DEVELOPMENT OF NOVEL AND COST-EFFECTIVE CORROSION RESISTANT COATINGS
FOR HIGH TEMPERATURE GEOTHERMAL APPLICATIONS

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# D9.3: Impact of Geo-Coat on the sustainability of geothermal power

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DEVELOPMENT OF NOVEL AND COST-EFFECTIVE CORROSION RESISTANT COATINGS FOR HIGH TEMPERATURE GEOTHERMAL APPLICATIONS

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# Executive Summary

This document describes the Geo-Coat impacts on the sustainability of Geothermal power and the potentialities of Geo-Coat technology for improving the growth of geothermal power in Europe and beyond. Sustainability of Geo- Coat is discussed in context to conventional power plants. Potential applications of Geo-Coat in some of the top geothermal power producing countries worldwide are also studied. Impacts of Geo-Coat in remote and underdeveloped areas in reducing electricity cost are also studied. The role of Geo-Coat to develop an overall acceptable Feed-In-Tariff scheme is also considered to draw the attention of geothermal investors in the future. The Geo-Coat technologies have been developed through Geo-Coat project and designed to protect the geothermal components from corrosion, scaling and erosion damages. Applications of the Geo-Coat technology on geothermal components as it enables to exploit corrosive and aggressive geofluid from medium to high temperature geothermal fields to generate electricity. A double flash perspective geothermal power plant with the adoption of the best candidate Geo-Coat technology LC_HEA2 instead of recommended state of art (SOA) materials for geothermal components (surface pipes, well casings and turbine components) showed a levelised cost of energy (LCOE) reduction of about 91% and demonstrated overall environmental footprints savings of about 60%. It is noted that the physical sizes of the components have only been considered from the double flash geothermal power plant, but the actual materials used in that plant have not been considered for the studies. The results of these LCOE and environmental footprint studies demonstrate the potentialities of Geo-Coat technology for improving the economic and environmental performances and thereby enhance the growth of geothermal power for medium to high temperature geothermal fields in European and other countries.

**Objectives met:**

The current deliverable contributes towards the following work package objectives:

Demonstrate the potentialities of Geo-Coat to enhance the sustainability and growth of the geothermal power.

# CONTENTS

# 1. INTRODUCTION

Large-scale geothermal power development is currently limited to tectonically active regions such as areas near plate boundaries, rift zones, and mantle plumes or hot spots. These active, high heat-flow areas include countries around the 'Ring of Fire' (Indonesia, The Philippines, Japan, New Zealand, Central America, and the West Coast of the United States) and rift zones such as Iceland and East Africa. These areas are the most promising for geothermal development in the next decade, with a potential increase of geothermal power plant running capacity from 12.7 $GW_e$ in 2017 to 32 $GW_e$ in 2030[2]. If technological advancements made new geothermal power technologies available such as Enhanced Geothermal System (EGS), then geothermal power might expand to other regions and commercial geothermal capacity could increase beyond 32 $GW_e$.

One of the key factors in increasing the output of geothermal systems is obtaining higher enthalpy fluid which could be obtained by drilling deeper wells in the Ring of fire and other tectonically active regions. But, as we move to deeper geothermal resources, geofluids become more aggressive due to high temperature and pressure and corrosive put the efficiency and longevity of the plant components at risk. The new coating materials and methodologies have been developed through the Geo-Coat project and designed to protect different parts and components in the geothermal power plant particularly from different types of corrosion, erosion and scaling damages. Geo-Coat technology can be applied on steam turbines, surface pipes, pumps, heat exchangers and well casings to extend their lifetime and reliability. The best candidate of Geo-Coat technology LC_HEA2 for surface pipes, well casings and turbine components has been obtained based on the results and analyses from the assessments of flow through and static corrosion, erosion-corrosion, stress corrosion cracking, permeability and mechanical & tribological measurements that can be used in future geothermal power plants as an alternative to highly recommended state of art (SOA) materials to exploit the corrosive and aggressive nature of geofluid from medium to high temperature and deep geothermal resources. This innovative Geo-Coat technology could increase the lifetime of geothermal components, and lead to a reduction in downtime and maintenance costs, thereby enhancing the sustainability and growth of the geothermal power. It not only reduces costs (CAPEX and OPEX), but also reduces environmental footprints for geothermal power plants operating with medium to high temperature and highly corrosive deep geothermal resources.

The CAPEX and OPEX reduction potentialities of Geo-Coat will certainly encourage the current operator regarding geothermal power to expand their existing capacity or to invest on new projects which will subsequently create more jobs in the EU. It has been demonstrated in Geo-Coat deliverable D9.1 that the adoption of the best candidate Geo-Coat technology LC_HEA2 instead of recommended SOA materials for pipes, well casings and turbine rotors and blades components showed a LCOE reduction of 91% for Icelandic (double flash) power plant perspectives. Benefits from Geo-Coat technologies are expected to be greater for a larger capacity of plant.

As elaborated in Geo-Coat deliverable D9.2, with the adoption of the best candidate Geo-Coat technology instead of recommended SOA materials for pipes, well casings and turbine rotors and blades components, the environmental footprint savings of about 60% for Icelandic (double flash) geothermal power plant perspectives. Geo-Coat technology will save 276 t $CO_2$ eq for every MW geothermal power installation, which means for a growth rate of geothermal plant capacity of 1GW/year in Europe, 276,000 tonnes of $CO_2$ eq emission per year

[2] Renewables Information 2018. International Energy Agency (IEA), Paris. Available at: http://www.oecd-ilibrary.org/energy/renewables-information-2015_renew-2015-en; accessed on 24 April 2021.

will be saved from the adoption of Geo-Coat concept and for the rest of the world this figure will be at least three times higher. Recently, a research by European Commission scientists predicted that, extreme weather could kill 150,000 people each year in Europe by the end of the century[3]. Geo-Coat will enhance the growth of geothermal power with reduced environmental impact and hence, Geo-Coat will significantly contribute to address the predicted social disaster.

In section 2, comparisons were drawn with fossil fuels base load power plants and how Geo-Coat will affect the geothermal power generation sector have been mentioned. Economic and environmental impacts of geothermal power generation have also been discussed. In section 3, the potentialities of Geo-Coat technology in Europe and the rest of the world have been discussed. Countries with underdeveloped geothermal potential and high energy cost and lower feed-in-tariff were also discussed where Geo-Coat technology can produce an impact in the future geothermal power development. The results and findings were concluded in section 4.

[3] www.independent.co.uk/environment/deaths-year-climate-change-global-warming-extreme-weather-events-2100-150000-a7877461.html; accessed on 24 April 2021.

# 2. GEO-COAT IMPACTS ON THE SUSTAINABILITY OF GEOTHERMAL POWER

## Economic and environmental Impacts of Geo-Coat Technology

Fossil fuels account for the majority of energy consumption around the world. The term 'fossil fuel' is broad and consists of many individual fuels such as coal and coal products, petroleum, crude oils, oil shell and oils sands etc. In 1990, fossil fuels provided more than 82% of gross available energy in Europe. This value has been declining since then and by 2019 has reached around 70%.[4] Currently, fossil fuel provides 85% of total global energy demand and by 2040 the value is expected to be 60%. [5]

Figure 1 shows a projection of electricity generation capacity from 2018-2050. By 2050, it is estimated that worldwide electricity generation capacity will be more than 12000 GW.[6]

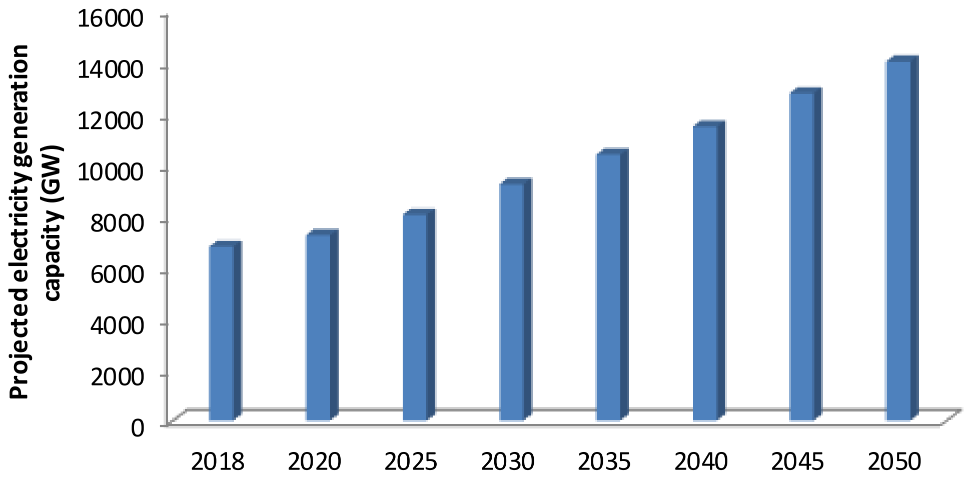


**Figure 1 -** Worldwide projected electricity generation capacity by 2050

Geothermal is a cleaner source of energy compared to fossil fuels. Geofluids comprising a variable quantity of gases, largely nitrogen and carbon dioxide, with some hydrogen sulphide and smaller percentages of ammonia, mercury, radon and boron. The amounts depend on the geological conditions of the geothermal fields. Most of the chemicals are concentrated in the disposal water which is routinely re-injected into the reinjection wells and thus not released into the environment. The range of $CO_2$ emissions from high-temperature geothermal fields used for electricity production is variable, but much lower than that for fossil fuel plants[7]. Geothermal

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[4] 'Share of Fossil Fuels in Gross Available Energy - Products Eurostat News - Eurostat' <https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20210204-1> [accessed 11 May 2021].

[5] 'Publications - The Future of Fossil Fuels' <https://www.copenhageneconomics.com/publications/publication/the-future-of-fossil-fuels> [accessed 11 May 2021].

[6] 'Electricity Generation Capacity Globally 2050 | Statista' <https://www.statista.com/statistics/859178/projected-world-electricity-generation-capacity-by-energy-source/> [accessed 11 May 2021].

[7] World Energy Resources: Geothermal; World Energy Council 2013; https://www.worldenergy.org/assets/images/imported/2013/10/WER_2013_9_Geothermal.pdf; accessed on 11 May 2021.

plants emit about 97 % less sulphur compounds and about 99 % less $CO_2$ emission compared to fossil fuels. [8] Hence, the low emission levels of geothermal energy have less negative impact on the environment.

Coal power plants are one of the most prominent examples of base load power plants. Half of Europe's 324 coal based plants have closed or announced retirement before 2030, emissions being the main reason. [9] Germany and Poland are responsible for 51% of EU's installed coal capacity and 54% of coal based emissions.[10]

In 2019, U.S coal-fired electricity generation was the lowest in 42 years.[11] According to U.S Energy Information Administration (EIA), since 2011, 121 coal based power plants were replaced or repurposed into natural gas based combined cycle power plants. Multiple reasons contributed to such decision such as strict emission policy, low natural gas price and more efficient gas turbine technology. However, since gas plants act as peak load plants, but they are incapable of meeting the base load demand.

Geothermal energy is not in the limelight like wind and solar since it is rumoured to be riskier than the other alternatives. It envisages some danger images like earthquakes, volcanoes, explosions those contributed to a distorted societal and political perceptions. Several measures such as public awareness programmes must be taken to ensure it is not only clean energy but also secure. To meet up the upcoming energy demand, alternate sources of energy must be sought out. Geothermal energy will be at high demand in the future due to it being one of the only few renewable sources that can handle base load. At the end of 2019, geothermal deployment accounted for 0.5% of the total installed capacity of renewable energy, worldwide, with a total installed capacity of 13.9 GW[12]. Bertani (2003)[13] found that, based on a compilation of estimates produced by a number of experts, the expected geothermal electricity potential ranges from a minimum of 35–70 $GW_e$ to a maximum of 140 $GW_e$. The potential may be orders of magnitude higher, based on enhanced geothermal systems (EGS) technology. Stefansson (2005)[14] concluded that the most likely value for the technical potential of geothermal resources suitable for electricity generation is 210 $GW_e$. Theoretical examinations indicate that the magnitude of hidden resource can be 5–10 times larger than the estimate of identified resources. Right now, only a small fraction of geothermal potential has been explored and exploited. High exploration, drilling, production costs, environmental misconceptions, public perceptions and support, corrosive nature of geothermal fluid, lack of knowledge of the benefits of development and utilisation etc. are some of the hurdles that are preventing the blooming of geothermal power generation.

[8] 'Geothermal Energy and the Environment - U.S. Energy Information Administration (EIA)' <https://www.eia.gov/energyexplained/geothermal/geothermal-energy-and-the-environment.php> [accessed 16 May 2021].

[9] 'Europe Halfway towards Closing All Coal Power Plants by 2030 – EURACTIV.Com' <https://www.euractiv.com/section/climate-environment/news/europe-halfway-towards-closing-all-coal-power-plants-by-2030/> [accessed 11 May 2021].

[10] 'EU Coal Phase Out / Climate Analytics' <https://climateanalytics.org/briefings/eu-coal-phase-out/> [accessed 11 May 2021].

[11] 'U.S. Coal-Fired Electricity Generation in 2019 Falls to 42-Year Low - Today in Energy - U.S. Energy Information Administration (EIA)' <https://www.eia.gov/todayinenergy/detail.php?id=43675> [accessed 11 May 2021].

[12] IRENA Renewable Power Generation Costs in 2019, IRNEA2022; www.Irena.org; accessed on 16 May 2021

[13] Bertani, R., 2003. What is Geothermal Potential? IGA News, 53, 1-3. http://iga.igg.cnr.it.

[14] V Stefansson, World Geothermal Assessment, Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005. https://orkustofnun.is/gogn/Greinargerdir/Jardhitavettvangur/World-geothermal-assessment-VS.pdf; accessed on 11 May 2021

The LCOE of geothermal plants vary depending on the plant type and geothermal resource temperatures. To meet the upcoming demand, high temperature geothermal resources must be utilised. Deep geothermal and EGS will be 2 main methods to ensure this. The projected value for LCOE of deep geothermal and EGS up to 2050 is more than 500 $/MWh which is not economically viable. [15] The overall cost of geothermal power is expected to increase more depending on the corrosive nature of geothermal resources which would require the application of highly recommended SOA materials.

Geo-Coat aims to reduce the cost of geothermal power providing better corrosion resistance compared to highly recommended SOA materials and to make geothermal energy economically and environmentally more attainable worldwide. In Geo-Coat D9.1, the economic impacts of the adoption of both Geo-Coat technology and the recommended state of art (SOA) materials for geothermal components have been analysed, while in D9.2 the environmental footprints of the best candidate Geo-Coat technology adoption alternative to recommended SOA materials for geothermal components have been evaluated, by a cradle to gate Life cycle assessment (LCA) approach. One double flash (Icelandic perspective) geothermal power plant has been considered for both the evaluation of economic and environmental impacts with and without adoption of Geo-Coat technology for pipes, turbine rotors, blades and well casings components. Note that only the physical sizes of the components, not the material selection, is considered from the Icelandic geothermal power plant for the Icelandic perspective study. The recommended SOA materials are therefore not representative of the material choices utilized at the Icelandic power plant.

The LCOE study shown in Figure 2 that the best candidate Geo-Coat technology (LC_HEA2) instead of recommended SOA materials for geothermal components offer the best cost in terms of economic performance and reduce LCOE for the Icelandic (ICS) and Romanian (RCS) perspectives. This is due to the lower cost, corrosion and erosion rates of the best ranked coating. The study also shows that the benefit from Geo-Coat is higher for larger plant size.

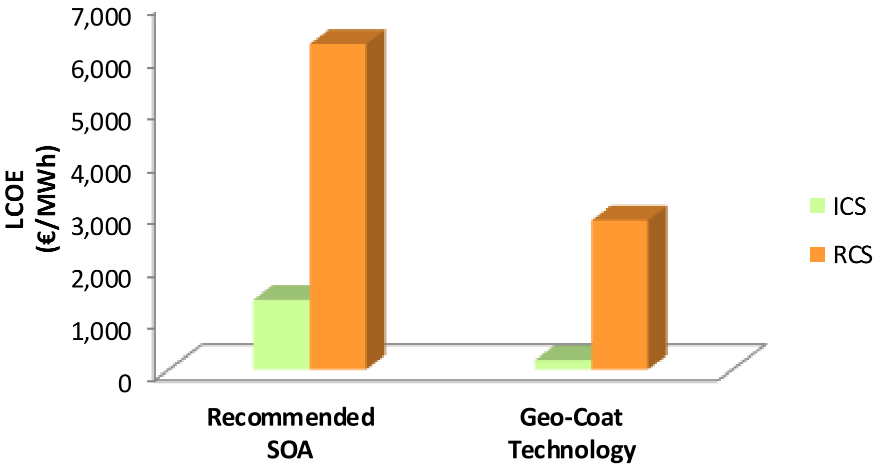


**Figure 2 -** LCOE comparisons of Geo-Coat technology with recommended SOA materials.

[15] '2019 Electricity ATB - Geothermal' <https://atb.nrel.gov/electricity/2019/index.html?t=gt&s=pr> [accessed 11 May 2021].

The LCOE analysis performed was hypothetical. Moreover, material and equipment costs were estimated based on laboratory scale. So actual LCOE will be much lower than the projected value. It is expected that mass scale production may reduce the actual cost making Geo-Coat technology commercially more attractive.

In Geo-Coat D9.2, the environmental impacts have been evaluated with and without adoption of the best candidate Geo-Coat technology for pipes, turbine rotors, blades and well casings of a geothermal power plant. The functional unit of the LCA impact study has been taken as 1 MW installed capacity of the plant. Figure 3 shows the single score results for 1 MW installed capacity with Geo-Coat technology and recommended SOA materials adopted for pipes, well casings, turbine rotors and turbine blades of the Icelandic perspective power plant. Icelandic (double flash) perspective geothermal power plant with the adoption of the best candidate Geo-Coat technology instead of recommended SOA materials demonstrated overall environmental footprints savings of about 60%. The results of this study demonstrate the potentialities for Geo-Coat technology to enable the design of green and sustainable components for future geothermal power plants.

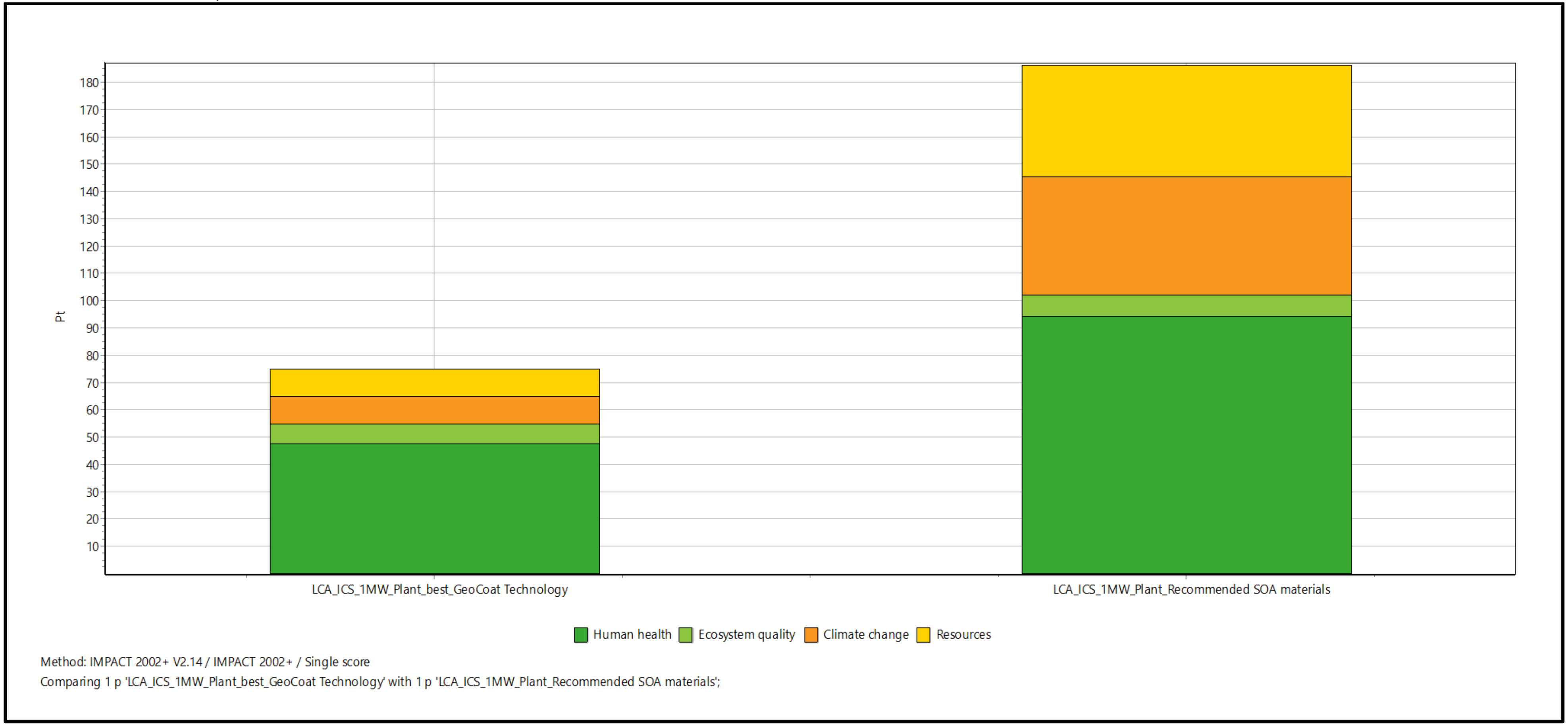


**Figure 3 -** Comparisons of single score results for 1 MW installed capacity with Geo-Coat technology and recommended SOA materials using Icelandic perspectives power plant.

# 3. GEO-COAT POTENTIALITIES

In this section potential application of Geo-Coat technology around different regions of the world have been discussed. Geothermal enriched countries in Pacific Ring of Fire, Asia, Europe, America, Africa have been identified and their potentialities have quantified based on their current power generation capacity and future projection.

## Ring of Fire

The ring of fire refers to a string of volcanoes and sites of seismic activity or earthquakes around the edges of Pacific Ocean. It is shaped like a 40000 km horseshoe. Total 452 volcanoes stretch from the southern tip of South America up along the coast of North America across the Berning Strait down through Japan and into New Zealand. [16]

Formation of ring of fire is considered as the result of tectonic plates. 2 main types of tectonic plate boundary, convergent and divergent are associated with geothermal resources.


**Figure 4 -** Major countries with geothermal potential in ring of fire

In 2020, 6 out of the top 10 geothermal power producing countries around the world were from the ring of fire region. [17]

[16] 'Plate Tectonics and the Ring of Fire | National Geographic Society' <https://www.nationalgeographic.org/article/plate-tectonics-ring-fire/> [accessed 12 April 2021].

[17] 'Top 10 Geothermal Countries 2020 – Installed Power Generation Capacity (MWe) | ThinkGeoEnergy - Geothermal Energy News' <https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2020-installed-power-generation-capacity-mwe/> [accessed 22 April 2021].

# European Scenarios

In terms of direct use of geothermal energy, Europe is leading the world.[18] However, geothermal power production in Europe is growing, both in the traditional high-enthalpy areas, and in the low-medium temperature resources through the extensive utilization of binary plants technologies. The number of European countries having operational geothermal power plants has been raised to 10, a number expected to further rise to 17 by 2025[19]. In the EU, the installed geothermal electricity capacity in 2018 was 1024 $MW_e$ with 56 geothermal power plants in operation[20]. According to EGEC Geothermal market report 2020, the newly installed capacity for electricity production in 2019 is 754 $MW_e$, brought a total generation capacity to 3300 $MW_e$ with 130 geothermal power plants operating across Europe. It is anticipated that the number of operating power plants could be double within 5-8 years[21]. The average growth rate of geothermal power production in Europe during 1999-2019 period is about 11.5%.

## Iceland

Iceland has a geothermal capacity of 755 $MW_e$ and is ranked 9$^{th}$ in the world.[17] Iceland almost exclusively utilizes renewable energy where hydroelectric and geothermal energy are the main sources of electric power, providing around 70% and 30% of total generation, respectively.[22] Geothermal energy accounts for about 65% of primary energy use in the country[23] and 90% of all buildings in Iceland are heated through utilizing this energy source.[24]

Iceland is located on the Mid-Atlantic ridge where the Eurasian and North American plates are diverging at a rate of around 2 cm per year. This explains the high tectonic activity and accessibility of the country to high temperature geothermal sources. There are both high and low temperature zones around the country and there are 3 main geothermal sites; the Krafla area, the Reykjanes area and the Hengill area. According to estimations the total capacity for electrical power generation ranges from 2550-7660 $MW_e$ and there is therefore considerable room for further utilization.[25]

Most geothermal wells in Iceland have a maximum temperature around 250-300°C and a typical Icelandic geothermal high temperature well is drilled down to 1500 - 3000 meters. More extreme scenarios can however be encountered and the first such project in Iceland, the Iceland Deep Drilling Project (IDDP), drilled a well that

[18] Beata Kępińska, 'Geothermal Energy Use in Europe - Geothermal Training Programme of the United Nations University Anniversary Workshop', *Geothermal Training Programme*, 2008, 14 <http://www.os.is/gogn/unu-gtp-30-ann/UNU-GTP-30-40.pdf>.accessed on 12 April 2021

[19] B Sanner, Summary of EGC 2019 Country Update Reports on Geothermal Energy in Europe; European Geothermal Congress 2019; Den Haag, The Netherlands, 11-14 June 2019.

[20] T Garabetian, reviewed by P Dumas; Report on competitiveness of geothermal industry; D4.6; Grant agreement No. 773392 — DG ETIP; 2019.

[21] EGEC Geothermal market report 2019, nineth edition June 2020

[22] Orkustofnun (2020). OS-2020-T012-01: Installed capacity and electricity production in Icelandic power stations in 2019. <https://orkustofnun.is/gogn/Talnaefni/OS-2020-T012-01.pdf>

[23] Orkustofnun (2020). OS-2020-T007-02: Primary Energy Use in Iceland 1940-2019 [data file]. <https://orkustofnun.is/gogn/Talnaefni/OS-2020-T007-02.pdf>

[24] Orkustofnun (2020). OS-2020-T008-01: Space heating in Iceland by energy source 1952-2019 [data file]. <https://orkustofnun.is/gogn/Talnaefni/OS-2020-T008-01.pdf>

[25] 'Preparing for WGC 2020 – Iceland's Geothermal Resources & Potential | ThinkGeoEnergy - Geothermal Energy News' <https://www.thinkgeoenergy.com/preparing-for-wgc-2020-icelands-geothermal-resources-potential/> [accessed 22 April 2021].

reached wellhead temperatures around 450°C from a depth of approximately 2km.[26] Estimated power generation from one such well is 30-60 $MW_e$, which is ten times greater than a normal high temperature well in Iceland can produce. IDDP is contributing to the next generations of well development. Iceland is currently working on expanding geothermal resources and the next IDDP well will be drilled in the Hengill area, owned by ON Power.

## Romania

Coal and gas are the main sources of power in Romania with 14002 GWh and 10258 GWh produced respectively in 2018.[27] Primary usage of geothermal energy is Romania is through district heating. Currently one 50 kW binary ORC (Organic Rankine Cycle) plant is operational since 2012.[28]

## Germany

Germany focuses on direct use of geothermal energy, more than power generation. Due to geological location, Germany lacks steam dominated reservoirs that can drive turbines. The geothermal electricity generation is based on the use of binary cycle (both Kalina and ORC) which allows power production at around 100 $^0$C. At the end of 2018, 190 geothermal installations provided geothermal energy for direct use. At the end of 2019, 10 geothermal plants with installed capacity of 43.05 $MW_e$ fed into German grid. Total geothermal power production in 2018 was 165.6 GWh.[29]

Most of the geothermal plants are located at Molasse Basin in Southern Germany, North Germany Basin and upper Rhine Graben. These three are the main resource for deep geothermal water.[30]. The technical potential of geothermal power is estimated to be 15-132 TWh. Most of the major combined heating and electricity plants are operating in the state of Bavaria.[31]

Using EGS in tight sedimentary and crystalline rocks can provide geothermal energy as an option in regions without hydrothermal resources.

## Turkey

Turkey achieved 4$^{th}$ position in 2020 with1526 $MW_e$ installed geothermal capacity.[17] In 2019, total 55 geothermal power plants were operational. 450 geothermal fields have been discovered. Exploration for deep geothermal resources have been performed which resulted in the discovery of reservoir with temperature around 240 $^0$C. The Manisa-Alasehir geothermal field contains geothermal fluid of around 287 $^0$C while 295 $^0$C

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[26] W.A. Elders, G.Ó. Friðleifsson, and G. Bignall, 'SAGA REPORT No 9', 2012. <http://iddp.is/wp-content/uploads/2012/09/SAGA_Report_2012.pdf>

[27] 'The Energy Sector in Romania - Bankwatch' <https://bankwatch.org/beyond-coal/the-energy-sector-in-romania> [accessed 16 May 2021].

[28] 'Four Areas for Potential Geothermal Power Generation Discovered in Romania | ThinkGeoEnergy - Geothermal Energy News' <https://www.thinkgeoenergy.com/four-areas-for-potential-geothermal-power-generation-discovered-in-romania/> [accessed 25 April 2021].

[29] Josef Weber and others, 'Geothermal Energy Use in Germany , Country Update 2015-2019', *World Geothermal Congress*, 2020, 1–15.

[30] 'Geothermal Energy – Germany's Largely Untapped Renewable Heat Source | Clean Energy Wire' <https://www.cleanenergywire.org/factsheets/geothermal-energy-germanys-largely-untapped-renewable-heat-source> [accessed 25 April 2021].

[31] 'Opportunities Geothermal Energy in Germany | Global Law Firm | Norton Rose Fulbright', h*ttps://www.Nortonrosefulbright.Com /En/Knowledge/Publications/Imported/2018/07/18/05* <https://www.nortonrosefulbright.com/en/knowledge/publications/3e005a80/opportunities-geothermal-energy-in-germany> [accessed 25 April 2021].

was recorded at Nigde province in Central Anatolia. The production capacity in Turkey by 2025 is estimated at 2600 $MW_e$. Turkey also has a very high EGS potential estimated at around 400 $GW_e$.[32]

## Italy

In 2018, main source of power production in Italy was thermal with a contribution of 66 %. Geothermal provided only 2 % of total generation. Tuscany contains all the major geothermal fields in Italy. 30 % of total production in the region of Tuscany was from geothermal. By 2018, 915 $MW_e$ installed capacity was available and it is projected to reach 975.5 $MW_e$ by 2025. [33]

## France

Nuclear is the dominant power source in France followed by hydroelectric. [34] Primary application of geothermal is for heating and cooling purposes. One geothermal power plant is operational at Guadeloupe archipelago with a capacity of 15 $MW_e$. Exploration permit for two wells have submitted which will add an estimated 10 $MW_e$. At Soultz-sous-Forêts a 1.7 $MW_e$ ORC plant has been established with temperature around 150 $^0$C. Soultz-sous-Forêts was also one of the earliest EGS based plants. [35]

# Global Scenarios

Currently, only 6-7% of the world's estimated geothermal potential is being harnessed for heat and power generation. Since many places in the world are not rich in hydrothermal sources, but still have vast untapped potential of geothermal heat, there is a need for the development of enhanced geothermal systems (EGS) technologies to tap into these resources on the large scale. Large scale EGS deployment will not be possible before high upfront costs such as drilling and resources assessment and elevated risk have been lowered. So far, EGS technology has only been demonstrated successfully in a handful of locations. Many countries are currently developing novel technologies to try to reduce EGS investment costs.

The installed capacity of global geothermal power plants reached 12.7 $GW_e$ in 2017 using mainly convective hydrothermal resources[36]. An increase of about 3650 $MW_e$ installed capacity has been achieved globally, given a total generation capacity of about 15,950 $MW_e$ with average annual global growth rate of about 5.9%. The World Energy Council has forecasted that the geothermal compound annual growth rate over the period 2015 to 2060 will approximate only 5.4%, 4.6%, and 3.4% considering optimistic, basic and pessimistic scenarios, respectively. Belgium (0.8 $MW_e$), Chile (48 $MW_e$), Croatia (16.5 $MW_e$), Honduras (35 $MW_e$) and Hungary (3

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[32] Orhan Mertoglu and others, 'Geothermal Energy Use, Country Update for Turkey', *European Geothermal Congress 2016*, September, 2019, 1–7.

[33] Adele Manzella and others, 'Geothermal Energy Use, Country Update for Italy', *Media.Geoenergicentrum.Se*, June, 2019, 11–14 <www.igrene.se> http://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-16-Italy.pdf. [accessed on 16 May 2021]

[34] Statista, 'Electricity Production by Source France 2019 | Statista', 2020 <https://www.statista.com/statistics/768066/electricity-production-france-source/> [accessed 16 May 2021].

[35] Christian Boissavy, Romain Vernier, and Philippe Laplaige, 'Geothermal Energy Use, Country Update for France', *European Geothermal Congress 2013*, July 2012, 2013, 12.

[36] Uihlein A: JRC Geothermal power plants dataset. European Commission, Petten; https://publications.jrc.ec.europa.eu/repository/bitstream/JRC113847/kjna29446enn_jrc113847.pdf; accessed on 04 May 2021.

$MW_e$) generated geothermal power for the first time since 2015. Additionally, in the decade beginning in 2020, it is possible that newly or greatly increased geothermally generated power will be on-line in Argentina, Australia, Canada, China, Dominica, Ecuador, Greece, Iran, Montserrat, Nevis, Saint Lucia, Saint Vincent, and Taiwan. Also, several African nations adjacent to the East African Rift Zone such as Tanzania, Uganda, Rwanda, and Malawi that are now being explored[23]. In the recent years, there has also been increased attention shown to the possibilities of developing Engineered Geothermal Systems (EGS) to tap the vast thermal energy resources trapped in rocks having low natural permeability. This work is ongoing in countries that include the USA, Iceland, UK, Germany, China, Portugal, and the Netherlands. If all countries fulfil their geothermal power development targets the global market could reach 32 $GW_e$ by the early 2030s[37], with the biggest capacity additions expected in Indonesia, Turkey, the Philippines and Mexico[38].

Most of the leading global geothermal industry are mainly located on highly active geological areas such as the Pacific Ring of Fire and rift zones and dominated by 'high temperature' geothermal fields that benefited for large-scale geothermal power development. Global geothermal power developments are mainly focused on conventional power technologies such as dry steam and flash type geothermal power plants using medium to high temperature geothermal fields. Recent innovations in geothermal sector carried by the European industry in particular EGS and binary turbines technologies, enabling a great and sustainable future development of geothermal power globally. In both cases, the applications of Geo-Coat technology for geothermal components can expedite the growth and sustainable of geothermal power globally.

One of the key factors in increasing the output of geothermal systems is obtaining higher enthalpy fluid which could be obtained by drilling deeper wells in the Ring of Fire regions. But, as we move to deeper geothermal resources, geofluids become more aggressive and the increased corrosion, erosion and scaling effects put the efficiency and longevity of the plant components at risk. Geo-Coat technology will enhance the growth of geothermal energy as it will enable to exploit corrosive and aggressive geofluid to generate electricity thereby reducing the environmental impacts and costs.

## USA

The Geysers dry steam plant was the first installed geothermal plant in the USA and after that many more flash-steam and binary plants are being operated. Currently, USA is the largest geothermal power producing country with 3714 MW production capacity in 2020. As of October 2019, a total of 3700 $MW_e$ geothermal power is produced in the USA. The states producing geothermal power are

- Alaska,
- California,
- Hawaii,
- Idaho,
- Nevada,
- New Mexico,
- Oregon and
- Utah.

[37] Matek B: Annual U.S. & Global Geothermal Power Production Report. Geothermal Energy Association, Baltimore. https://www.eesi.org/files/2016_Annual_US_Global_Geothermal_Power_Production.pdf; accessed on 03 May 2021

[38] IEA: Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations (443). DOI:10.1787/energy_tech-2017-en; accessed on 03 May 2021.

California and Nevada are generating most of the power (3478 $MW_e$).[39]

Conventional fossil fuel based power generation has showed decline in production rate. The main reason contributing to this phenomenon is the retirement of coal based power plants. Hydro and nuclear plant have shown stable rate of production along with geothermal plants.

Wind and solar have shown the largest growth among the renewable energy sources. Through 31 December, 2018, renewable energy provides 17 % of total power in USA where geothermal was 2 % of renewable and 0.4 % of total generation. A large amount of coal nuclear retirements was expected. Gas, wind and solar would be the main source of the upcoming demand. Earlier study by United States Geological Survey (USGS) showed the potential of known undeveloped hydrothermal resources to be approximately 9000 $MW_e$ and undiscovered resource to be 30000 $MW_e$. Geo-Vision study conducted by Department of Energy's Geothermal Technologies Office (DOE-GTO) estimated that generation possibility of geothermal energy to be around 60000 $MW_e$. From January 1, 2015 to December 31, 2019, 13 production wells were drilled with temperature greater than 150$^0$C, 11 wells with temperature 100-150 $^0$C.

## Mexico

With 962.7 MW production capacity, Mexico ranked 6$^{th}$ position as top geothermal power producing countries in 2020[17]**.** There are 5 main geothermal fields in Mexico: Cerro Pierto, Los Azufres, Los Humeros, Las Tres Virgenes, Domo de San Pedro. Cerro Pierto is the largest in Mexico and the second largest geothermal field in the world with 947 $MW_e$ operating capacity.

As of December 2018, 62475 $MW_e$ power was generated in Mexico where the major contributor was fossil fuel. The renewable sources provided 18.9 % of total power generated. As of December 2019, Mexico has geothermal capacity of 1005.8 $MW_e$. After 2014, CFE (Comision Federal de Electricidad) awarded exploration permits on 13 geothermal zones. The energy ministry envisions that by 2030, 1670 $MW_e$ of geothermal power would be generated through conventional hydrothermal sources. [40]

## Philippines

With 1918 MW capacity in 2020, Philippines ranked 3$^{rd}$ position in the top geothermal energy producing countries.[17] Additional 646 MW has been envisioned to meet the increasing demand.

In 2017, geothermal provided 11 % of total generation and in 2018 it was 8 %. The most recent estimation of geothermal potential is 4064 $MW_e$ of which 50% has been developed. 3 main geothermal fields are the main sources: Visayas, Luzon, Mindanao.[41] 18 sites are in exploration stage and additional 91 $MW_e$ is expected to be generated within 2021-2026.[23]

[39] 'Use of Geothermal Energy - U.S. Energy Information Administration (EIA)' <https://www.eia.gov/energyexplained/geothermal/use-of-geothermal-energy.php> [accessed 15 April 2021].

[40] José M Romo-jones and Luis C Gutiérrez-negrín, '2019 Mexico Country Report', June, 2020. https://www.researchgate.net/publication/343111483_Geothermal_energy_in_Mexico_update_and_perspectives; [accessed on 12 April 2021]

[41] Ariel D Fronda and others, 'Geothermal Energy Development: The Philippines Country Update', 5, 2020, 1–8. http://large.stanford.edu/courses/2016/ph240/makalinao1/docs/01053.pdf; [accessed on 14 April 2021]

## Indonesia

Indonesia is ranked 2nd among largest geothermal power installed countries with 2133 $MW_e$ capacity.[17] It is estimated that 40 % of world's geothermal energy rests beneath the surface of Indonesia but only 4-5 % of it is currently being used. The largest number of geothermal resources is located at West Indonesia. Sumatra, Java and Bali are the 3 main islands containing this resource. North Sulawesi province is most advanced in terms geothermal energy usage with approximately 40% electricity demand is fulfilled from geothermal resources. [42]

## New Zealand

New Zealand is the 5th ranked geothermal energy producing country with a capacity of 1005 $MW_e$**[17].**

In 2017 geothermal accounted for 17 % of total electricity supply. The Taupo volcanic zone contains the largest geothermal resources of the country with small amount in Ngawha in Northland. By July 2018, there was addition of 350 $MW_e$ generation**.[43]** 129 geothermal zones have been identified in New Zealand with varying temperature range. In last 5 years 7 wells have been drilled, 3 production and 4 injection. With an addition of 31.5 $MW_e$ by 2020, the total installed capacity is expected to reach 1064 $MW_e$**.**

## Kenya

With 855 $MW_e$, Kenya is the 8th country in the world in geothermal power generation capacity.[17] Currently fossil and hydro are the predominant power sources in Kenya. 13.2 % of it is contribution of geothermal. Major geothermal resources are located at rift valley with a potential greater than 2000 MW. According to Kenya's Least Cost Power Development Plan, geothermal is identified as a cost effective option for power generation. Geothermal Development Company (GDC) was responsible for fast tracking the potential resources.[44]

# Different Regions with Underdeveloped or Unexploited Geo-resources

Primary evidence of the geothermal potential which exists comes from an underground hydrothermal system in the subsoil of Tenerife region in the Canary Islands with a temperature of 275 $^0$C. The geothermal potential of Gran Canaria region in the Canary Islands found that the temperature of hot underground water is around 150 $^0$C at a depth of 2.5 km and it is estimated that enough geothermal energy is present in Gran Canaria to generate electricity. The Spanish Canary Islands, where fossil fuels imports increased in 2016, have enormous geothermal potential, but its vast majority still lies unutilized[45].

Meanwhile, imported oil in the Caribbean has gone up to an estimated 722,000 barrels per year. Yet, despite the total geothermal potential for electricity being estimated up to 3500 $MW_e$, Guadeloupe is the only island that uses geothermal energy for electricity, with a 15.7 $MW_e$ geothermal power plant. Developments are however ongoing in the regions, notably in Dominica, Montserrat, Saint Vincent & Grenadines, or St Kitts. Development is particularly supported by multilateral financial institutions such as World Bank, the EU, the Caribbean Development Bank, or the Green Climate Fund. The geothermal resources of several prospective

[42] 'Geothermal Energy in Indonesia | Indonesia Investments' <https://www.indonesia-investments.com/business/commodities/geothermal-energy/item268> [accessed 16 May 2021].

[43] 'Geothermal Energy Generation | Ministry of Business, Innovation & Employment' <https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-generation-and-markets/geothermal-energy-generation/> [accessed 22 April 2021].

[44] 'Kenya Energy Situation - Energypedia.Info' <https://energypedia.info/wiki/Kenya_Energy_Situation> [accessed 16 May 2021].

[45] https://www.geoenergymarketing.com/energy-blog/geothermal-country-overivew-the-canary-islands/; accessed on 04 May 2021

areas in Dominica have been explored where the temperatures above 235 $^{0}$C were recorded at a depth of just over 1500 m. The geothermal potential of Montserrat was studied prior to and following the eruptions of the Soufriere Hills volcano in 1995, and that led to the drilling of two exploratory wells more than 2,350 meters deep by the Icelandic Drilling Company where the temperatures of 298 $^{0}$C were recorded. In St Vincent, geothermal development plans are being carried out for the generation of about 10 $MW_e$ capacity and the power plant is anticipated to be online in 2021 or 2022. The work, funded by the Caribbean Development Bank and Caribbean Community, reportedly identified a potential for geothermal resources able to fuel 18-35 $MW_e$ of power in St Kitts[23].

In the Mediterranean region, the Aegean Islands in Greece, where 80% of the electricity demand is covered by oil, show potential both for high and low temperature geothermal fields, but only a small share of this potential is currently exploited, mainly for greenhouse heating and balneological uses.

Geothermal energy has a large potential in islands, especially in volcanic ones where deep geothermal can provide flexible electricity at a competitive cost – despite some infrastructure challenges to project development. Some island economies are already relying on geothermal energy, most notably the Azores Archipelago which has set quite the successful example in demonstrating what can be achieved with geothermal energy. With a power production from geothermal that presently meets 42% of the electrical consumption of São Miguel Island, and over 22% of the total demand of the archipelago, the Azores have shown that geothermal energy can provide a local, stable, and clean energy source that can help EU islands achieve the energy transition. The Pico Alto power plant utilises a binary system from Exergy that provides a sustainable and reliable source of electricity to more than 56,000 inhabitants, meeting up to 10% of the island electricity needs. The utilization of geothermal as a baseload renewable energy source, available 24/7, has brought the island a stable electricity supply and economic savings thanks to a reduced reliance on imported fossil fuels.

The cost of electricity is one of the highest in the Caribbean islands. One of the main reasons being, the smaller the market, the higher the per unit fuel cost. When islands are not interconnected, the cost of import also increases, especially when fuel price is declining worldwide. These islands are vulnerable during natural disasters such as cyclonic phenomenon which may have huge environmental impact. Considering all these factors, Geo-Coat will encourage investors in geothermal power production in these regions which will lower the dependency on fossil fuels and reduce electricity cost.

# Countries with Higher Energy cost & Lower Feed-In-Tariffs

Countries around the world are increasingly turning to feed-in-tariffs (FiTs) as an instrument to enhance the development of renewable energy sources. A FiTs is a guarantee that renewable energy producers will be able to sell the electricity they generate at a price set in advance by the government under the long-term contract. FiTs are an important economic instrument for all kinds of renewable energy to support the payments per kilowatt-hour for the electricity generation and guaranteed for 15-20 years. In most of EU countries and other countries in the world, the feed-in-tariffs (FiTs) instrument plays a vital role to boost up the commercial interest of investors concerning geothermal electricity production. Germany has the highest electricity prices worldwide. In September 2020, German households were charged around 0.36 U.S. dollars per kilowatt hour plus value added tax. By comparison, in neighbouring Poland, residents paid half as much, while households in the United States were charged even less. Feed-in tariffs are being used in Turkey, Germany, Iceland, USA and the Philippines and have driven these countries to world leadership in geothermal and other renewable energy development. The aim of the FiTs is to promote renewable energies in order to increase the share renewable energy in the electricity mix and produce no greenhouse gases (GHGs) for a sustainable environment for future generations.

Currently, FiTs are determined on the basis of a calculation of LCOE of the power sources. For example, In Indonesia, tariff design is differentiated by the technology and resource based on power generation cost. In many FiTs schemes, investors are eligible for payment of additional bonuses due to innovative applications such as enhanced geothermal systems.[46]

For those countries with higher energy cost and feed-in-tariffs for renewable energy, the applications of Geo-Coat technology for geothermal components in future geothermal plants can reduce the LCOE and environmental footprints resulting in a well-designed and balanced FiTs scheme thereby expedite the growth of geothermal energy in Europe and beyond.

# 4. CONCLUSIONS

In this report, the Geo-Coat impacts on the sustainability of geothermal power and the potentialities of the applications of the best candidate Geo-Coat technology have been described for improving the growth of geothermal power in European and global countries. The following important points have been described:

- economic and environmental impacts of Geo-Coat were discussed.
- Future potential of Geo-Coat has been mentioned when coal and other fossil fuel based plants would become obsolete.
- Current projection of geothermal LCOE was compared with the Geo-Coat projection.
- A double flash perspective power plant was used for the LCOE and LCA to compare the best candidate Geo-Coat technology and selected state of art (SOA) materials for geothermal components (surface pipes, well casings and turbine components). These analyses showed
    - a levelised cost of energy (LCOE) reduction of about 91% and
    - overall environmental footprints savings of about 60%.
- The potentialities of Geo-Coat technology were also explored in different regions of the world where geothermal power production is already operational. The ring of fire could be a strong region where application of Geo-Coat can be exploited. Countries with unexplored and underdeveloped geothermal resources were also studied. Countries with low energy tariff and remote islands where conventional energy costs are very high would be benefitted from Geo-Coat.

In geothermal power generation, drilling and exploration costs (about 40 % of total plant development cost) are needed to be reduced through developing new and innovative drilling technology. Geofluid is re-injected at a relatively high temperature to prevent scaling formation which prevents full utilization of high enthalpy of geofluid. There are also lack of smart control and flexible ORC systems to utilize geothermal energy in seasonal variations. Innovations and combined outcomes from all these sectors along with Geo-Coat will make geothermal power more sustainable and affordable.

[46] 'Feed-in Tariffs (FIT) - Energypedia.Info' <https://energypedia.info/wiki/Feed-in_Tariffs_(FIT)#Overview> [accessed 19 May 2021].