed CHPM technology for the society and policy implications will also be reviewed.
- e) Task 5.5 Environmental Impact Assessment will be focused on the development of a framework for a future environmental impact assessment (EIA) for CHPM technological infrastructure.
- f) Task 5.6 Ethics Assessment will be focusing on ethical issues, which needs to be considered in relation for CHPM technology.

### 2.3 Scope and role of Task 5.2

The main goal of Task 5.2, the baseline economics for energy and mineral raw materials, is to gather economically relevant data for assessing an economic feasibility of proposed CHPM technology (Deliverable 5.2 – Economic feasibility assessment methodology).

The assessment of CHPM economic feasibility will be based on an analysis of public information available related to economic issues of energy and mining infrastructures using a technology similar to CHPM. It is mainly EGS power plants and secondly experiments and pilot plants of mineral extraction from geothermal brines. The critical parameters acquired during laboratory experiments and other work on previous and ongoing work packages will also be taken into consideration of the analysis.

The public information available includes scientific papers (journals Renewable and Sustainable Energy Reviews, Energy, Stanford University Workshop on Geothermal Reservoir, etc.), governmental reports (e.g. U.S. DOE), company profiles and reports, market and stock exchange release, energy & economy news and open source databases (e.g. Eurostat, OpenEI Transparent Cost Database, U.S. DOE Geothermal Data Repository or World Energy Council).

Economic feasibility modelling and assessing itself will be part of the next task 5.3 – Decision support for economic feasibility assessment, when the data gathered in D5.2 as well as critical parameters provided by previous WPs will serve to evaluate CHPM with help of the self-assessment tool. The self-assessment tool will use Vensim© software (Vensim 2018) and the system dynamic approach.

As CHPM technology aims at combining two, at first sight unrelated business activates – renewable energy production and mining (metal extraction), the deliverable 5.2 will be divided into energy level and metal extraction level of the CHPM project. These two parts will provide an overview and comparison of economy related issues for both levels of proposed CHPM infrastructure.

Energy production (electricity and heat) of CHPM technology is based on the EGS concept (MIT 2006; Potter et al. 1974), therefore a comparative analysis at energy level will focus mainly on already operating EGS power plants and their economic feasibility. Position of EGS will be correlated with different both renewable and non-renewable energy sources based on levelized cost of

energy/electricity (LCOE<sup>1</sup>) and, finally economy related experiences from all operational and many developing EGS projects will be described.

Extraction of raw materials (or metals) from geothermal fluids as business, sellable products is a relatively new concept with untested commercial operation. Only a few demonstration plants for lithium and silica recovery were verified for their possible economic feasibility (Neupane and Wendt 2017). Economic assessments for extraction of other materials or metals are based mainly on research & development (R&D) laboratory scale experiments and theoretical calculations and comparison with similar technology with known financial costs. Also, a comparison of different, competitive mining methods is described in the mining level chapter.

Finally, the conclusion chapter combines both levels and discusses the analysis with proposed CHPM technology.

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<sup>1</sup> Levelized Cost of Electricity or sometimes also Levelized Cost of Energy (LCOE) is a comparative analysis on a \$/MWh (€/kWh or similar) basis. The projection of LCOE should include both capital expenditures (CapEx) as well as operational expenditures (OpEx) ( LAZARD 2017; Mines and Nathawani 2013).

### 3 Economics of energy level of the CHPM project

The term “energy infrastructure” may be used for proposed CHPM technology because the main aim of CHPM technology is to use unconventional geothermal energy to generate both electricity and heat. In spite of the fact that hot geothermal fluids used for power generation have various chemical composition and include some valuable metals (Neupane and Wendt 2017), the possible extracted inorganic materials are not considered as Geothermal Energy Product in “Specifications for the application of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 to Geothermal Energy Resources (UN Geothermal Working Group 2016).

Nevertheless, the same UN document mentions that if the additional products to power generation are sold, the revenue streams should be included in the economic assessment. This is the case with the CHPM project, which is considering co-extraction and sale of raw materials from working geothermal fluid as possible economic benefit which could help with lowering a significantly high OpEx of unconventional geothermal power plant (Mines and Nathawani 2013).

#### 3.1 Baseline of EU energy market

Energy demand in the EU: The EU’s electricity consumption in 2017 was estimated to be at 23 TWh and there has been a growing trend since 2014. Europe’s GDP has been rising steadily since 2010 and the 2017 levels are around 10% higher than in 2010 (Agora Energiewende and Sandbag, 2018) (Figure 1).

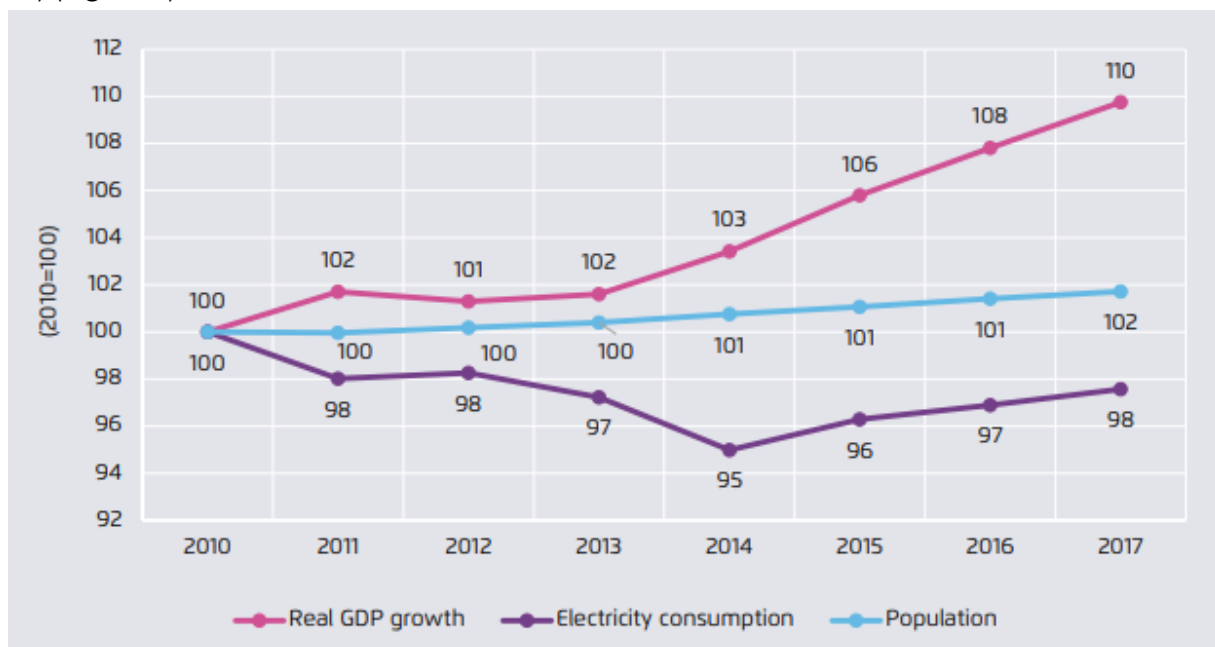


Figure 1: EU electricity consumption index (Agora Energiewende and Sandbag 2018)

The reasons for the increasing power consumption can be attributed to:

- European policies that have been pushing for more energy efficiency in the economy. The 2% annual growth in GDP compared to the annual growth of 1% for power demand suggests that although energy efficiency is increasing within the economy, it might not be enough to meet EU targets. This leads to higher than expected energy demands from the economy.

- b) Industrial production rose faster than GDP (industrial production rose by 4% (Eurostat 2018b)) suggesting that economic growth was more energy intensive than normal.
- c) Rising EU population both due to growth of inherited population and rise in immigration.
- d) Emergence of new sectors such as the wide spread adoption of electric vehicles (European Environment Agency, 2016), the use of electricity for heating and cooling and totally new sectors caused by the digital revolution like cryptocurrency mining (de Vries, 2018) which also consumes a lot of electricity.

Energy supply in the EU: Figure 2 shows the production and supply data for EU-28, Norway and Turkey by using monthly cumulated data for 2017 (2015 and 2016 data are annual figures). Malta (+94.9 %), Latvia (+23.9 %), Estonia (+7.8 %), Austria (+7.0 %) and the Czech Republic (+6.0 %) were the Member States that recorded the largest increases in electricity production in 2017. Against this trend, Croatia (-6.0 %), Germany (-5.9 %), Romania (-4.1 %) and Belgium (-2.4 %) decreased the most significantly their electricity production. In Norway, the production decreased by 0.3 % while in Turkey it increased by 8.2 %.

	EU-28					Eurozone 19				
	2015	2016	2017	2016/2015	2017/2016	2015	2016	2017	2016/2015	2017/2016
<b>1.Total net production</b>	3073 627	3099 839	3074 892	0.9%	-0.8%	2191 736	2222 470	2193 060	1.4%	-1.3%
<i>of which :</i>										
Conventional thermal	1477 236	1508 772	1486 057	2.1%	-1.5%	1004 361	1031 382	1022 277	2.7%	-5.6%
Nuclear	812 535	795 629	786 005	-2.1%	-1.2%	628 776	606 769	591 830	-3.5%	-2.5%
Hydro	365 509	374 593	317 023	2.5%	-15.4%	246 521	268 765	219 064	9.0%	-18.5%
<i>of which from pumped storage</i>	29 564	29 561	:	0.0%		23 835	23 502	24 717	-1.4%	5.2%
Wind	299 498	300 233	358 987	0.2%	19.6%	207 583	212 211	251 512	2.2%	18.5%
Solar	106 938	109 750	118 653	2.6%	8.1%	92 847	92 737	100 244	-0.1%	8.1%
Geothermal	6 098	6 188	6 134	1.5%	-0.9%	6 098	6 188	6 134	1.5%	-0.9%
Other	5 813	4 674	:	-19.6%		5 550	4 418	:	-20.4%	
<b>2. Imports</b>	410 335	382 221	383 256	-6.9%	0.3%	290 239	266 331	270 444	-8.2%	1.5%
<b>3. Exports</b>	396 076	364 031	361 912	-8.1%	-0.6%	270 552	256 887	260 256	-5.1%	1.3%
<b>4. Energy absorbed by pumping</b>	41 495	41 130	42 500	-0.9%	3.3%	33 600	32 760	34 349	-2.5%	4.9%
<b>5. Energy supplied</b>	3046 391	3076 899	3054 507	1.0%	-0.7%	2177 823	2199 154	2168 899	1.0%	-1.4%

"e" estimated data

":" non available data

Source: Eurostat (online data code: nrg\_105a, nrg\_105m)

	Contribution of the sources to the production in %					
	EU-28			Eurozone 19		
	2015	2016	2017	2015	2016	2017
Conventional thermal	48.1%	48.7%	48.3%	45.8%	46.4%	46.6%
Nuclear	26.4%	25.7%	25.6%	28.7%	27.3%	27.0%
Hydro	11.9%	12.1%	10.3%	11.2%	12.1%	10.0%
Wind	9.7%	9.7%	11.7%	9.5%	9.5%	11.5%
Solar	3.5%	3.5%	3.9%	4.2%	4.2%	4.6%
Geothermal	0.2%	0.2%	0.2%	0.3%	0.3%	0.3%
Other	0.2%	0.2%		0.3%	0.2%	

":" non available data

Figure 2: Electricity statistics 2015-2017 (Eurostat 2017)

The current structure of the EU-28 electricity mix is shown in Figure 3. Almost half of the electricity generated in the EU-28 was from thermal sources which includes natural gas, coal and oil



(Tiess 2014, Eurostat 2017). The European Commission has a long-term vision of decarbonisation but as the graph suggests, coal and gas remain key components in the fuel mix of many EU countries. As part of the efforts to reduce carbon emissions, the commission has established the 'EU Platform on Coal Regions in Transition' to advance the economic and technological transformation of coal mining regions (European Commission, 2018).

A quarter of the electricity generated in EU-28 comes from Nuclear sources, although there has been a trend in decreasing dependence on nuclear energy in Europe (this decrease is led by Germany and France (World Nuclear Association, 2018 and Le Monde.fr, 2017).

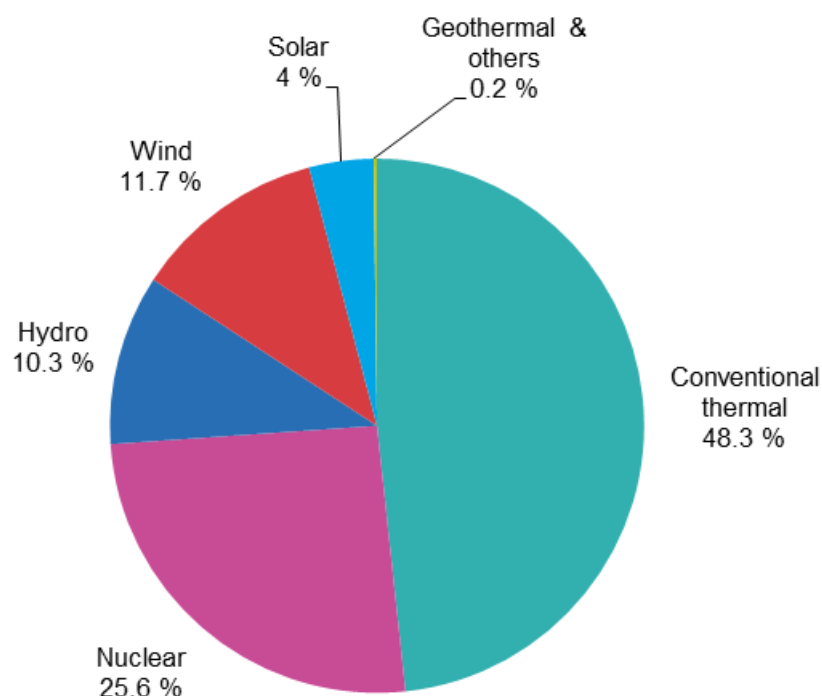


Figure 3: Electricity production by source, 2017 (Eurostat 2017)

### 3.2 Position and market trends of geothermal energy – focus on Europe

The energy level of the CHPM technology is based on enhanced geothermal system (EGS), which can be considered as renewable unconventional geothermal source of energy (MIT 2006). The development of modern concepts of renewable energy has a stable position in Europe, as the gross electricity production from renewable sources is increasing compared to other energy from non-renewable sources, which yield either stagnation or slightly decreasing trend (Figure 4, Eurostat 2017). This is in accordance with energy outlooks for the European Union predicting continuous increase of shares of renewable energy sources from 9% (excluding conventional hydro power) in 2016 to 27% in 2040 (BP Energy Economics 2018).

It is however important to mention that the major share among renewable sources of electricity generation is conventional hydropower, closely followed by wind power (Figure 4), whereas geothermal power for electricity generation does not exceed 1% of total electricity generation (Eurostat 2018a).

Geothermal power can be divided in two parts:

- a) Electrical power
- b) Direct use of heat

### 3.2.1 Geothermal electricity generation

Total installed capacity for geothermal electricity generation in the EU is about 1 GW<sub>e</sub> (EGEC Geothermal 2017) and annual production reached 6,640 GWh in 2016 (Eurostat 2018b), but, almost the entire installed capacity is conventional geothermal (hydrothermal) power plants which exploit reservoirs of shallower geothermal water compared to the hot-dry rock concept of the EGS technology (MIT 2006). The only exceptions are three EGS demonstration sites – Soultz-sous-Forêts (1.5 MW<sub>e</sub>) in France and two power plants – Landau (3.8 MW<sub>e</sub>) and Insheim (4.8 MW<sub>e</sub>) in Germany, which are already in production (BESTEC GmbH 2018). Italy has almost all reported installed electricity capacity of 916 MW<sub>e</sub>; Germany, France, Portugal and Romania have small shares up to the first tens of MW<sub>e</sub> (Annex 1). Beyond the border of the 28 EU member countries are two countries with installed electricity capacity at similar level to Italy. It is Iceland with 663 MW<sub>e</sub> and Turkey with 853 MW<sub>e</sub> (EGEC Geothermal 2017).

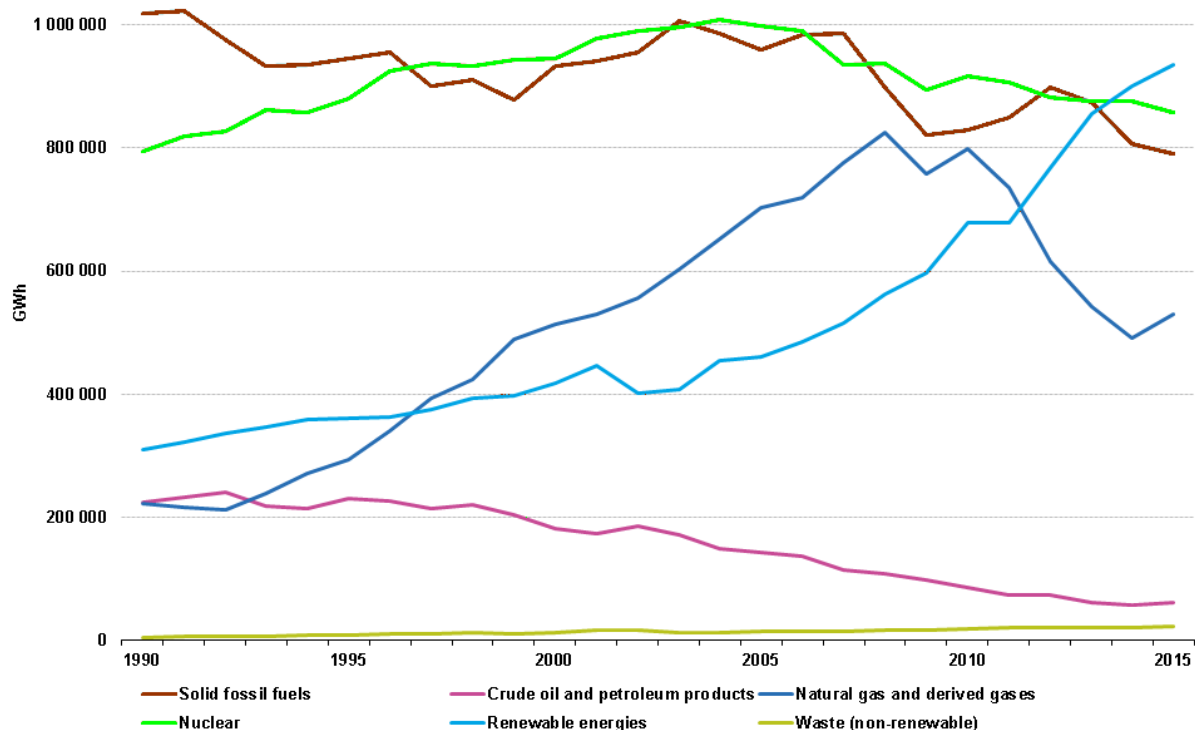


Figure 4: Total gross electricity production within the EU-28 in 2015 was 3 234 TWh. Renewable sources accounted for 29.9 % of total electricity production in 2015 (Eurostat 2017).

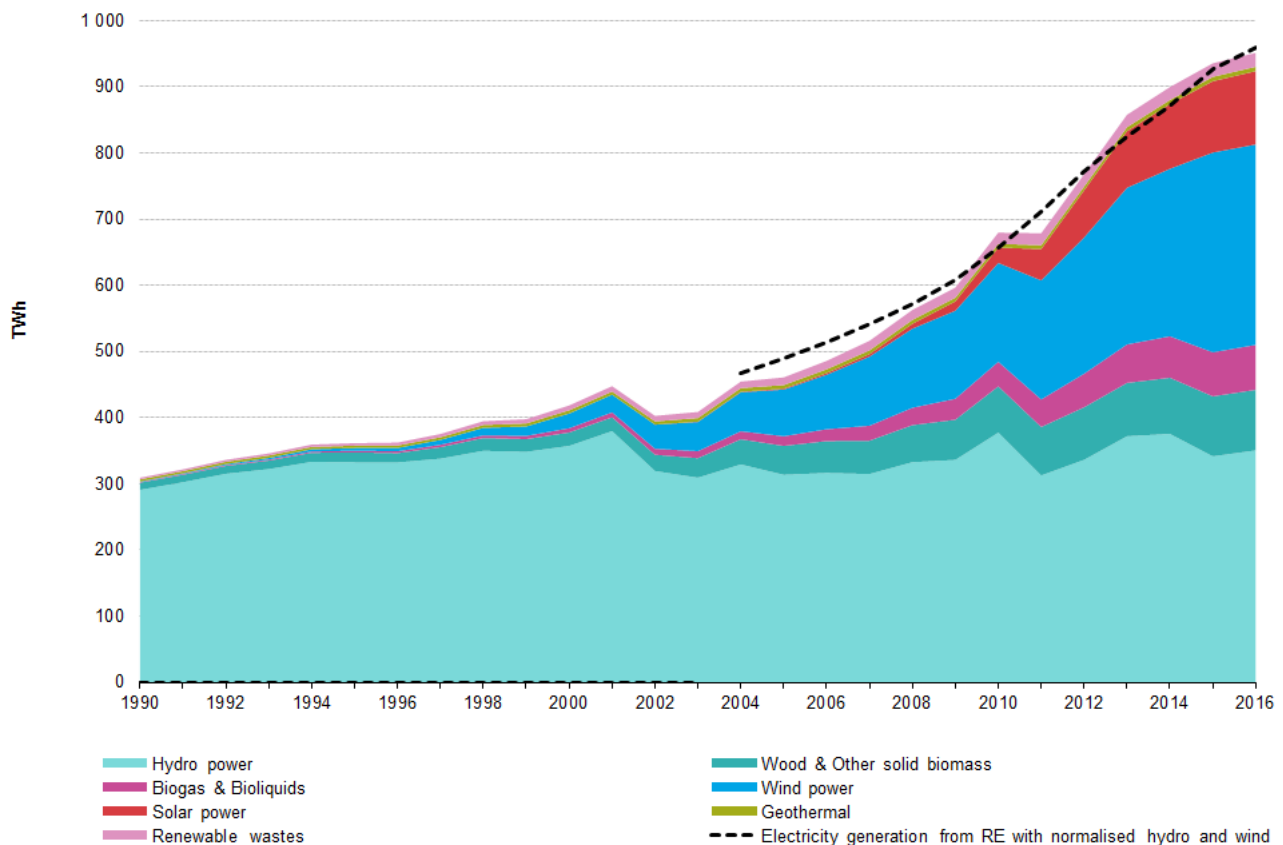


Figure 5: Gross electricity generation from renewable sources in the 28 EU member countries. The main renewable source is hydro power with 36.9 % of total electricity production in 2016, followed by wind power with 31.8 % in 2016 (Eurostat 2018a).

The United States are the largest producer of electricity from geothermal resources with an installed capacity of 3570 MW<sub>e</sub> in 2016; the Philippines, Indonesia, Mexico and New Zealand are the other countries with an installed capacity of electric geothermal power of almost 1000 MW<sub>e</sub> or higher – see Annex 2 (World Energy Council 2018).

Production of electricity from geothermal resources is nowadays mainly in private ownership, operated by a fewer large private companies. In fact, more than 70% of the world electricity production from geothermal sources is controlled by only 20 operators, with the Italian based company ENEL Green Power being among the largest geothermal electricity producers (World Energy Council 2016). ENEL Green Power company operates 34 geothermal power plants in the Tuscony region in Italy, with an installed electricity capacity of 761 MW. Other big players on the geothermal energy market include for example the largest geothermal Philippine Energy Development Corporation (EDC), Calpine Corporation in the USA or Israel company Ormat Industries (World Energy Council 2016). The last two mentioned companies are also active in the development of EGS demonstration sites in the United States (U.S. Department of Energy 2017).

### 3.2.2 Geothermal direct use of heat

A much higher installed capacity in geothermal energy is in direct use of heat (district heating, direct heating or geothermal district heating). Installed capacity in geothermal direct use of heat is almost 19 GW<sub>th</sub> within 28 EU member countries with annual power generation nearly 30 000 GWh (Annex 1). The largest European user of geothermal direct heating is Sweden, with an installed

capacity of 5600 MW<sub>th</sub>; about half of the Swedish installed capacity is reported by Germany (2850 MW<sub>th</sub>) and France (2350 MW<sub>th</sub>), followed by Finland with installed capacity of 1560 MW<sub>th</sub> (World Energy Council 2018).

Also, some of the European non-EU member countries have a significant installed capacity in direct use of heat in geothermal power; Iceland holds the first place with 2 GW<sub>th</sub>, followed by Switzerland with an installed capacity of 1733 MW<sub>th</sub> and Norway, with an installed capacity of 1300 MW<sub>th</sub> (World Energy Council 2018).

Differently to geothermal electricity generation controlled by fewer large companies, geothermal direct use is exploited mostly by smaller enterprises for heating of greenhouses or spa complexes; municipalities are using geothermal energy for district heating or it is used by individual households (World Energy Council 2016).

The question is whether only heat can be the primary and only product of an EGS power plant. Brown et al. (2012) suggest that this situation could be economically feasible only in case of co-location of other industrial plant. It can be example of the newly commissioned EGS power plant in Rittershoffen, France, with an installed capacity of 24 MW<sub>th</sub> producing steam for an industrial site (Roquette Group, food industry). On the other hand, an important statement for economic feasibility is the governmental subsidy for development of the Rittershoffen EGS power plant which reached 73% of total required funds (Roquette 2016).

A focus only on district heating for municipalities and households is questionable and would be depend on the geographical location of the EGS power plant and the season. The northern and Central European countries have a higher installed capacity of geothermal district heating, but the southern countries with the exception of Italy have significantly lower installed capacity (Annex 1). It is even more obvious in case of countries with a capacity of geothermal electricity generation higher than 1 GW<sub>e</sub> such as the Philippines, Indonesia or Mexico which are situated in the tropics and their installed thermal capacity is only 3.3, 2.3 and 156 MW<sub>th</sub>, respectively (Annex 2, World Energy Council 2018).

### 3.3 Enhanced Geothermal System power plants

The CHPM technology's primary focus is to establish the enhanced geothermal system for the generation of both electricity and heat. EGS is considered unconventional geothermal plants using the concept of the Hot Dry Rock (HDR) which originated from the Geothermal Energy Program of Los Alamos National Laboratory (MIT 2006). The first EGS plant was built at Fenton Hill in New Mexico (USA) and patented in 1974 (Potter et al. 1974). The pilot EGS power plant at Fenton Hill targeted a reservoir at a depth of 4.4 km and rock temperature of 300°C. The power plant successfully tested 60 kW<sub>e</sub> binary cycle power generation (MIT 2016). Despite the Fenton Hill EGS project failed in achieving commercial scale operation, due to problems with fluid circulation in the reservoir; it proved that the HDR concept for EGS power plants is possible from a technological point of view (Lu 2018).



### 3.3.1 Economic feasibility of EGS power plants

Technically, unconventional geothermal energy has a large potential; Chamorro et al. (2014) calculated the EGS technical and sustainable potential for Europe on 6560 GW<sub>e</sub> and 35 GW<sub>e</sub>, respectively. The installed electrical capacity in EU-28 was 982 GW<sub>e</sub> in 2015 (Eurostat 2017).

Power plants exploiting geothermal energy can also operate almost continuously and thus geothermal power plants are achieving a very high capacity factor<sup>2</sup>, especially in comparison with other sources of renewable energy (Figure 6), which are very dependent on day time or the season.

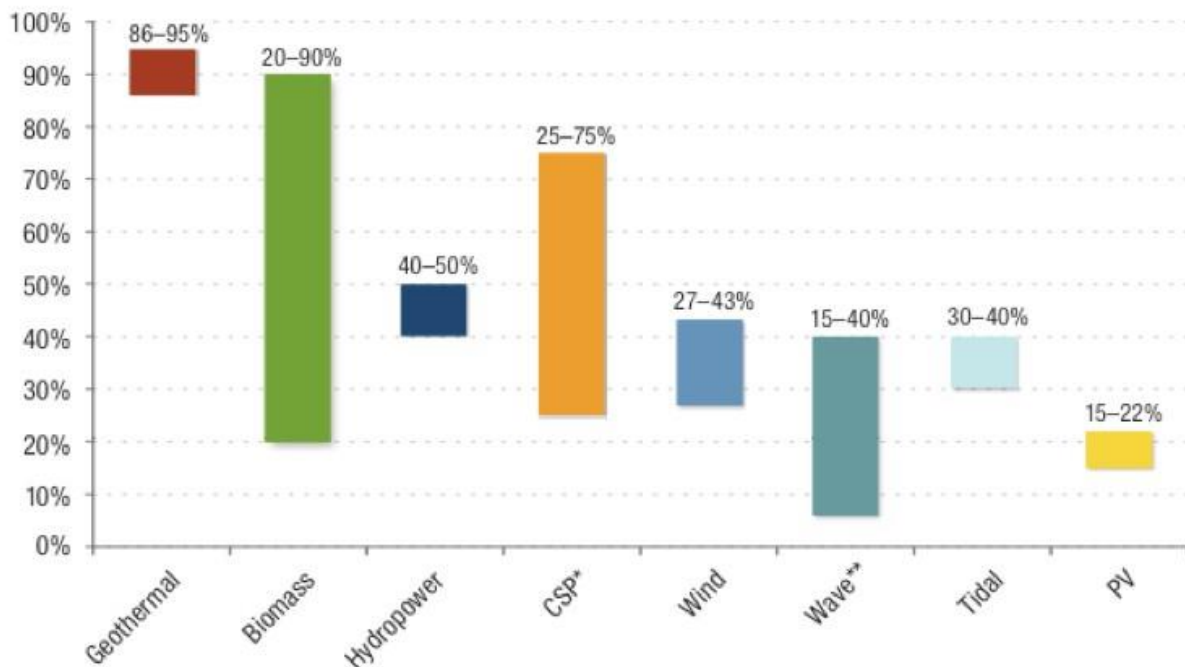


Figure 6: Capacity factor of renewable energy sources in the U.S. for 2008 produced by National Renewable Energy Laboratory (Gelman and Hockett 2009). CSP is the Concentrated Solar Power.

The capacity factor can be calculated using the following formula:

$$\frac{\text{annual electricity generation MWh}}{(365 \text{ days}) \times (24 \text{ hours/day}) \times (\text{installed capacity MWe})} = 0.xx = xx\% \text{ (capacity factor in \%)}$$

For example, the capacity factor for Landau EGS power plant with characteristic values of 2.9 MW<sub>e</sub> installed capacity and annual electricity generation of 22000 MWh (BINE 2007) would be 87%.

$$\frac{22000 \text{ MWh}}{(365 \text{ days}) \times (24 \text{ hours/day}) \times (2.9 \text{ MWe})} = 0.87 = 87\%$$

However, the economic feasibility and commercialization of EGS power plants is still a problematic issue even after over 40 years of EGS R&D projects and filed demonstrations since the

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<sup>2</sup> Capacity factor is the ratio of the net electricity generated for the time considered, to the energy that could have been generated at continuous full-power operation during the same period (U.S. NRC 2018).

first EGS test at the Fenton Hill. On a global basis, there is no commercial scale EGS power plant developed without a significant governmental funding (Annex 3), which in some cases reaches over 70% of the total project budget (Annex 3 – EGS power plants in operation / in developed – Economic information). This suggests a serious problem in raising funds from private sources for development of EGS.

The main problem in raising funds is very high capital expenditure (CapEx; sometimes also capital or initial costs), which is needed for the development of the EGS power plant together with a long-term duration and a significant project risk during development phase. The geological and engineering risk in geothermal industry as defined by Cooper et al. (2010) is even higher in case of EGS, because in conventional geothermal energy the exploration is targeting for hydrothermal reservoir, which is situated in many cases in shallower levels compare to EGS target. On the other hand, EGS is targeting hot rock located mostly much deeper than hydrothermal reservoirs, which significantly increasing cost of drilling. After drilling an injection and production well, a stimulation of deep hot reservoir has to be completed to allow fluid flow between the wells and surface heat exchanger. A stimulation of reservoir followed by circulation of working fluid is another critical phase in development of EGS burdened by a high engineering and geological risk.

According to a model simulation done by Olasolo et al. (2016) the fraction of capital cost required for drilling and reservoir stimulation can exceed 70% of the total CapEx amount.

In many cases, investors use the Net Present Value<sup>3</sup> (NPV) calculations to analyse profitability and relative value of project seeking for funds. However, due to very high CapEx, long project life, lack of historical data which leads to poorly constrained revenues and problematic incorporation of high risk to the NPV formula<sup>4</sup>, NPV calculations are not commonly used in geothermal energy industry (Cooper et al. 2010). Cooper et al. (2010) also calculated NPV for geothermal projects based on theoretical data and calculations not uncommonly yielded NPV values less than zero, which commonly results in the rejection of the project by the investor.

Very often, the method used in the energy sector feasibility assessment is the levelized cost of energy (or levelized cost of electricity – LCOE) and in case of hybrid system producing both electricity and heat, also levelized cost of heat (LCOH) can be utilized (Beckers et al. 2014). But, Cooper et al. (2010) noticed that the same problems which are in NPV calculations (especially lack of historical data) should be taken into consideration in case of LCOE calculations. Also, EGS are very site-specific and definition of EGS is not narrowly specified which leads to significant differences in CapEx for individual EGS power plants (Annex 3

EGS power plants in operation / in developed – Economic information). For this reason, most of simulations are using more EGS scenarios with different variables, e.g. Beckers et al. (2014), Mines and Nathawani (2013) or Olasolo et al. (2016).

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<sup>3</sup> Investopedia: “Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV is used in capital budgeting to analyse the profitability of a projected investment or project” (Investopedia 2018a).

<sup>4</sup> One possibility how can be higher risk incorporate into NPV is the risk-adjusted discount rate (Investopedia 2018b). The investor willing to put money into a riskier project will require higher returns, because losses are more probable.

Beckers et al. (2014) used the LCOE methodology to assess the feasibility of EGS systems, separated into three distinct categories: Low-grade (30 °C/km); Medium-grade (50 °C/km); and High-grade (70 °C/km). It shows that the EGS systems have a very high LCOE compared to the other sources of energy and that only the systems coming from the High-grade sources can be compatible (Figure 7). However, it does mention that with advancing technology projected to 2030, the LCOE for all types of reservoirs will become competitive with other sources (striped columns at Figure 7). This also corresponds to CHPM developmental timeframe.

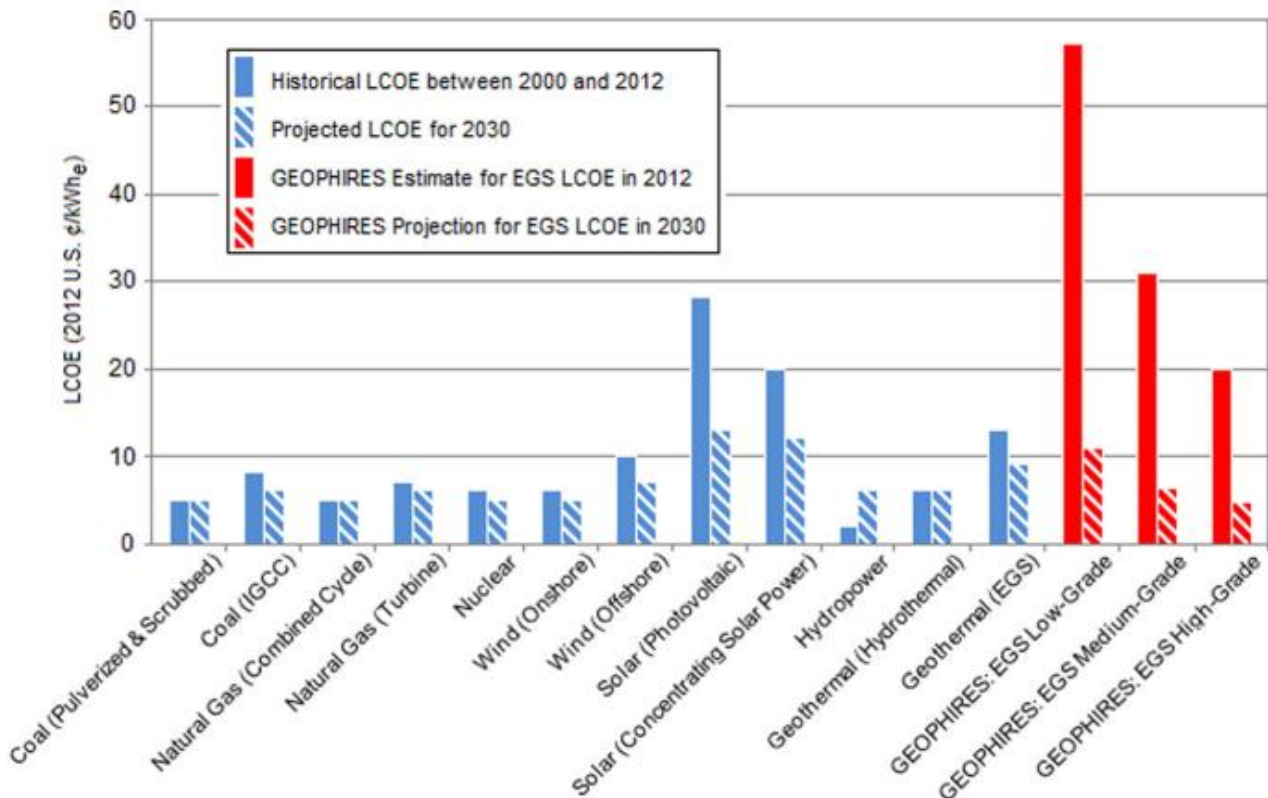


Figure 7: Beckers et al. (2014) comparison of LCOE (¢/kWh<sub>e</sub>) for EGS modelled in GEOPHIRES (red bars) with data from OpenEI Transparent Cost Database (OpenEI 2016).

Very detailed estimations of both CapEx (capital expenditures) and OpEx (operational expenditures) for a five different EGS scenarios were created by Mines and Nathawani (2013). Differently to Beckers et al. (2014) using a 7% discount factor for all scenarios, Mines and Nathawani (2013) assigned a different discount rate (factor) to individual stages of EGS development based on how risky the phase can be. A discount rate of 30% is set for early phases of exploration and confirmation (exploration drilling and stimulation). For well field development and completion, which include final completion of wells and cost for successful fluid circulation, the discount rate lowers to 15%. The last phase, a power plant construction and entire operation of the plant is burdened by a 7% discount rate. The results (Figure 8) show a trend similar to Becker et al. (2014) suggesting that only EGS targets with high thermal gradient and installed electricity capacity on more than 20 MW<sub>e</sub> can reach a LCOE lower than 20 ¢/kWh (Mines and Nathawani 2013).

EGS Results	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Resource Temperature	100°C	150°C	175°C	250°C	325°C
Resource Depth	2 km	2.5 km	3 km	3.5 km	4 km
Plant type	Air-Cooled Binary	Air-Cooled Binary	Air-Cooled Binary	Flash Steam	Flash Steam
# of Production Wells	21.5	7.6	7.9	6.4	4.3
Ratio of Production to Injection Wells	2:1	2:1	2:1	2:1	2:1
Production Well Cost - each	\$5,187K	\$6,965K	\$8,973K	\$8,237K	\$10,280K
Injection Well Cost - each	\$5,187K	\$6,965K	\$8,973K	\$11,210K	\$13,678K
Total Geothermal Flow	860 kg/s	303 kg/s	316 kg/s	256 kg/s	171 kg/s
Power Sales	10 MW	15 MW	20 MW	25 MW	30 MW
Geothermal Pumping Power	3,499 kW	738 kW	383 kW	997 kW	679 kW
Plant Output	13.50 MW	15.74 MW	20.38 MW	26 MW	30.68 MW
Generator Output	17.07 MW	20.34 MW	24.4 MW	27.42 MW	31.72 MW
Power Plant Cost	\$8,128/kW	\$4,668/kW	\$3,597/kW	\$2,091/kW	\$1,571/kW
Overnight Project Capital Cost (with contingency)	\$343,960K	\$187,291K	\$217,994K	\$176,620K	\$152,299K
Present Value of Project Capital Cost	\$396,252K	\$235,706K	\$276,042K	\$229,634K	\$211,177K
Exploration & Confirmation (€/kW-hr)	9.44	7.27	6.56	4.83	4.88
Well Field Completion - Including Stimulation (€/kW-hr)	32.46	7.47	7.24	4.56	2.53
Permitting (€/kW-hr)	0.37	0.23	0.17	0.13	0.11
Power Plant (€/kW-hr)	16.98	7.13	5.30	3.09	2.33
O&M (€/kW-hr)	17.22	5.65	4.74	4.78	3.53
Levelized Cost of Electricity - LCOE (€/kW-hr)	76.47	27.75	24.01	17.4	13.39

Figure 8: Description of individual scenarios, CapEx, OpEx and estimated LCOE for a five EGS scenarios (Mines and Nathawani 2013).

Nowadays LCOE of EGS calculated Mines and Nathawani (2013) is falling in range from 76 to 13 €/kWh for individual scenarios (Figure 8). Electricity price for non-household consumers in EU-28 was 13 €/kWh (included taxes, excluded VAT) in second half of 2017 (Eurostat 2018c).

Nevertheless, despite LCOE of unconventional EGS which are not too competitive with conventional non-renewable sources (Figure 7), the cost of an EGS development is supposed to decrease due to further developments in technology based on numerous ongoing R&D projects as well as experience gained from EGS demonstration plants (Lu 2018, MIT 2006). Lessons learned from previous and ongoing demonstration plants can significantly contribute to the cheaper development of new facilities (e.g. Latimer and Meier 2017).



### 3.4 Economic-related overview of EGS demonstration plants

As mentioned previously, a development of every single EGS demonstration plant benefits from a significant governmental subsidy (Annex 3). Thus, only high-income economy countries supported development of such costly energy projects. Until recently only the United States, several European countries (UK, Sweden, Switzerland, France and Germany), Japan, South Korea and Australia contributed to the EGS topic through the development of demonstration plants. Nowadays, potential of the EGS technology is explored or considered in many other countries, e.g. China (He et al. 2018) or Taiwan (Lu 2018) or Mexico (GEMex 2016).

#### 3.4.1 European EGS experience

After the first EGS test at Fenton Hill, the two pilot plants were tested in Europe (Figure 9) - Rosemanowes (1991-1997) in Cornwall, UK (MIT 2006) and Fjällbacka (1984-1989) in Sweden (Wallroth et al. 1999). All of these early EGS projects were more less successful in exploration drilling of deep wells into targeted hot rock, but economic power generation failed due to an enormous loss of circulation fluids in stimulated reservoir. The loss of fluids was within the range of 50 to 90% (MIT 2006).

It suggests that a reservoir stimulation is a critical factor in achieving economical feasible EGS power plant. Since then, many R&D projects were and still are focusing on technological improvement and cost-reduction of reservoir stimulation, for example the H2020 DESTRESS project (DESTRESS 2016).

The flagship EU EGS project – the Soultz-sous-Forêts located in Upper Rhine Graben (Figure 9) also started in the eighties and drilling began in 1993. The power plant with an installed capacity of 2.1 MW<sub>e</sub> (0.6 MW<sub>e</sub> is internal consumption of the plant) was connected to the national grid in 2007. Pumped heat is equal to 13 MW<sub>th</sub>. Incentives and grants for the development of the Soultz-sous-Forêts EGS power plant reached 94 million USD (BINE 2009). The Solutz was the first EGS plant which offered a stable production of electricity to the national grid, although it took 23 years of development from the first preparatory geological work.

Still in Europe, the Upper Rhine Graben is hosting the three other operational EGS power plants. Landau and Insheim EGS power plants are situated close to the Solutz, but already in Germany. Both power plants benefited from information and experiments done at the nearby Solutz EGS project, which allow its commission in much shorter term and at lower cost. Landau EGS power plant went onto continuous operation with an installed capacity of 3.8 MW<sub>e</sub> and 3 MW<sub>th</sub> 5 years from the beginning of preparations. Total expenditure is estimated at 24 million USD (BINE 2007).

The last EGS power plant situated in Upper Rhine Graben (Figure 9) is at the same time the most recently commissioned EGS power plant located at Rittershoffen in France. Interestingly, this EGS power plant is not focusing on more profitable electricity generation, but only on direct heat for industrial purposes with an installed capacity on 24 MW<sub>th</sub>. The plant was developed quite fast in five years, however despite 80% shares of the company is held by large private companies, the governmental subsidy of almost 50 million USD representing a share of over 70% of the total requirements.

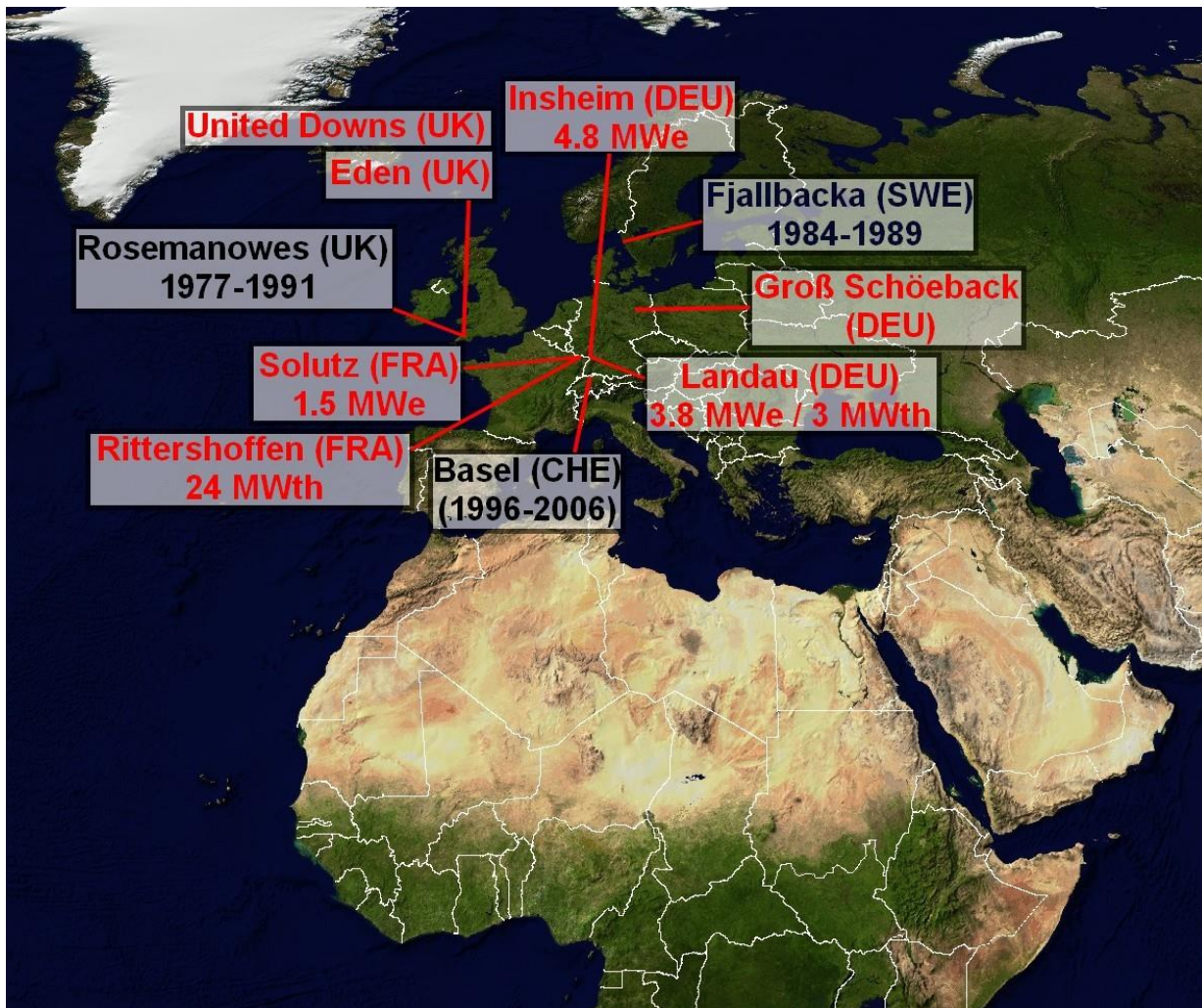


Figure 9: Map of the European EGS projects. The red ones are in operation or in development, the black ones are past, stopped projects.

The important experience was gained from the Basel EGS project, preparation of which started in 1996. A drilling successfully targeted granite rock with approximately 200 °C at a depth of 5000 meters (Wyss and Rybach 2010). A hydraulic fracturing of the granite started to cause micro seismic events, which unfortunately sharply increased in intensity until a magnitude 3.4 earthquake occurred and caused damage at local structures (Lu 2018). The risk of the continuation of seismic events led to the termination of the project and the subsequent creation of the EU funded GEISIR project – Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs (GEISIR 2010).

Groß Schönebeck, an EGS project of federal research institute, is located in Germany near Berlin and verifies the concept of using an old abandoned oil & gas exploration well for EGS purposes. This can be crucial for the economic feasibility of EGS, as drilling consumes a major part of CapEx (ENGINE 2008).

Very recently, two other EGS projects – Eden (EGS Energy 2012) and United Downs (Geothermal Engineering Ltd. 2018) raised the first funds and started their exploration drilling phase in Cornwall, UK.

Beside these EGS demonstration plants, the EU is funding many R&D EGS related projects, led by large research team called ENGINE – The Enhanced Geothermal Innovative Network for Europe. The goals of the ENGINE are to reduce cost of EGS related technologies by 20-30% by 2020 (ENGINE Coordination Action 2008).

### 3.4.2 The United States EGS experience

EGS related R&D as well as development of EGS demonstration plants is very strong in the United States. The US DOE (the United States Department of Energy) funded the EGS R&D sector by 224.3 million USD from 2007-2013 (Hollet 2013), the main funding instruments being FOA (Funding opportunity announcement), ARRA (American Recovery and Reinvestment Act) or RFP (Request for Proposal). In 2013, the EGS R&D projects were represented by 130 projects and by the development of five field demonstration EGS plants (Figure 10). 47% of projects were run by the national labs, 36% by industry and 17% by university research teams (Ziagos et al. 2013). The ambitious goal presented by US DOE (Hollet 2012) is to reduce the LCOE for EGS development from 23 ¢/kWh in 2011 to 0.6 ¢/kWh by 2030.

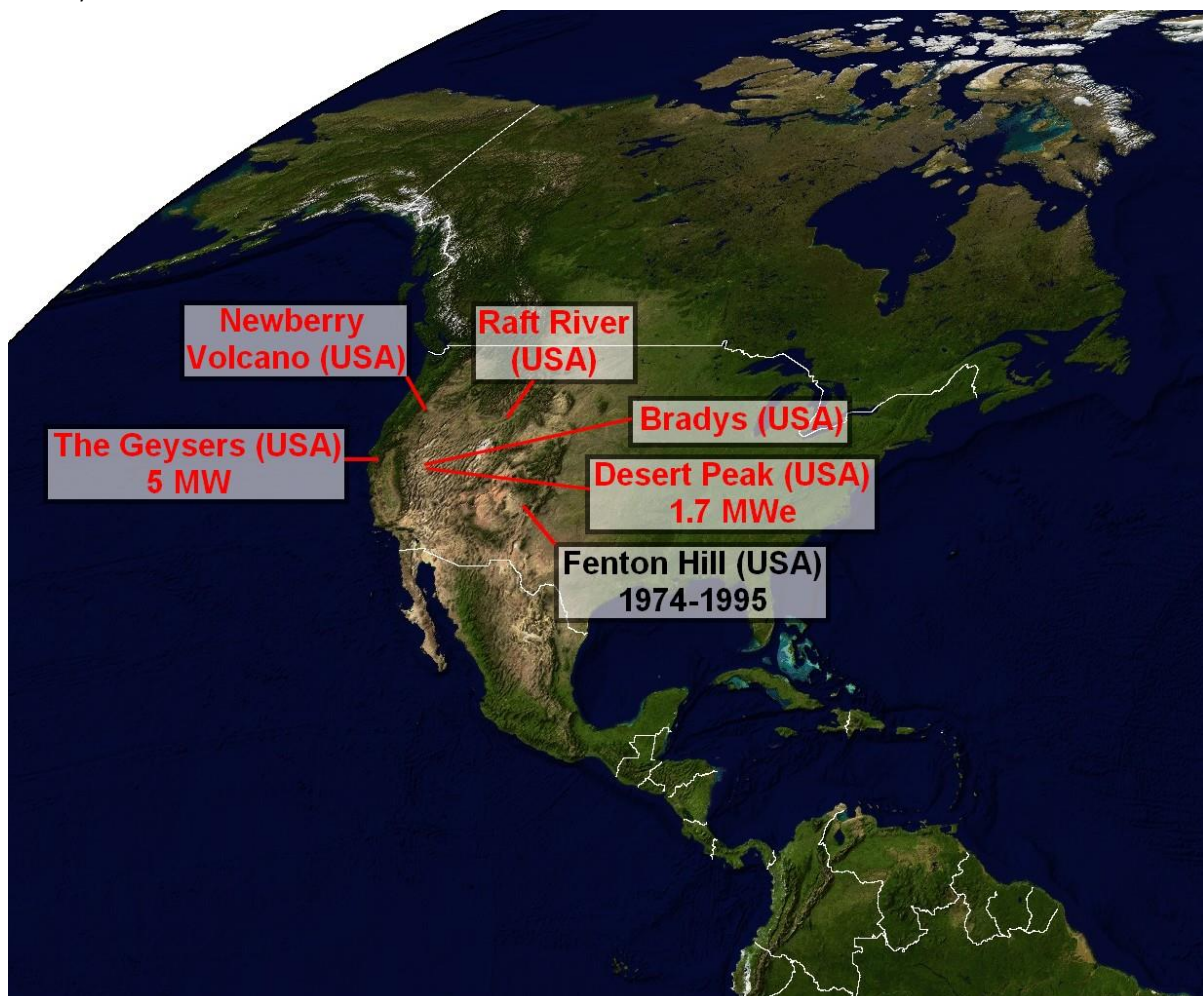


Figure 10: The United States – location of demonstration EGS plants as well as the pilot EGS plant at Fenton Hill.

Very important is the definition and dividing of EGS into the three types: Greenfield, Near Field and In Field. The CapEx of EGS development is strongly reflects this division.



- a) Greenfield EGS – it is similar to the definition of greenfield – to build or construct something in a place which is not built-on or inhabited. But the EGS definition of greenfield particularly means that the EGS site is developed away from any conventional geothermal field, targeting hot-dry rock. The development of the greenfield EGS power plant requires the highest CapEx from all three earmarked types. All European EGS demonstration plants in operation or in development (Figure 9) can be considered as the greenfield EGS.

From the U.S. demonstrations plants, only the Newberry Volcano EGS project run by AltaRock Energy Inc. is the greenfield EGS. The project has been in development since 2009, and recently successfully stimulated reservoir at a depth of 3067 m and temperature of 331°C. The total funding required for the development of the Newberry Volcano EGS plant is 44 million USD, from which the US DOE subsidy is 21 million USD (Petty 2013).

- b) Near field EGS – it can be defined as deployment of EGS technology near to “conventional” geothermal field, which increases the possibility of higher thermal gradient or shallower depth needed for reservoir stimulation. This can subsequently lead to a cheaper development of near field EGS power plant, because deep drilling, together with reservoir stimulation, consumes the major share of CapEx.

The geysers EGS demonstration plant (Calpine Corporation) represents already operational near field EGS power plant with installed capacity of 5 MW<sub>e</sub>. The development of this EGS plant took only 4 years and required 13 million USD, from which 6 million USD was subsidized by the U.S. (Walters 2013).

The second near field EGS project is Raft River, led by a research team from the University of Utah. The Raft River EGS site achieves 150°C at a depth of only 1800 meters and the objective is to develop a 5 MW<sub>e</sub> power plant with a flow rate of 20 kg/s by 2020. Total funding for the development of the Raft River EGS is 10 million USD and a government subsidy of 8.6 million USD covers the major share of the project funding.

- c) In field EGS – it can be described as a transitional type between unconventional EGS and conventional geothermal (hydrothermal) energy sources. In field EGS is deploying EGS technology especially focused on reservoir stimulation to extend the life of unproductive (or poorly productive) conventional geothermal well fields. This type of EGS is the cheapest “EGS option”, because it uses already drilled wells.

Israel based company Ormat Technologies Inc. is developing two in field EGS power plants in Nevada, U.S. One of them, Desert Peak, is already in operation and joined the national grid in 2013 with an installed capacity of 1.7 MW<sub>e</sub>. Up to 27 old geothermal wells are used for power generation at this EGS site. The total required funds were 7.6 million USD, with a 5.5 million USD share from government subsidy (Chabora and Zemach 2013).



The second in-field EGS, the Bradys, located only about 7 km from the Desert Peak well field, is still in development. The Bradys project is planning to incorporate the same technology used at the Desert Peak to improve productivity of a geothermal well. The project budget is calculated at 6.4 million USD, 4.4 million USD of which was granted by the U.S. government.

### 3.4.3 EGS experience in the East Asia region

Two of the early EGS sites were located in Japan (Figure 11) – Hijori 1981-1989 and Ogachi 1989-2001 (Kaieda 2015). Both projects would be possible, from today's perspective, considered as near field (or in field) EGS, as both were located in volcanic geothermal fields. However, this early EGS projects suffer of the same problems as the early European projects – the loss of circulation fluids reached even 70-90%, which subsequently led to the termination of both projects (Kaieda 2015).

South Korea is furthest in development of commercial scale EGS power plant – the Pohang EGS (Figure 11) successfully demonstrated a 1.5 MW<sub>e</sub> capacity generation in 2017 (Lu 2018). However, the operation is temporally suspended due to investigation of possible EGS induced earthquake, that occurred in November 2017 with an unprecedented intensity of magnitude-5.5. This was the most intensive earthquake which is probably associated with EGS technology (Grigoli et al. 2018).

China reported the first well drilled for development of EGS technology in the Gonghe basin (Qinghai province, NW China, Figure 11). Temperature was measured at 236°C at a depth of 3705 meters (Wei 2007).

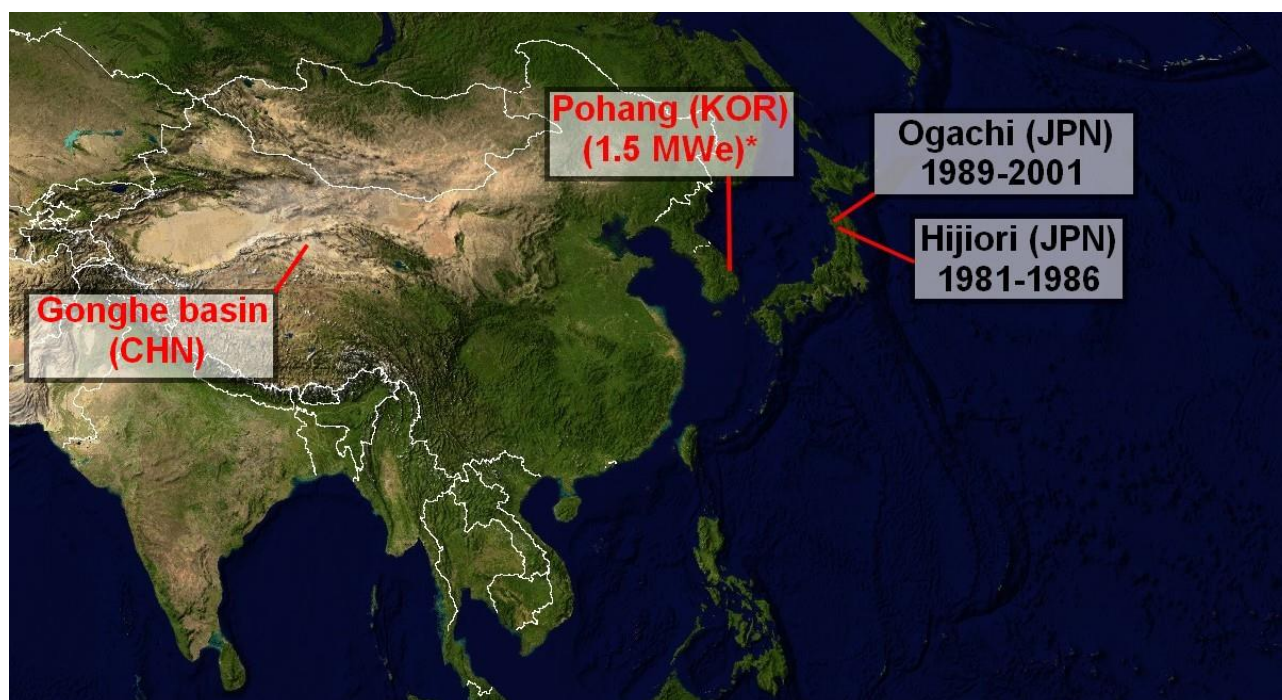


Figure 11: Location of EGS projects in the East Asia; \*) Pohang EGS has 1.5 MW<sub>e</sub> installed, but it is currently suspended.

### 3.4.4 Australian EGS experience

Some Australian private companies are among the world leaders in mineral exploration and mining, for which they raise investment capital by offering their shares to the public through initial

public offerings<sup>5</sup> and trading on stock exchanges. Most of the Australian private companies exploring and developing EGS projects are also listed on the Australian Stock Exchange (ASX), e.g. Petratherm Ltd. or formal companies Geodynamics or Green Rock Energy Ltd.

Beside private capital, the Australian companies are applying for significant governmental grants for the development of EGS projects from ARENA (Australian Renewable Energy Agency; REDP<sup>6</sup> and REF<sup>7</sup> grants) or other state initiatives. All significant projects were located in the South Australia state (Figure 12), which also raised state fund PACE: South Australia's Plan to ACcelerate Exploration.

There are three significant projects to describe:

- a) Habanero – Cooper Basin project, which was run by Geodynamics Ltd. This was the first Australian EGS project, which successfully tested an EGS power plant with an installed capacity of 1 MW<sub>e</sub>. Total expenditures for the project were calculated on 108 million USD, from which ARENA's share was 25 million USD (ARENA 2016). In 2016, Geodynamics Ltd. announced termination of the projects from the reason that OpEx costs were just greater than revenue stream obtained from electricity production. The company returned funding to ARENA, renamed itself ReNu Energy and shifted its business focus to solar photovoltaic, battery storage and hybrid energy solutions (Vorath 2016).



Figure 12: Location of the main Australian EGS projects, all written in black as all of them are abandoned.

- b) The Paralana EGS project was developed by Petratherm Ltd., when they successfully drilled three wells and an artificially stimulated reservoir and the installation of a 3.5 MW<sub>e</sub> power generator was scheduled on 2015. However, the Petratherm ASX Release from July 2014

<sup>5</sup> Initial public offering: this is when a private company or corporation raises investment capital by offering its stock to the public for the first time (Investopedia 2018c).

<sup>6</sup> REDP: Renewable Energy Development Program

<sup>7</sup> REF: Renewable Energy Fund

announced that the company failed to secure an additional 5 million USD, which was the condition for the spending of a 13 million USD grant from ARENA as well as the obtention of 24.5 million USD from REDP (Petratherm 2014). This led to termination of the project and remediation works at Paralana.

- c) The Olympic Dam EGS project was very interesting from CHPM's point of view, as its location was close to the BHP Billiton's giant Olympic Dam copper-uranium-silver-gold deposit. It would be possible to call it with usage of U.S. definition as the near-mine EGS. Unfortunately, the situation was probably similar to Paralana case, the Green Rock Energy Ltd. apparently abandoned this EGS project in 2015 and, renamed itself Black Rock Mining Ltd. and has recently been developing Mahenge Graphite Project in Tanzania (InvestoGain 2018).

### 3.5 Conclusions of the Energy level

The exploration for unconventional EGS power plants share many similar features with mineral exploration projects run by junior companies, which do not have sufficient funds for an entire project and have to search for additional funding. One possibility can be the stock exchange market – but as the Australian case suggest, EGS developing companies were not too successful in securing private money to develop or run feasibility operation. It is very likely that shareholders are not willing to bear large risk of the insufficiently proven feasibility of EGS technology.

Interestingly, many EGS developing companies are not small or junior companies with low income, there are also large companies from geothermal energy industry (e.g. Ormat Technologies Inc. or Calpine Corporation), conventional energy (e.g. Électricité de Strasbourg) or other industry sectors (e.g. Roquette). But even such large companies are rather looking for governmental subsidies than seeking private funding or bank loans. Fortunately, unlike the mineral exploration industry, the exploration and development of EGS power plants is heavily subsidized by governmental funds, which allows a positive progress of this unconventional EGS energy sector.

The Levelized cost of energy (LCOE) is probably the best methodological tool for assessing feasibility of individual power plants using different energy sources. LCOE for EGS power plants are nowadays too high to be competitive with conventional non-renewable hydropower or in many cases also conventional geothermal power plants. But EGS technology has enormous potential, which can be developed and most probably will secure renewable energy needs for society in a near future, if results of many R&D projects tested on governmental funded demonstrations plans achieve reduction of both CapEx and OpEx. Both EGS development leading regions, the United States and the EU, set and subsidize programs aimed at significantly reducing the cost of EGS technology toward 2030. This is in accordance with the CHPM2030 time framework.

## 4 Economics of metal extraction level of the CHPM project

In the proposed CHPM technology, the mining level is represented by the extraction of valuable raw materials from circulating geothermal fluids, which are used for electricity and heat production. Revenue from co-produced and sold raw materials would then help with high operational expenditures of EGS technology at CHPM plant. Also, if the extraction metals dissolved in working fluid would be economically feasible, it can provide EU market with highly demanded raw materials.

### 4.1 Baseline economic of raw material supply for the EU (Critical Raw Materials)

The European Union is a region with a highly developed global-scope economy, hi-tech oriented industry and population demanding high life standards which all result in a very high consumption rate of numerous raw materials (European Commission 2014a, Figure 13). On the other hand, the domestic production rate of many demanded raw materials is either zero or very low. Low domestic raw materials production in the EU-28, increasing demand and risk of supply shortages were main the reasons which led to the announcement of the Raw Material Initiative (RMI) in 2008 (European Commission 2008) and subsequently the creation of the first list of Critical Raw Materials (CRMs) in 2011 (European Commission 2011). Criticality (or non-criticality) of individual raw materials for the EU is based on numerical calculations of economic and industry related factors.

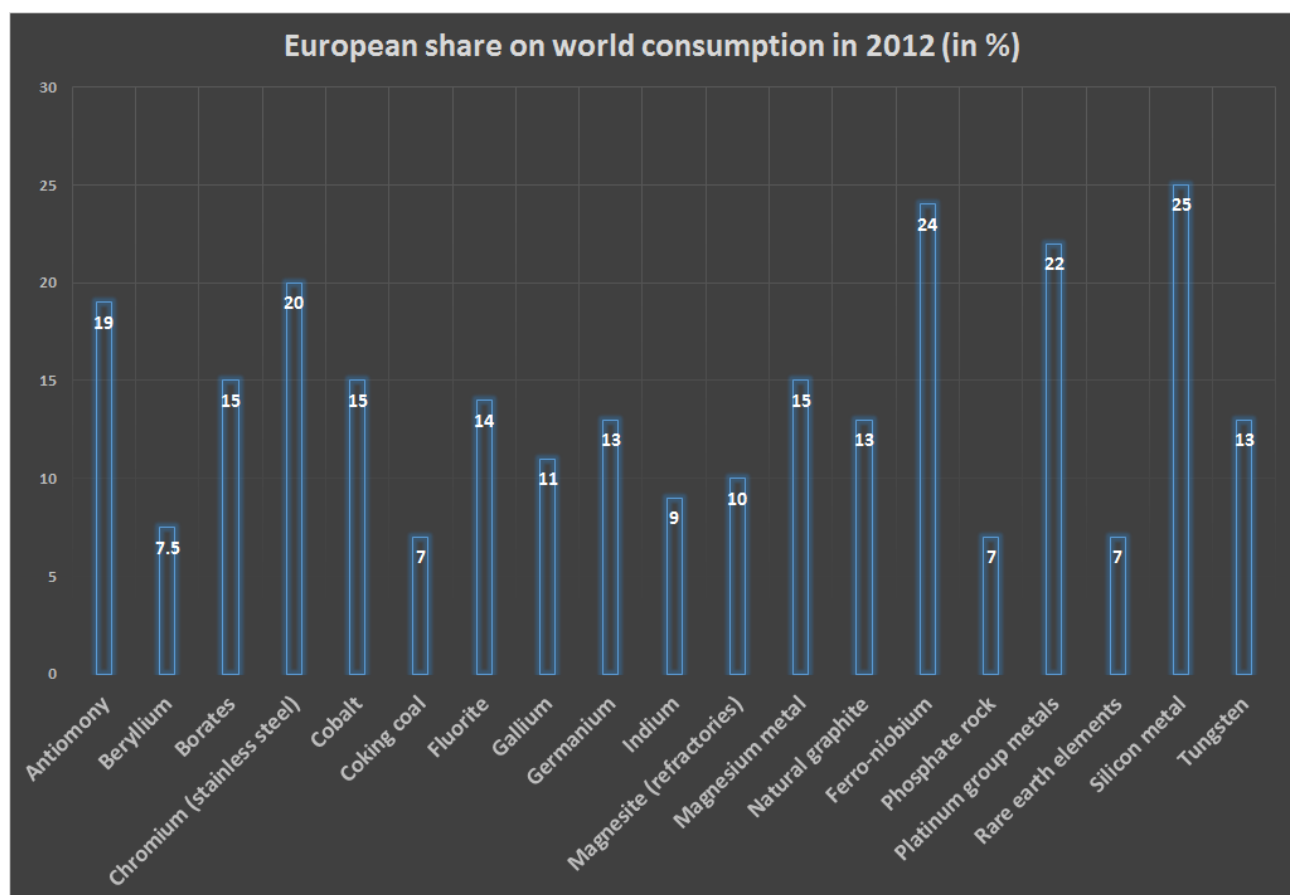


Figure 13: Estimated European share (in percentages) on world consumption of “critical raw material” in 2012 based on industry & research associations reports for individual CRMs compiled in Critical raw materials profiles (European Commission 2014).



In general, the definition and methodology of the EU CRMs is based on two variables:

- a) economic importance calculated from the share of consumption of raw material in the end-use sector and the sector's gross value added.
- b) formula of the supply risk that uses the rate of substitutability, recycling rate, geographical factor – production shares by individual countries and economic and political stability of the producing country.

The list was revised twice since its introduction, first in 2014 (European Commission 2014b) and the most recent update was in 2017 (European Commission 2017). The 2017's update assessed the criticality of a total of 61 raw materials (including three grouped raw materials – light and heavy rare earth elements and platinum group minerals). 27 of them were considered as critical for sustainable supply of EU industry and society. E.g. in case of eight CRMs, only one non-EU country is the major EU supplier with more than 70% share: antimony – China 90%, beryllium – U.S. 90%, bismuth – China 84%, borate – Turkey 98%, magnesium – China 94%, niobium – Brazil 71%, phosphorus – Kazakhstan 77% and tantalum – Nigeria 81% (European Commission 2017).

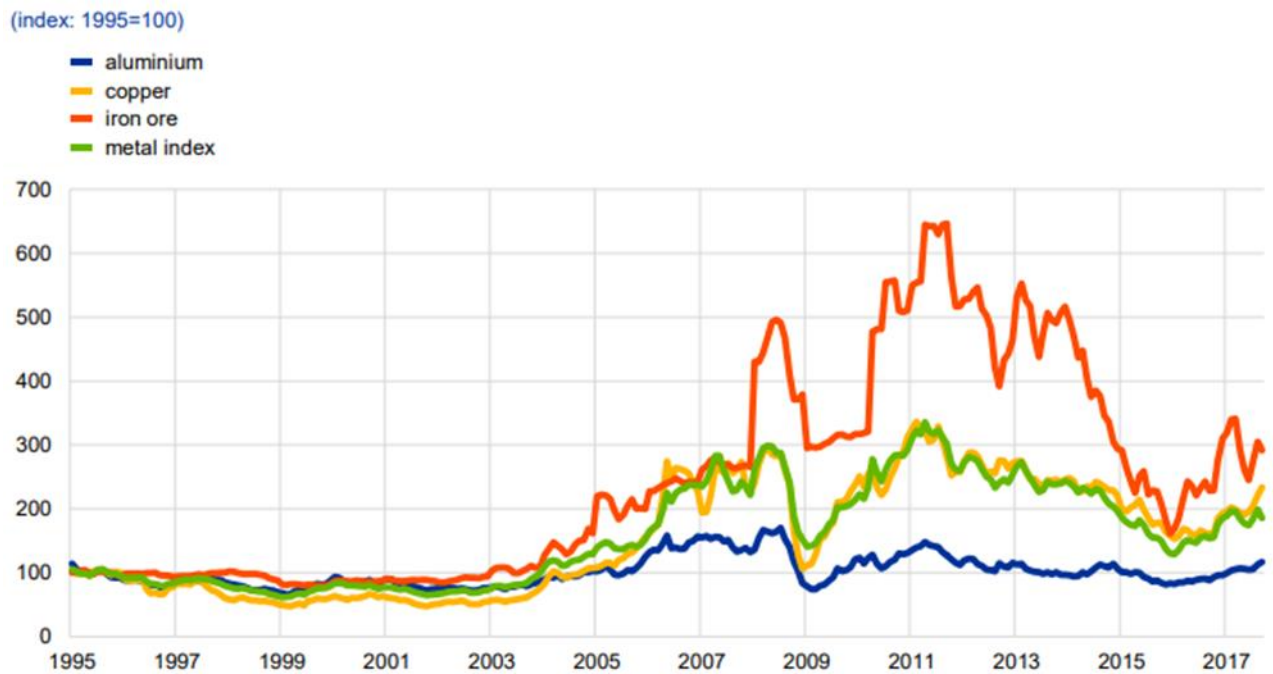
This situation represents a very problematic issue for EU industry in case of supply outages from such monopolistic suppliers. New mining operations within the EU, including possible extraction from the CHPM plants, can help diversifying the portfolio of suppliers and the reduce supply risk for the European market.

## 4.2 Metal prices and basics of price forecasting

To understand the dynamics of metal prices and also the metal market, we must understand the factors that drive them. Ultimately, the factors are some form of supply-demand issue in the current economic situation. The European Central Bank (ECB Economic Bulletin, 2017) released a report highlighting the different factors which affect the prices of base metals.

Historically, metal prices were relatively stable until the early 2000s. There was a steep rise in metal prices until 2011 (with a short dip during the recession) followed by a decrease in prices until 2016 (Figure 14). Since then, metal prices have been slowly rising. The steep rise in metal prices in the later part of the decade was due to a strong demand from developing countries, mainly China. On the other hand, supply issues may also have negative impacted the stability of prices. For example, bottlenecks in the production of copper from Chile and Peru have resulted in higher prices during this time. The bottlenecks in production were also in the form of government policies such export restrictions for REEs in China, which in turn drove up the prices (Mancheri 2015).

To further our understanding of metal markets and to develop System Dynamic (SD) models for them, we need to understand the metal cycles and quantify where materials were introduced into the economy, how they are processed and used, and how they are recycled or discarded. In this regard, a popular concept is a dynamic material flow analysis or substance flow analysis when analysing only one metal (Brunner ,2012). Performing calculations over a time window (dynamic analysis) provides an accounting of stock variations within the individual items of the value chain and captures the development of material flow over time.



Sources: Bloomberg, Hamburg Institute of International Economics (HWWI) and ECB calculations.

Figure 14: Price indexes of base metals with 1995 as base year (ECB Economic Bulletin, 2017). The numbers on the Y-axis are percentages with 100% at the base year.

One of the major features of the metal markets which is identified as the main reason for cyclic behaviour is the delayed adjustment of supply due to long planning and construction phases of new mining projects (Humphreys, 2012). Since interest and investment into new mining projects are highly linked to the metal prices at the time and since new mining projects generally take a long time to be completed, this led to the delay in supply adjustment which in turn led to a cyclic market behaviour. This, of course, is assuming that the entire mining capacity was utilized. There might be a chance that only a fraction of the mining capacity would be used, allowing the companies to react almost instantaneously to demand changes. An example of the cyclic nature of metal prices is shown below within the SD framework (Figure 15).

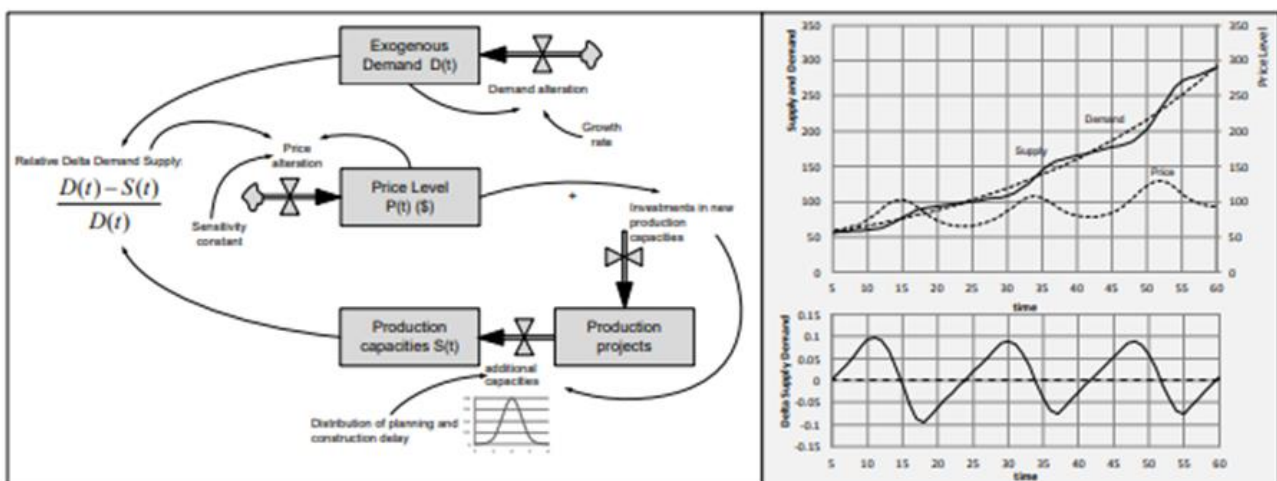


Figure 15: Simple model of price fluctuations due to delayed supply adjustment (Glöser and Hartwig 2015)



Gloser and Hartwig (2015) presented an example of a copper market model based on the demand, supply and MFA. The figure presented earlier was part of their SD model for the copper market. The entire model considered the material flows, delayed supply adjustment and the increasing demand requirements from the market from the top-down level. They calibrated the model using historical copper price and mining development and correlated it to economic development indicators such as GDP. After the model was calibrated, copper prices were forecasted based on expected economic development (GDP forecast based on Global Economic Prospects 2015, Figure 16).

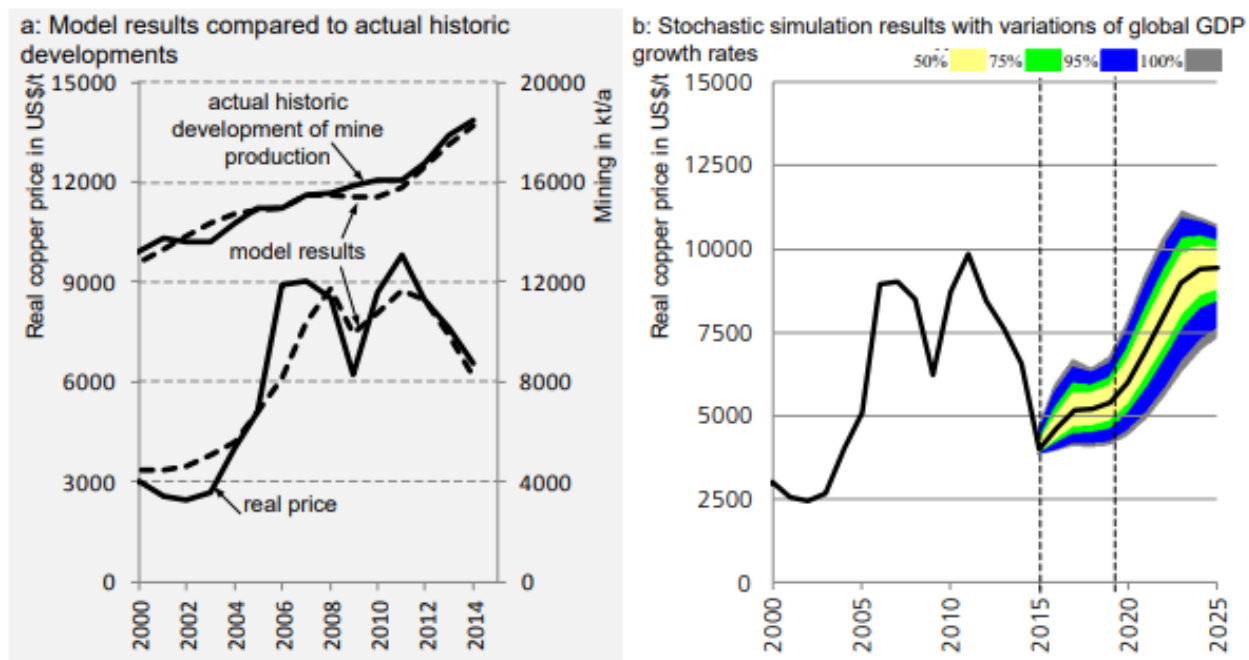


Figure 16: Forecasted price from copper model of Glöser and Hartwig (2015)

The copper price model (Figure 16), shows the relative accuracy of SD modelling during the calibration stage and its ability to predict future price developments in the long term using the development indicators from Global Economic Prospects reported by the World Bank. Using sensitivity analysis, the range of copper prices was forecasted, and these can also be thought of as results from particular scenarios. Gloser and Hartwig (2015) highlighted the advantage of SD modelling because it is possible to make a systematic approach for modelling, implement the concepts of supply delays in the metal markets and take into account the flexibility in varying the exogenous variables for sensitivity analysis.

### 4.3 Economic-related overview of different mining methods

Basically, there are two to three main methods of mineral extraction: two of them, underground mining and surface or open pit mining may be considered as “traditional” or “conventional” methods. The list is complemented by in-situ leaching (ISL) or in-situ recovery (ISR) mining method. The methods differ from each other mainly by its impacts on environment and society. In most of the cases, these methods are not substitutable to each other as mining methods as well as individual mineral deposits are very site-specific. It means that it is impossible (or more exactly economically non-feasible) to exploit e.g. oil & gas by an underground mining method or to

excavate deep narrow ore bodies through open-pit mining. Even when using one mining method, both CapEx and OpEx will vary significantly as one mineral deposit differs from another. The cost of mining operations is driven by numerous factors including geological (e.g. depth of deposit, texture and structure, mineralisation type, grade, etc.), technological (e.g. requirements for surface and underground infrastructure, technology needed for mining and mineral processing etc.), or environmental and social factors (additional costs needed for avoidance or mitigation of possible negative impact on nature and society – e.g. dust, noise, fresh water and mine water management).

The CHPM metal extraction technology (metal extraction from geothermal brines) can be included into the ISL / ISR mining method group.

#### 4.3.1 *Surface / Open-pit mining*

Surface mining was probably the first mining method used by humans in the Palaeolithic era on surface raw material/ore bodies through the use of very shallow pits. Nowadays, the open-pit mining method is used for the exploitation of near-surface large deposits of mostly lower grades in the case of ore deposits (typically giant porphyry Cu-(Au-Mo) deposits such as Chuquibambilla in Chile, Bingham Canyon in the U.S., Grasberg in Indonesia etc.). Surface mining is also used in almost all cases of construction aggregates mining and limestone mining for cement production. Large scale open-pits are set also in the European tertiary basins for excavation of brown coals (e.g. Saar and Ruhr basins in Germany or the North Bohemian basins in the Czech Republic).

Surface mining is a predominant mining method; about 85% of all raw materials (excluding oil & gas industry) was exploited in the U.S. by this method (Hartman and Mutmansky 2002). Generally, open-pit mining required high CapEx, but it mostly results in lower OpEx in comparison with underground mining, although it is very dependent on the type of deposit.

#### 4.3.2 *Underground mining*

Underground mining is often deployed on mineral deposits which cannot be economically mined by surface mining. These can be cases of deeper or narrower metallic/non-metallic bodies where the amount of waste rock would be too large to allow economically feasible surface mining. The underground mining method holds some advantages against surface mining, especially a very reduced surface impact, which in many cases makes easier (and cheaper) the land acquisition and whole permission process. Underground mining however generally achieves a higher OpEx.

#### 4.3.3 *In-situ leaching / in-situ recovery*

In-situ leaching (ISL) or in-situ recovery (ISR) is quite a new mining technology in comparison with the long-history of the other two mentioned mining methods. The definition of ISL / ISR for metals<sup>8</sup> can be summarized as the use of hydrometallurgical processing on subsurface orebodies to directly obtain solutions of demanded metals (Seredkin et al. 2016). The great advantage of ISL / ISR is an even smaller surface disruption than in the case of underground mining. ISR does not require any waste dump, tailings, surface pits. Also, with the exception of the exploration drilling phase, ISR

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<sup>8</sup> Extraction of conventional oil & gas deposits as well as unconventional shale gas deposits from wells can be also considered as specific case of in-situ recovery.

is a very quiet and dustless mining operation. One of the problematic issues of the ISR mining method is requirement for use of leaching reagents directly in the targeting ore bodies. Strict technological control (including monitoring wells around ore body) is necessary to prevent leakage of these reagents and possible contamination of the surrounding environment. Another one is the limitation of deposit characterization for which the method can be used. The ore body has to be naturally fractured, porous or permeable (e.g. sedimentary, sandstone-hosted mineralization). If not, the artificial fractures have to be developed to allow the implementation of this extraction method.

The development of ISR technology is related to an increasing demand in uranium for both energy and military purposes in the U.S and the USSR in the late 1950's and early 1960's (Seredkin et al. 2016). The method was developed independently in both countries with some modifications in the type of leaching reagents. USSR engineers used acidic solutions for the uranium leaching and mobilizing, while the U.S. technology development was based on alkaline (carbonate-based) reagents<sup>9</sup> (Seredkin et al. 2016). Nowadays, 50% of the world uranium is produced by the ISL / ISR mining method, with a major share of Kazakhstan mineral deposits (WNA 2018).

Beside uranium, some other metals are exploited or were mined by ISR and some new pilot mining sites are tested for the development of this technology. Also, extraction of metals from geothermal brines can be classified as ISL / ISR mining method. It has to be noted that the use of ISL / ISR in mineral deposits other than uranium is a totally minor part of the mining sector – we are talking only about the first tens of mines or test sites, where the ISR method is utilized for metal extraction.

Among other metals, copper is another material for which the ISR / ISL method is considered. A few mines where combined surface / underground and in-situ leaching method for copper production, such as San Manuel and Pinto Valley in Arizona or Mount Isa in Australia, have seen the termination of ISR mining. One example of operating facility of ISR copper production is Gumeshevskoye deposit in Russia (Seredkin et al. 2016). Beside copper, other metals such as gold, nickel or zinc are only at pilot test stages without economically commercial operation (Robinson and Kuhar 2018). Some elements for hi-tech industry such as REE, scandium, rhenium, vanadium or selenium are pioneering for extraction as by products at several ISR uranium operations in Kazakhstan and Uzbekistan (Seredkin et al. 2016).

#### 4.3.4 *Economic comparison of individual mining methods*

Only a direct comparison of costs between individual mining methods can be done for uranium mining, because all three main mining methods are commonly used in uranium mining industry. Boytsov (2014) compared both CapEx (Figure 17) and OpEx (Figure 18) for ISL, open-pit and underground method for uranium mining.

In many cases the ISR / ISL mining method offers the lowest both CapEx and OpEx, whereas other uranium mines with underground or surface mining methods reaches much higher costs. Only two mines which are competitive with ISR mines in OpEx below 30 USD per pound of  $U_3O_8$  are the

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<sup>9</sup> It is important to mention that both types of acidic or alkaline leaching reagents which are presently being used in uranium ISR mining cannot be considered as 'mild-leaching agents' which were tested for the CHPM technology in WP2.

Olympic Dam deposit in the South Australia and Canadian MacArthur River deposit. Both of the deposits are very specific, which favours the achievement of low OpEx. Lower OpEx at the Olympic Dam deposit is affected by the co-production of copper, gold and silver together with uranium. Uranium is considered rather as by-product at the deposit, despite the fact that the amount of uranium produced accounts for 4% of the annual world production (WNA 2018). The MacArthur River deposit is another highly specific deposit type that has an abnormally high-grade uranium ore (average grade is almost 10% of  $U_3O_8$ ).

However, the recent market price (July 2018) of uranium is as low as 26 USD per pound of  $U_3O_8$  which renders many ISR operations as well as MacArthur River non-feasible and the development of uranium related ISR technology will stagnate during the uranium market recession.

## Uranium mining

### Comparison of CAPEX for different mining methods

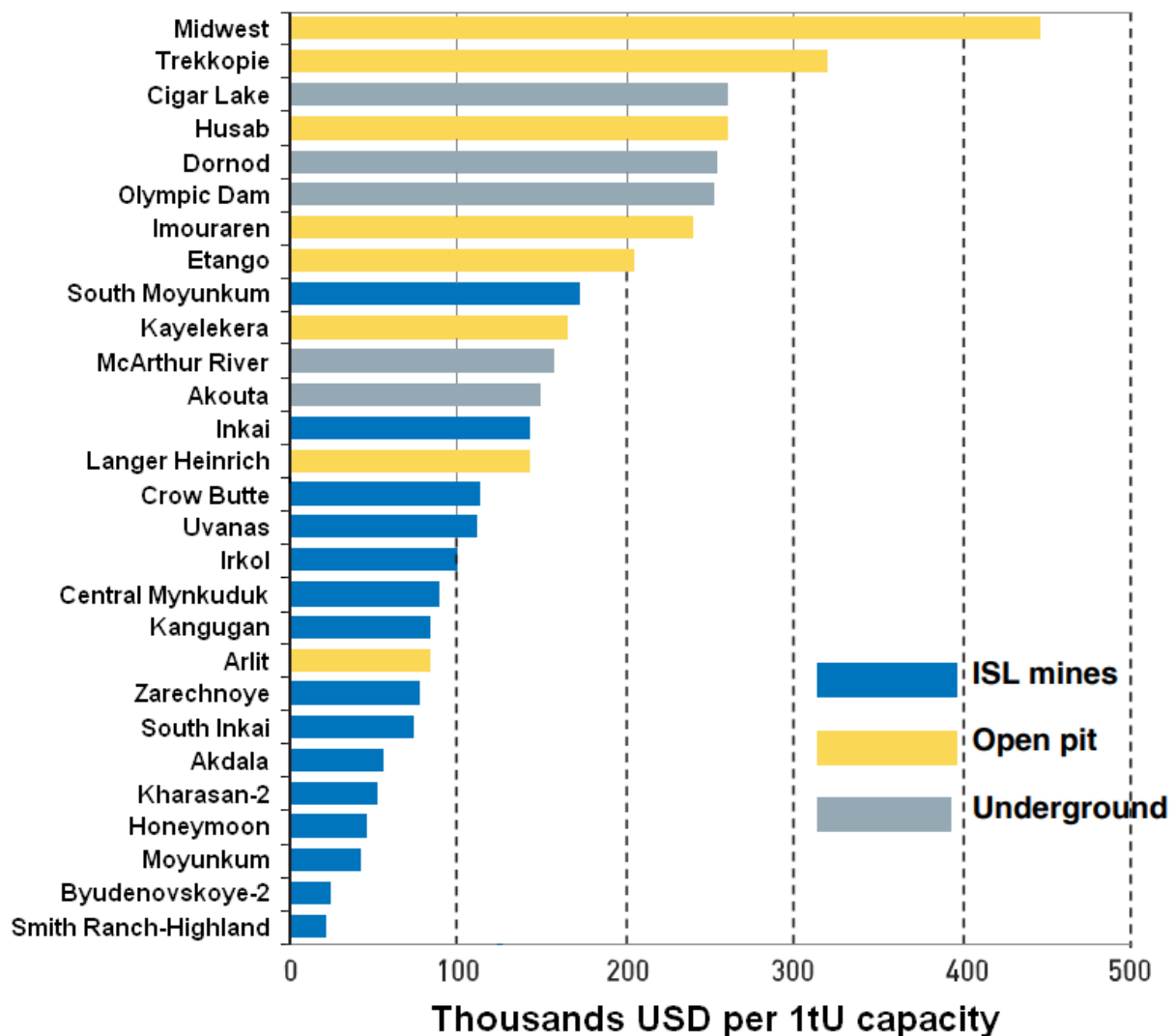


Figure 17: Comparison of CapEx required for development of uranium mines using underground, open-pit or ISL / ISR mining methods (edited after Boytsov 2014).

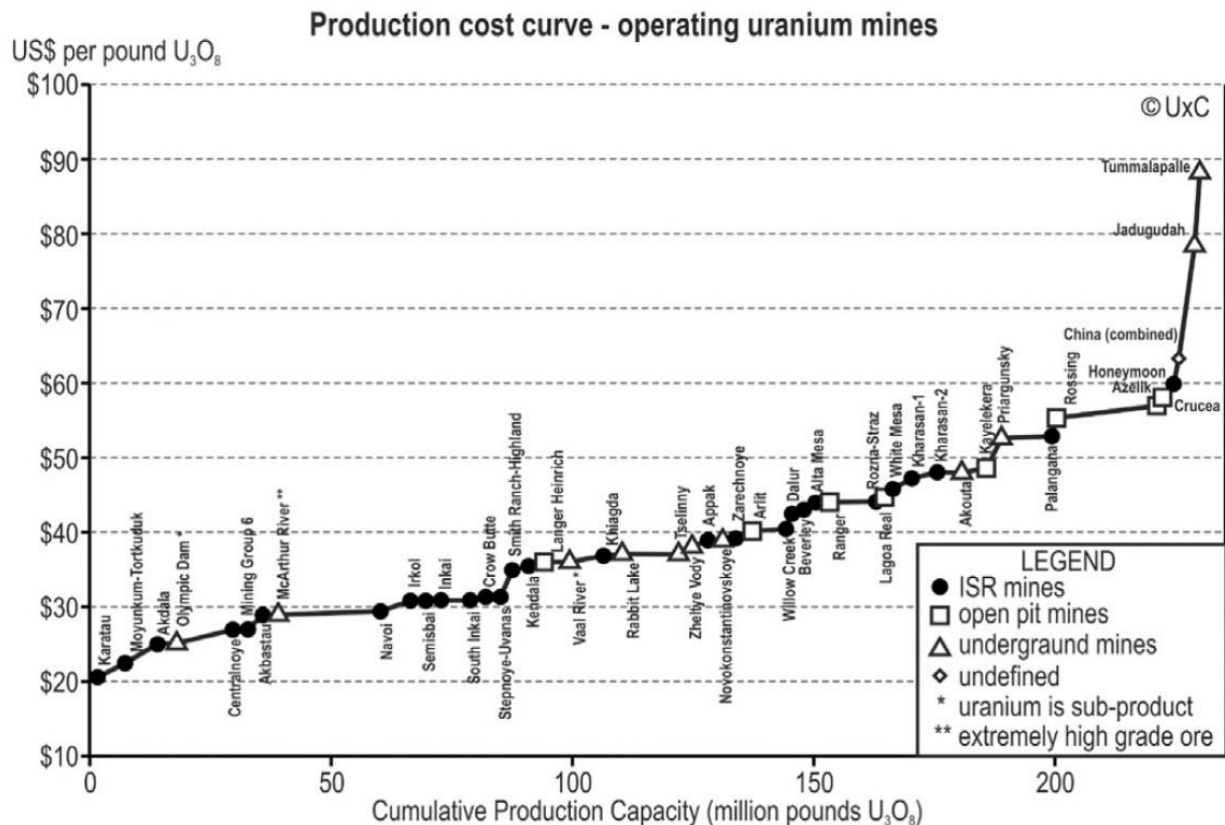


Figure 18: Operational expenditures for uranium deposits using ISL / ISR, surface or underground mining method (Boytsov 2014).

#### 4.4 Economic related overview of geothermal brine composition and extraction pilot plants

Geothermal brines often contain a lot of dissolved minerals, in some cases even in interestingly high concentrations. Probably the most comprehensive database (almost 2300 samples) of geothermal brines composition for the whole U.S territory (Figure 19) was collected by Neupane and Wendt (2017) and the database is publicly available at OpenEI data repository from following URL:

[http://gdr.openEI.org/files/194/GEOTHERM\\_ALL.xls](http://gdr.openEI.org/files/194/GEOTHERM_ALL.xls)

Many operational geothermal power plants considered dissolved elements and metals (called also TDS – Total Dissolved Solids) in brines as a problematic issue rather than an economic benefit. Dissolved solids can precipitate in surface or near surface power plant equipment (in pipeline or heat exchanger, etc.) due to change in temperature and pressure conditions of geothermal brines. These so-called scaling issues can cause performance drop, increase OpEx or in the worst cases entail the suspension of whole power plant. Geothermal power plants are trying to avoid scaling by using copper-nickel alloys or e.g. by application of chemical precipitation inhibitors (Zarrouk et al. 2014).

Useful information related to the CHPM project are detailed analyses of brine composition from two operational EGS power plants located in the EU, Solutz-sous-Forêts and Rittershoffen, provided by studies of Sanjuan et al. (2010) and Mouchot et al. (2018). The highest concentration was measured for chlorine (more than 5% of the brine; 50-60 g/l) and sodium (about 2%; 20 g/l). Potassium and calcium reach concentrations in tenths of a percent; and strontium, lithium,



magnesium, bromine and sulphate ( $\text{SO}_4$ ) have concentrations in hundreds of ppm (mg/l). Other elements including also zinc or arsenic have at maximum a few ppm.

Mouchot et al. (2018) also studied the geochemistry of a black-grey metallic deposit found in the heat exchanger during a technological stop after a one-year operation of Soultz-sous-Forêts and Rittershoffen EGS power plants. The majority of the deposit, 30-70%, was composed of lead, followed by antimony at a stable concentration of 10%. But both the lead and the antimony do not appear in the chemical analyses of the brines, it means, that lead and antimony are not present in the brines or they are below the limit of detection). Mouchot et al. (2018) suggests that the origin of the metallic deposit is an electrochemical interaction between brine and steel (heat exchangers, pipelines).

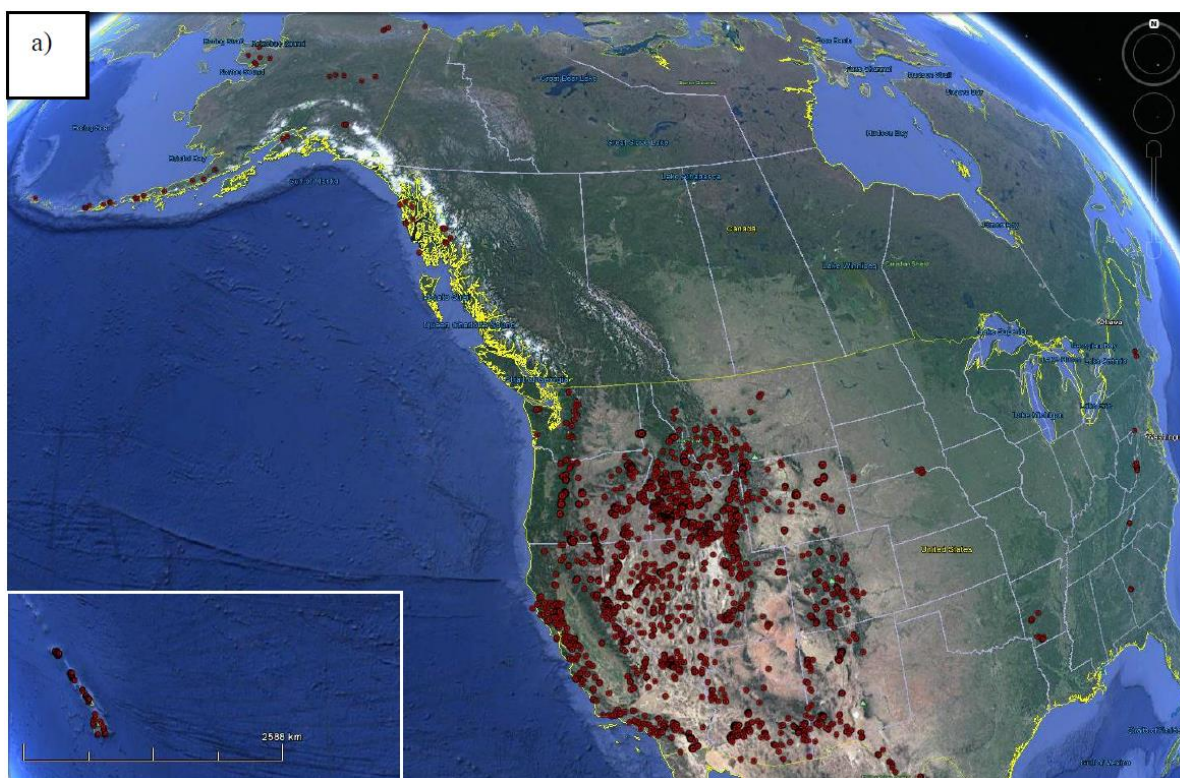


Figure 19: Locations of geothermal brines samples from the U.S. territory (Neupane and Wendt 2017)

Demonstration pilot plants for extraction of raw materials from geothermal brines can be considered as the technology the most similar to the metal extraction level of the proposed CHPM power plant. Several pilot plants were demonstrated or are in development at traditional geothermal regions (e.g. Salton Sea or Hot Creek in California, the U.S. or Taupa Volcanic Zone at the New Zealand).

#### 4.4.1 Silica

Geothermal brines very often contain a high concentration of dissolved silica, and a generally valid rule suggests that the silica content in geothermal brines increases with the increase of the geothermal brine temperature. Silica ( $\text{SiO}_2$ ) has a wide range of industrial uses; besides glass or the foundry industry, silica is also essential in the manufacture of silicon metal, one of the CRM for the EU.



The geothermal sites of Mammoth Lake and Dixie Valley (both in California, U.S) were identified for development of silica extraction plant. Calculations done for these sites used known CapEx and OpEx from drinking water treatment facilities (desalination) to assess costs for silica extraction (Bourcier et al. 2009). Even though they have different purposes, both facilities types are cleaning the water from dissolved particles. CapEx for silica extraction plant were estimated on 2.3 million USD and annual OpEx on 670 000 USD. The technology is considered the pre-concentrating of silica to 600 ppm via reverse osmosis and flow rate of 79 l/s. Total net profit for this scenario was calculated on 400 000 USD per year with 14% rate of return and pay-out in 7th year (Bourcier et al. 2009).

According to Bourcier et al. (2009), silica extraction would have a positive effect on LCOE with an offset of more than 1 ¢/kWh. In such conditions and with the implementation of EGS power plants (Mammoth Lake is conventional geothermal site), extraction of silica would help fulfilling the strategic goal of US DOE in decreasing LCOE for EGS.

Probably on the best manner to implement the first commercial scale operation for silica extraction is New Zealand based company Geo40 Ltd. The company had tested some technology for silica extraction on several conventional geothermal sites in the Taupo Volcanic Zone, namely at Wairakei and Kawerau pilot plants (Geo40). Recently, they have been planning to start the operation of the first commercial plant for silica extraction at Ohaaki (Taupo Volcanic Zone, New Zealand), which should start its silica production in August 2018 (NZ Herald 2018).

#### 4.4.2 Lithium

Lithium is another raw material which is considered as suitable for extraction from geothermal brines, because it is commonly present in brines and in high market demand. The global demand in lithium carbonate equivalent (LCE)<sup>10</sup> reached more than 230 thousand metric tons in 2017 and future projections suggest almost double that amount toward 2030 (Statista 2018a). The price of lithium carbonate has recently been changing quite fast, from 7 500 USD per ton of  $\text{Li}_2\text{CO}_3$  to an estimated 13 500 USD per ton of  $\text{Li}_2\text{CO}_3$  in 2017 (Statista 2018b). The price has even been breaking the 20 thousand USD level (Els 2018).

Probably well-known pilot plant for lithium extraction from geothermal brine was the Simbol operation plant at the Salton Sea conventional geothermal site (California, U.S.). Salton Sea brine is quite exceptional among other brines with its very high lithium concentration at 90-440 ppm or mg/kg (Neupane and Wendt 2017). Simbol Mining Corp. (Simbol) intention was to build a processing plant based on novel technology which would



Figure 20: Ohaaki silica extraction pilot plant (Geo40)

<sup>10</sup> All traded forms of lithium (Li hydroxides  $\text{LiOH}$ , Li oxides  $\text{Li}_2\text{O}$ , Li metal, Li chloride  $\text{LiCl}$ ) recalculated for the price of lithium carbonate ( $\text{Li}_2\text{CO}_3$ ), which is the most common marketable form of lithium

produce 16 000 tons of LCE/year, 8 000 tons of zinc and 24 000 tons of manganese dioxide from each of the four planned 50 MW power plants in the Salton Sea area (Harrison 2011). Simbol raised some private funds, also applied to additional funding from US DOE (30% share) but after a few years of development and positive technological reports, the company become insolvent and ceased operation at the Salton Sea geothermal area and gone into receivership (Roth 2017).

Formal Simbol property was acquired by the new company – Alger Alternative Energy, LLC, which signed a development agreement with the new owner of the geothermal exploration licences at Salton Sea, the Australian company Controlled Thermal Resources which is planning to build 280 MW geothermal plant (Roth 2017). Alger Alternative Energy has very ambitious goals, and signed contracts with one U.S. technology company and one state-owned Chinese energy company to start with 60 000 tons of  $\text{Li}_2\text{CO}_3$  per year (Roth 2017). Such production would take care of almost one quarter of whole annual demand, which would have a large impact on the lithium market. However, the whole project is currently in its early exploration phase.

Another economic calculation for lithium extraction from geothermal brines was done as part of the “From Waste to Wealth” project aiming at the assessment of the possibilities of metal extraction from geothermal brines in the Taupo Volcanic Zone in New Zealand (GNS Science 2015). Robinson (2015) calculated a lithium concentration of only 11 ppm (mg/kg), which is considered as average concentration for Wairakei geothermal site. They are calculating with a total geothermal fluid flow at 180 000  $\text{m}^3/\text{day}$  (more than 2000 l/s) from the whole Wairakei site. This would yield 3200 tons of  $\text{Li}_2\text{CO}_3$  per year, and assuming 20 thousand USD per ton of  $\text{Li}_2\text{CO}_3$  it would create a cash flow of 64 million USD (efficiency factor at 85%). Using a comparison with CapEx and OpEx of electrodialysis desalination water treatment plants capable of processing similar amount of water, the costs of the theoretical Wairakei processing plant were calculated on 96 million USD of CapEx and 12 million USD of OpEx (Robinson 2015). This theoretical scenario suggests that the operation is feasible; however, the project was not primarily focused on the metal extraction technology.

Secondly, lithium market and production are driven by so called salar brine (salt lakes) mining (especially Chile, China), which represents about half of annual lithium production. Such operations are using the salt evaporation ponds and are able to achieve a much lower cost per ton of produced lithium carbonate. Salar mining is on 2000 USD / ton, compared with 4000 USD / ton for extraction from geothermal brines based on electrodialysis technology (Robinson 2015). Also, Neupane and Wendt (2017) and Roth (2017) suggested that Simbol’s lithium extraction plant, which failed due to the lack of investors, could be influenced by market forces and competition raised by conventional lithium mining companies, that would not welcome a new large player on the lithium market.

#### 4.4.3 Precious metals

The US database of geothermal brines composition records some brines with known concentration of gold (4% of samples) and silver (7% of samples). The majority of these samples have content of both Au and Ag in the range of 0.01-0.1 ppm (mg/kg). Only a very few brines have higher content of precious metals, e.g. famous Salton Sea with a silver concentration of up to 1.4 ppm (Neupane and Wendt 2017).

Brown (2015) assessed potential of precious metals extraction from New Zealand's brines. He saw the main difficulty as the compatibility of extraction technology and operational geothermal power plant. His economic analysis suggests that the extraction of precious metals from geothermal brines as non-financially viable.

In contrast to silica or lithium extraction with some limited technological demonstrations, there was no pilot plant for precious metal extraction yet. The extraction of gold and silver from geothermal brines is on a very low technology readiness level.

#### 4.4.4 Other examples

The Tuscany, Italia geothermal region is known also for boron extraction from geothermal brines, namely at Larderello geothermal plant (Allegrini et al. 1992). However, the extraction method used at Larderello is based on the evaporation process (Neupane and Wendt 2017), which is quite different from the proposed CHPM extraction technology. Evaporation and salt evaporation ponds are also used in the production of lithium from salt brine lakes such as Salar de Atacama in Chile or Zabuye lake in China.

Another preliminary economic assessment was done for the potential extraction of rare earth elements (REEs) from geothermal brines (Stull 2016). His cost estimations for REEs extraction were about 90 USD per kg of blended REEs, but the price for blended REEs was only about 16 USD per kg in 2016. The recovery of REE from geothermal brines is not economic under current market prices.

#### 4.5 Conclusion of metal extraction level

In general, concepts of extraction of metals from geothermal brines are on lower technology readiness level (TRL 2-4). The TRL assessment was designed by the U.S. Department of Defense (ASD(R&E) 2011)). Basic definition of mentioned levels is as follow: TRL 2 – technology concept formulated; TRL 3 – analytical and experimental proof of concept; TRL 4 – technology validated in laboratory environment. Most of the projects are on laboratory scale; only a very few field demonstrations were or are tested for lithium and silica recovery (e.g. Geo40 Ltd. announcement of commissioning of silica extraction plant planned for August 2018). The Salton Sea brines have probably the richest concentrations of valuable metals from known geothermal brines with measured composition. Despite this fact, the pilot plant for lithium extraction failed due to lack of investments.

Demonstration projects for metals extraction such as Salton Sea lithium extraction run by Simbol and now by Alger Alternative Energy or silica extraction demonstrations developed by Geo40 are indicating that metal extraction concepts are mostly developed by another company, then a company which operates the linked geothermal power plant. It is probably due to high uncertainty of the project feasibility and subsequent security of necessary investment. Development of geothermal power plants have their own difficulties in raising an investment and a simultaneous development of infrastructure of extraction technology with untested commercial feasibility would not be helpful in convincing potential financiers about the benefits associated with their investments. In the above-mentioned cases, the energy companies agreed on cooperation, but did not enter into some kind of joint ventures.

On the other hand, if both development projects are searching investments independently, they are able to concentrate on details and address more specific investors or funding institutions. Still, the competitiveness level in the mining industry is very high and many investors would prefer projects with verified extraction technologies, which promise a higher chance for better return rate.

## 5 Final conclusions

The energy level of the CHPM technology is based on unconventional geothermal energy source, which can be utilized by EGS power plants. Concepts and types of EGS power plants are quite well defined from a technological point of view. Many research projects, including CHPM2030, are aiming at the development of novel technologies, which would help EGS to become a very common and effective source of energy. However, current LCOE for a different EGS scenarios is higher or at the same level as the current price of electricity for non-household consumers in the EU-28.

All of the operational EGS power plants in the World were financially subsidized by governmental institutions, even when the operator is a large company with high capital. The level of uncertainty and possible return rate is still quite low and thus willingness to invest to EGS projects is not high. The main barrier is a lack of historical data from long commercial operation of EGS power plants. The more EGS power plants will be put into operation, the higher will be an assurance of investment for EGS. Also, greater usage of the near field and in field concept of EGS (U.S. definition) would help for greater awareness, because in field EGS can be developed in a few years with much lower CapEx (Annex 3). Additionally, such EGS power plants are built in areas where local people and stakeholders have experience with geothermal infrastructure projects, which can facilitate the construction of the power plant.

Both the EU and the U.S. funded EGS related projects are aiming at the reduction of LCOE for EGS development to competitiveness level by 2030, which would shift EGS to economic feasibility and which would also correspond well with the time framework of CHPM2030 the project.

The metal extraction level of the CHPM technology is a type of in-situ recovery (ISR) or in-situ leaching (ISL) mining method. Direct comparison of mining methods is possible only in the case of the uranium mining industry, where all three main methods are commonly utilized. The ISR / ISL method comes out as the most cost-effective, however this method is using strong reagents for dissolving metals, not mild leaching reagents considered for a CHPM project. It is questionable if using a weaker reagent would not decrease cost-effectivity of this method in comparison with surface and underground mining.

Extraction of metals from geothermal brines are on low technology readiness level (TRL). At the moment, only the first pilot plants are in development or are about to start their operations. Commercial feasibility studies are based on laboratory scale experiments and theoretical calculations. Lack of historical data for economic calculations is even higher than in case of EGS power plants, because a several of the EGS power plants are already operating and now they are producing the data and experience needed for more precise economic assessments. Main barrier in economic feasibility assessments of metal extraction are unknown or ambiguously defined CapEx and OpEx for such technology. The CapEx and OpEx of many public available models and economic calculations are based only on derivation of costs from electrodialysis process which is similar technology used in

water treatment facilities. In some models, the costs for metal extraction operations were higher than a possible revenue obtained from extracted metals. Lower TRL and lack of data from at least a few years of operations make it very difficult to assess precise annual OpEx and other possible maintenance costs.

Secondly, all pilot plants or projects of metal extraction are now designed for conventional geothermal power plants (Alger Alternative Energy – Salton Sea, Geo40 – Ohaaki), which are able to achieve much higher total fluid flow from more wells, than a concept of mostly single production well of the EGS power plant. The economic assessment for lithium extraction from the entire Wairakei (NZ) geothermal site is counting with more than 2000 l/s (Robinson 2015), the Salton Sea calculations suggest an even higher total fluid flow (Neupane and Wendt 2017). Other studied general cost assessments are working with a processing capacity of several hundred liters per second. However, most of the EGS are working with fluid flow from tens to one hundred l/s. The CHPM concept is working with 50-60 l/s. This of course leads to much smaller amounts of possible extracted metals.

On the other hand, the composition of brines at two European operational EGS power plants, Soultz-sous-Forêts and Rittershoffen, have an economically interested concentration of e.g. lithium at 140 ppm or mg/kg (Mouchot et al. 2018), for comparison the Wairakei lithium extraction model calculated with only 11 mg/kg of lithium (Robinson 2015). Using the Rittershoffen data (fluid flow 73 l/s and efficiency factor at 85%), the annual production of lithium carbonate would be 1166 ton, which would create a revenue of more than 16 million USD per year at a conservative  $\text{Li}_2\text{CO}_3$  price of 13 900 USD/ton.

Assessments done for lithium recovery from geothermal brines suggests OpEx in ranges from 11 to 17 million USD per year for a larger extraction plant than would potentially be the one at Rittershoffen. This means that, that in the case of Rittershoffen, there would be some reduction in OpEx but still the revenue from lithium extraction would not be large enough to be considered as clearly economically feasible.

Substantial enhancing of lithium (or other metals) concentration by mild leaching reagents or increasing of fluid flow (operational capacity) would be necessary to achieve economic feasibility of such extraction operations. Field tests of the CHPM metal extraction technology on e.g. already operating EGS power plants or also conventional geothermal power plants would prove its cost-effectiveness in order to determine more accurate OpEx of the metal extraction operation.

The development of EGS power plants (energy level of CHPM) toward their 2030 commercial feasibility is well on track, supported by many governmentally funded technological projects and pilot plants. The metal extraction level of the CHPM, represented by in-situ recovery of metals from geothermal brines are still on a low technology readiness level, with only a few demonstration pilots in development. The new pilot plants at both conventional geothermal and unconventional EGS power plants can prove feasibility and profitability of metal extraction from geothermal brines.



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## 7 Annex 1

## Installed Capacity and Generation of Geothermal Energy in 28 EU member countries

Geothermal Energy	Installed Capacity in 2016		Power Generation in 2016	
	Electricity Generation (MWe)	Direct Use of Heat (MW <sub>th</sub> )	Electricity Generation (GWh/year)	Direct Use of Heat (GWh/year)
Austria	1.4	903	2.2	1814
Belgium	---	206	---	24
Bulgaria	---	93.1	---	340
Croatia	---	79.9	---	190
Cyprus	---	---	---	---
Czech Republic	---	305	---	498
Denmark	---	353	---	1043
Estonia	---	63	---	99
Finland	---	1560	---	5001
France	16	2350	115	4408
Germany	38	2850	98	5431
Greece	---	222	---	369
Hungary	---	906	---	2849
Ireland	---	266	---	344
Italy	824	1010	5920	2407
Latvia	---	1.6	---	9
Lithuania	---	94.6	---	198
Luxembourg	---	---	---	---
Malta	---	---	---	---
Netherlands	---	790	---	1779
Poland	---	489	---	762
Portugal	25	35.2	205	132
Romania	0.1	245	0.3	529
Slovakia	---	149	---	686
Slovenia	---	153	---	316
Spain	---	64.1	---	96
Sweden	---	5600	---	14421
United Kingdom	---	284	---	529
Total <sup>11</sup>	905 MWe	18851 MW <sub>th</sub>	6334 GWh/year	29485 GWh/year

<sup>11</sup> Data are for the year 2016, based on database of World Energy Council (World Energy Council 2018), rounded to whole numbers

## 8 Annex 2

## Installed capacity and generation of geothermal energy in other selected countries with developed geothermal energy sector

Geothermal Energy <sup>12</sup>	Installed Capacity in 2016		Power Generation in 2016	
	Electricity Generation (MW <sub>e</sub> )	Direct Use of Heat (MW <sub>th</sub> )	Electricity Generation (GWh/year)	Direct Use of Heat (GWh/year)
Iceland	665	2040	5234	7420
Norway	---	1300	---	2291
Switzerland	---	1730	---	3291
Turkey	624	2890	2361	12560
China	27	17900	145	48380
Japan	533	2190	2605	7257
South Korea	---	836	---	746
Philippines	1930	3.3	10304	11
New Zealand	979	487	7257	2396
Indonesia	1400	2.3	10037	12
Australia	2.1	16.1	0.5	54
India	---	986	---	1198
Kenya	607	22.4	3175	51
Brazil	---	360	---	1838
Mexico	1070	156	6001	1158
United States	3570	17400	16747	21050
Canada	---	1470	---	3222

<sup>12</sup> Data are for the year 2016, based on database of World Energy Council (World Energy Council 2018)

## 9 Annex 3

## EGS power plants in operation / in developed – Economic information

EGS power plants	Status	Requirements (millions USD)	Governmental Subsidy	Note, reference
Europe				
Soultz-sous-Forêts (France)	In operation, 2007, 1.5 MW <sub>e</sub> .	Incentives and grants up to 94 million USD. Late stages co-funded by industry (BINE 2009)	Public funds from France, Germany, EU and Switzerland	EEIG "Heat Mining" - industrial consortium: Electricité de Strasbourg, Electricité de France, EnBW and BESTEC (BESTEC 2018)
Landau (Germany)	In operation, 2007, 3.8 MW <sub>e</sub> / 3 MW <sub>th</sub>	Approx. 24 million USD (Bine 2007)	12 million USD (Brüns et al. 2011)	geo x GmbH, subsidiary of Geysir Europe GmbH (BESTEC 2018)
Insheim (Germany)	In operation, 2012, 4.3 MW <sub>e</sub> / production of heat is planned	Not available	Not available	Pfalzwerke geofuture GmbH, subsidiary of Pfalzwerke Aktiengesellschaft (BESTEC 2018)
Groß Schönebeck (Germany)	In development since 2002, drilling of third well	GFZ – Federal research organization	16.5 million USD (Brüns et al. 2011)	GFZ Helmholtz Centre Postdam
Rittershoffen (France)	In operation, 2016 24 MW <sub>th</sub> for industrial site	65 million USD	47 million USD	40% Électricité de Strasbourg, 40%Roquette and 20% Caisse des Dépôts (Roquette 2016)
Eden (UK)	In development since 2010, goal: 4 MW <sub>e</sub>	41 million USD (METRIC 2018)	Application for 2 million USD (Whitehouse 2018)	EGS Energy Ltd. (EGS Energy 2012)
United Downs (UK)	In development since 2018	24 million USD	17 million USD	Geothermal Engineering Ltd (2018)
The United States of America				
Desert Peak (Nevada)	In operation, 2013, joined to national grid 1.7 MW <sub>e</sub>	7.6 million USD	5.5 million USD	<u>In field EGS</u> ; Ormat Technologies Inc. (Chabora and Zemach 2013)
Newberry Volcano (Oregon)	In development since 2009	44 million USD	21 million USD	<u>Greenfield EGS</u> ; AltaRock Energy (Petty 2013)
The Geysers (California)	In operation, 2013, dry 5 MW, dry steam generation	13 million USD	6 million USD	<u>Near field EGS</u> ; Calpine Corporation (Walters 2013)
Raft River (Utah)	In development since 2008 (goal: 5 MW by 2020)	10 million USD	8.6 million USD	<u>Near field EGS</u> ; University of Utah (Moore and McLennan 2013)
Bradys field (Nevada)	In development since 2008 (goal: 2-3 MW)	6.4 million USD	4.4 million USD	<u>In field EGS</u> ; Ormat Technologies Inc. (Snyder and Zemach 2013)
Australia				
Habanero (Queensland)	Closed after successful test of 1MW <sub>e</sub> (in 2013)	108 million USD	25 million USD	Geodynamics Ltd. (ARENA 2016)

Asia				
Pohang (South Korea)	1.5 MW <sub>e</sub> demonstration in 2017 (Lu 2018)	38 million USD	16 million USD	NexGeo; operation suspended, investigation of possible induced seismicity (Grigoli et al. 2018)