D14.4 Report on the impact of OPTIDRILL on the sustainability of geothermal power

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

No table of figures entries found.

EXECUTIVE SUMMARY

This deliverable describes the OPTIDRILL's impacts on the sustainability of Geothermal power and the potentialities to improve the growth of geothermal power in Europe and beyond. The sustainability is discussed in the context of conventional power plants. The OPTIDRILL project has developed a drilling advisory system utilising machine learning methods to predict ROP, lithology, and drilling problems uniting those under one system for drilling process optimisation and intelligent decision-making. The drilling advisory system advises drillers on optimum drilling parameters to improve efficiency. It recommends drilling parameters to reduce mechanical specific energy (MSE), i.e., the most efficient drilling in terms of energy consumed. Optimising MSE minimises wasted energy during drilling, reducing fuel usage and carbon footprint. Economic analysis of OPTIDRILL showed a 1.69% - 4.19% reduction in LCOE (levelized cost of energy). OPTIDRILL LCA (Lifecycle impact analysis) showed about 16.2 % carbon footprint (long-term climate change impact) savings. The results of the economic and environmental footprint studies demonstrate the potentialities of OPTIDRILL technology for improving economic and environmental performances and thereby enhancing geothermal power growth in Europe and other countries.

1. INTRODUCTION

Geothermal power generation 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. According to IEA the future of geothermal energy report[1] the share of total supply for next-generation geothermal is expected to be 14.4% in 2040 and 21.1% in 2050.

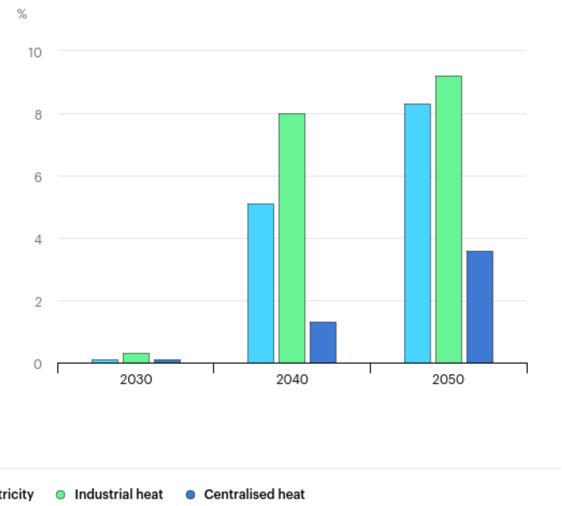


Figure 1: Share of total supply for next-generation geothermal, 2030-2050

With access to higher heat resources at greater depths, geothermal energy potential increases. New drilling technologies enabling cost effective drilling enables exploitation of geothermal resources at depths beyond 3km opens potential in nearly all countries in the word. Thermal resources at depths below 8km can deliver almost 600TW of geothermal capacity.[1]

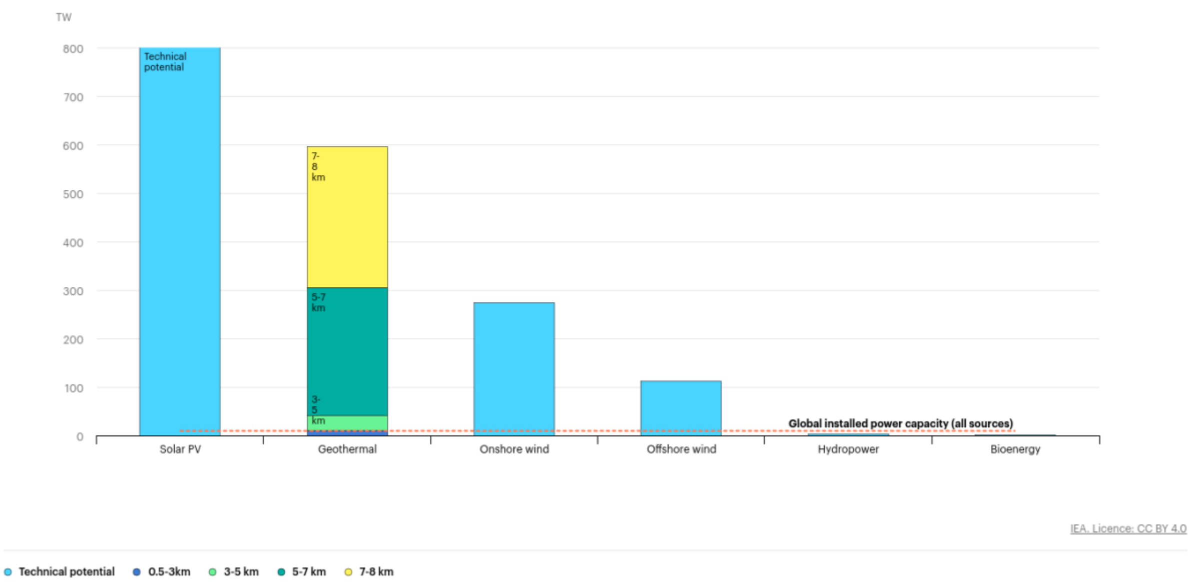


Figure 2: Technical potential of renewable sources for electricity generation

[1] https://www.iea.org/reports/the-future-of-geothermal-energy

Global geothermal heat potential at depths up to 3 km and temperatures greater than 90°C is about 320TW. This could be used to decarbonise existing fossil fuel-fired district heating networks. The potential increases about tenfold for lower temperature requirements. [1]

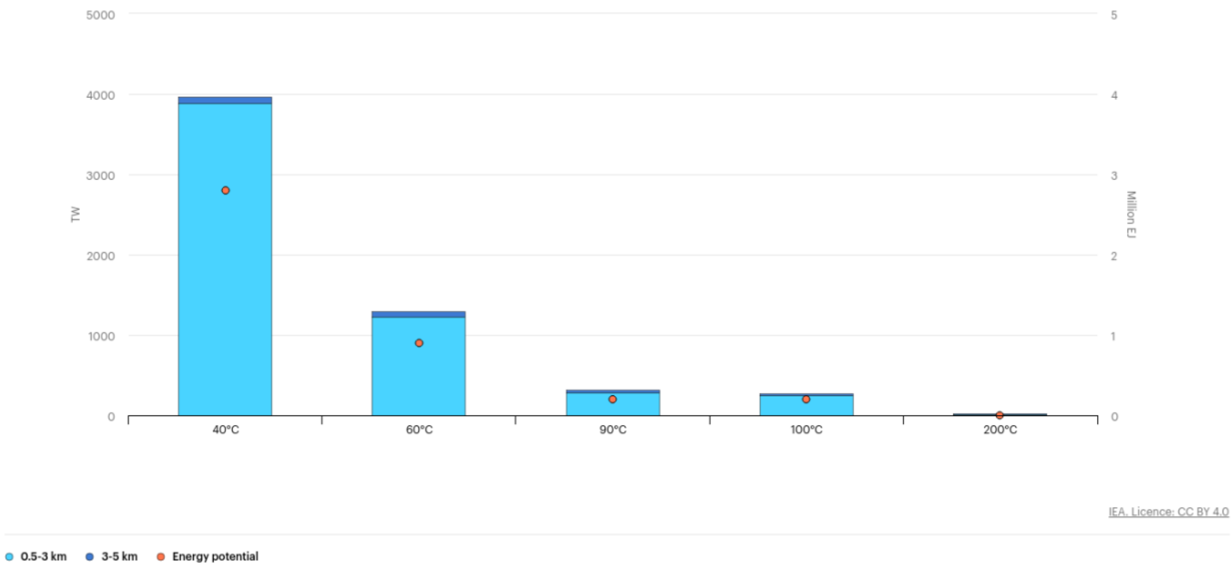
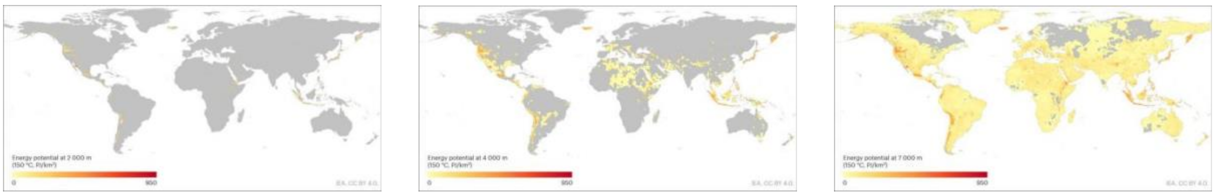


Figure 3: Global technical potential for geothermal heat

Global geothermal electricity potential is almost 600TW using resources within 8km depth. This is almost 2,000 times the technical potential of conventional geothermal power.[1]



(a) (b) (c)

Figure 4: Global EGS potential at (a) 2km, (b) 4km, and (c) 7km depth

The expansion of geothermal power depends on economic and technological viability to exploit geothermal resources. New drilling technologies allowing reaching geothermal resources cost-effectively will enable the exploitation of resources that are, at present, commercially unviable. By recommending optimum parameters to improve drilling efficiency, the OPTIDRILL drilling advisory system has the potential to reduce geothermal drilling costs. The drilling advisory system recommends parameters that will minimise mechanical specific energy (MSE), i.e., the most efficient drilling in terms of energy consumed. This not only improves ROP (rate of penetration) thereby reducing time to drill a wellbore, but it also reduces wear thereby reducing the number of replacement drill-bits. The reduction in fuel usage from shorter drilling time and reduces drill-bit consumption also contributes to the reduction of drilling carbon footprint.

Section 2 compares geothermal with fossil fuel baseload plants and how OPTIDRILL will affect the geothermal sector. The economic and environmental impacts of geothermal power generation have also been discussed. Section 3 discusses the potentialities of OPTIDRILL technology in Europe and the rest of the world. Countries with underdeveloped geothermal potential, high energy costs, and lower feed-in-tariff are also discussed, where OPTIDRILL technology could impact future geothermal power development. The results and findings are concluded in section 4.

2. IMPACTS ON THE SUSTAINABILITY OF GEOTHERMAL POWER

Fossil fuels account for most of the energy consumption around the world. Fossil fuel share of Europe's gross available energy has reduced from more than 82% in 1990 to about 70% in 2019.[2] Global electricity generation is expected to double by 2050[3], and fossil fuel contribution to global energy demand is expected to be 60% in 2040 from the current value of about 85%.[4]

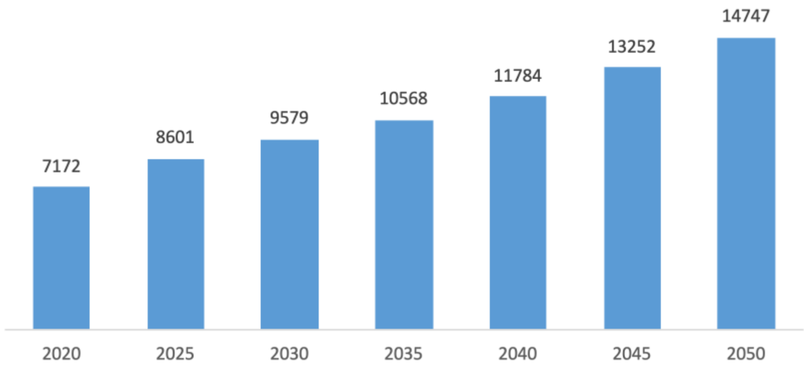


Figure 5: Global electricity generation capacity (GW_e) by 2050

Compared to fossil fuels, geothermal is a cleaner source of energy. Though geofluid (source of geothermal energy) has different pollutants and greenhouse gases, the amount is dependent upon the geological conditions of the reservoir and is typically re-injected into the reservoir and, therefore, not released into the environment. CO_2 emissions of geothermal power are much lower than that of fossil fuel plants.[5] *Geothermal power plants emit 97% less acid rain-causing sulphur compounds and about 99% less carbon dioxide than fossil fuel power plants of similar size*.[6] This sets geothermal energy apart from conventional power sources, underscoring its exceptional environmental friendliness and sustainable nature.

As a continuous energy source, geothermal power can operate at their maximum capacity 24/7. Global average geothermal utilisation was over 75% in 2023, in contrast to wind (30%) and solar PV (15%).[1] In addition, geothermal power plants can contribute to the stability of electricity girds supporting the integration of variable renewables such as wind, solar PV.

Base load is defined as the minimum level of electricity demand over a period of 24 hours. Coal power plants are one of the most prominent examples of baseload power plants. Half of Europe's 324 coal power plants have been closed or announced retirement before 2030, emissions being the main reason.[7] Germany and Poland have 51% of the EU's installed coal capacity and 54% of coal-based emissions.[8] U.S. coal-fired electricity generation, in 2019, was the lowest in 42 years.[9] According to U.S. Energy Information Administration (EIA), 121 coal-based power plants were replaced or repurposed into natural gas based combined cycle power plants since 2011. Geothermal energy will be in high demand in the future because it is one of the few renewable sources that can handle base load. In 2019, geothermal deployment

[2] Share of Fossil Fuels in Gross Available Energy, https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20210204-1

[3] Electricity Generation Capacity Globally 2050, https://www.statista.com/statistics/859178/projected-world-electricity-generation-capacity-by-energy-source/

[4] The future of fossil fuels, https://copenhageneconomics.com/publication/the-future-of-fossil-fuels/

[5] Ladislaus Rybach, CO_2 Emission Mitigation by Geothermal Development – Especially with Geothermal Heat Pumps, Proceedings World Geothermal Congress 2010, https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0209.pdf

[6] Geothermal Energy and the Environment - EIA, https://www.eia.gov/energyexplained/geothermal/geothermal-energy-and-the-environment.php

[7] Europe Halfway towards Closing All Coal Power Plants by 2030, https://www.euractiv.com/section/climate-environment/news/europe-halfway-towards-closing-all-coal-power-plants-by-2030/

[8] EU Coal Phase Out / Climate Analytics, https://climateanalytics.org/briefings/eu-coal-phase-out/

[9] U.S. Coal-Fired Electricity Generation in 2019 Falls to 42-Year Low, https://www.eia.gov/todayinenergy/detail.php?id=43675

accounted for 0.5% of the total installed capacity of renewable energy worldwide, with a total installed capacity of 13.9 GW.[10] At present, only a small fraction of geothermal potential has been explored and exploited[11]. As shown in Figure 6, the outlook of geothermal installed capacity in 2050 is about 70 GW.[12] High CAPEX, public perceptions, and support, etc., are some hurdles preventing the blooming of geothermal power generation.

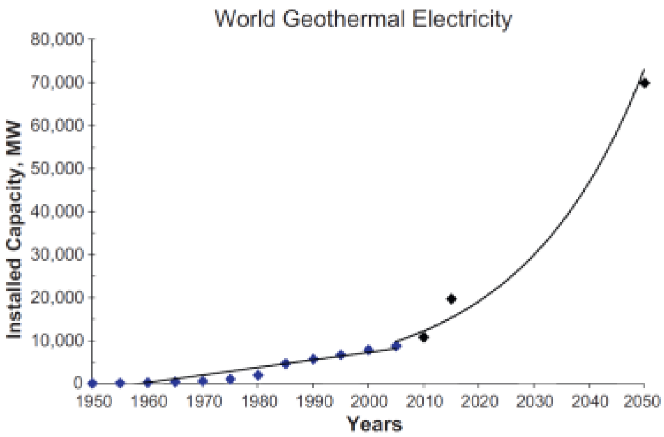


Figure 6: Global geothermal power installed capacity forecast

Despite that, as shown in ***Figure 7*** cumulative investment for next-generation geothermal is expected to be $1,136.7 billion in 2035, $1,998.9 billion in 2040 and $2,815.6 billion in 2050. This investment will be in geothermal electricity generation, combined heat and power, and industrial heat sector.

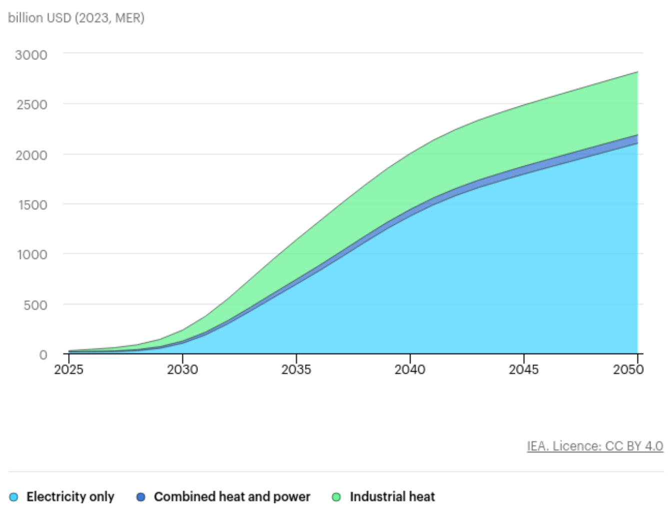


Figure 7: Cumulative investment for next-generation geothermal, 2025-2050

The OPTIDRILL project aimed to reduce drilling costs by developing an advisory system that recommends parameter to improve drilling efficiency which results in faster drilling and less wear in tools. Economic analysis showed a 1.69% - 4.19% reduction in LCOE (levelized cost of energy).[13] LCA (Lifecycle impact analysis) showed about 16.2 % carbon footprint (long-term climate change impact) savings[14] from

[10] IRENA Renewable Power Generation Costs in 2019, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Jun/IRENA_Power_Generation_Costs_2019.pdf
[11] https://www.worldbank.org/en/results/2017/12/01/geothermal
[12] Ruggero Bertani, Geothermal Power Generation in the World 2005–2010 Update Report, https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/0008.pdf
[13] OPTIDRILL D14.2 Report on the impact of OPTIDRILL on LCOE
[14] OPTIDRILL D14.3 Report on the impact of OPTIDRILL on environmental footprint of geothermal power

OPTIDRILL. Though OPTIDRILL by itself cannot make geothermal power competitive with other electricity generation technologies, it contributes to making geothermal more competitive enhancing the growth of geothermal power. In addition, OPTIDRILL will contribute towards direct utilisation of geothermal heat in district heating, industrial heat etc by reducing the cost of drilling.

3. OPTIDRILL POTENTIALITIES

In this section potential application of OPTIDRILL technology around different regions of the world are discussed. Geothermal enriched countries in Pacific Ring of Fire, Asia, Europe, America, Africa have been identified and their potentialities quantified based on their current power generation capacity and future projection. Some of the leading countries in geothermal energy production include the United States, Indonesia, the Philippines, Kenya, Turkey, and Iceland. Countries such as Japan, Italy, Mexico, Germany, France, and New Zealand, are also increasing their geothermal energy usage. In addition, Africa's Great Rift Valley has significant untapped geothermal energy potential, with many countries like Ethiopia and Rwanda investing in geothermal energy projects. As of 2021, around 26 countries are using geothermal energy. These countries account for more than 15.64GW of installed capacity[15], with the United States being the largest producer, followed by Indonesia, the Philippines, and Turkey. This section discussed the enormous untapped potential of geothermal energy and the projected growth of geothermal power in the energy mix. Extraction of the untapped geothermal energy will need drilling new wellbores. At 5.9MW/well[16] energy production from deep geothermal wells, we will need to drill a large number of production and injection wells. Utilising OPTIDRILL technology in drilling these wells will reduce drilling costs and thereby reduce the cost of geothermal energy, promoting the sustainability and growth of geothermal power.

Figure 8: Ring of Fire (Transparent white) and installed capacity

3.1 Ring of Fire

The Pacific Ocean's ring of fire, often called the Circum-Pacific Belt, is marked by intense seismic and volcanic activity. It was formed because of the subduction process, the collision of moving tectonic plates. This area is home to geothermal phenomena, including hot springs and geysers, earthquakes, and volcanic activity. This 40,000km horse-shoe-shaped fringe housing 452 volcanoes stretches from the southern point of South America to the northern tip of North America, through the Bering Strait, through Japan, and into New Zealand[17]. Roughly 40% of the world's geothermal resources are found within the Ring of Fire. 6 out of the top 10 geothermal power-producing countries around the world are from the Ring of

[15] Khaled Salhein et al., Forecasting Installation Capacity for the Top 10 Countries Utilizing Geothermal Energy by 2030, *Thermo,* vol. 2, pp. 334-337, 2022

[16] Bjorn Mar Sveinbjornsson et al., Drilling performance, injectivity and productivity of geothermal wells, Iceland GeoSurvey (ISOR), Grensasvegur 9, 108 Reykjavik, Iceland

[17] Jeannie Evers, Plate Tectonics and the Ring of Fire, National Geographic Society, 2023

Fire region, totalling 10.34GW installed capacity.[18] It goes without saying that the geothermal sector has only just begun to explore this abundant energy source.

3.2 European Scenarios

In terms of direct use of geothermal energy, Europe is leading the world.[19] Geothermal energy has enormous potential to play an important role in the continent's energy landscape. However, it is still a comparatively unexplored resource. In the past, technological frontiers were limited to lower enthalpy geofluids in Europe. However, intermediate enthalpy geofluids in accessible depths are now being discovered because of advancements in better geothermal systems and the chase for sustainable energy sources. Joint efforts in several European countries have led to the development of 142 geothermal power plants with an installed capacity of about 3.5 GWe and generating more than 22,000 GWh.[20] Countries such as Iceland, Italy, and Turkey have pioneered geothermal energy development and are using their geothermal resources to supply energy to industry and households. The number of geothermal power plants is expected to be doubled within 5-8 years[21], and geothermal energy is estimated to supply up to 4–7% of total electricity generation needs by mid-century, with 880–1050TWh/year.[22]

Iceland

Iceland was formed due to an interaction between spreading plate boundaries, the North American and Eurasian plates, and a hot spot fed by a deep mantle plume beneath it.[23] The Mid-Atlantic Ridge (MAR) dissects Iceland into these two separate plates and due to tectonic movement diverges from east to west at a rate of 2cm per year. This area's main fault structures, volcanic zones, and belts are called volcanic rift zones, characterized by intense volcanic, seismic, and high-temperature geothermal activity.[24] [25] Therefore, Iceland has high accessibility to high-temperature geothermal sources. Geothermal energy provides around 30% of the Iceland's electricity needs, with a total installed capacity of 755.9MWe, which is projected to increase further.[26] [27] Geothermal energy accounts for 66% of Iceland's primary energy use[28] and 90% of all buildings in Iceland are heated through utilizing this energy source.[29] Iceland aims to completely replace fossil fuel with renewables by 2050, with geothermal being a major component of this plan.[30] There are both high and low-temperature zones around the country and the total potential for electrical power generation ranges from 2.55-7.66$GW_{e,}$ and therefore there is considerable room for further utilization.[31] Geothermal wells in these regions typically reach depths of 1500-3000 meters, with maximum temperatures around 200–300°C. However, the recent undertakings of the Iceland Deep

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[18] Top 10 Geothermal Countries 2020 – Installed Power Generation Capacity (MWe), https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2020-installed-power-generation-capacity-mwe/

[19] Beata Kępińska, Geothermal Energy Use in Europe - Geothermal Training Programme of the United Nations University Anniversary Workshop, *Geothermal Training Programme*, 2008, http://www.os.is/gogn/unu-gtp-30-ann/UNU-GTP-30-40.pdf

[20] EGEC-Press-Realease-Market-Report-2022, European Geothermal Energy Council, 2023

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

[22] Francesco Dalla Longa et al., Scenarios for geothermal energy deployment in Europe, *Energy,* vol. 206, 2020, https://doi.org/10.1016/j.energy.2020.118060

[23] K. Saemundsson, Outline of the geology of Iceland, 1997.

[24] Wolfgang Jacoby, Hotspot Iceland: An introduction., *Geophysics,* vol. 43, no. 1, 2007

[25] T. Thórdarson et al., Volcanism in Iceland in historical time: Volcano types, eruption styles and eruptive history, *Geodynamics,* vol. 43, 2007

[26] Installed Electrical Capacity and Electricity Generation of Geothermal Power Plants in Iceland 1969-2021, https://orkustofnun.is/gogn/Talnaefni/OS-2022-T004-01.pdf

[27] Development of electricity production in Iceland (2021), https://orkustofnun.is/gogn/Talnaefni/OS-2022-T003-01.pdf

[28] https://www.government.is/topics/business-and-industry/energy/geothermal/

[29] Proportion of energy source in space heating based on heated space in Iceland 1952-2019, https://orkustofnun.is/gogn/Talnaefni/OS-2020-T008-01.pdf

[30] A Sustainable Energy Future: An Energy Policy to the year 2050, Government of Iceland, 2020

[31] 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/

Drilling Projects 1 and 2 (IDDP) have opened a new horizon for acquiring supercritical geothermal fluids of over 450°C at 2km and around 4.5 km, respectively.[32] [33] Estimated Power generation from one such well is 30–60MWe, which is ten times greater than a normal high-temperature well in Iceland.

Germany

Germany focuses on the direct use of geothermal energy more than power generation. Most of the geothermal plants developed are in the Molasse Basin in Southern Germany, North Germany Basin, and Upper Rhine Graben, and are the main resources for deep geothermal resources.[34] Due to geological location, Germany lacks steam-dominated reservoirs that can drive turbines. At the end of 2021, 190 geothermal plants were operational to generate geothermal energy for direct use, and 11 geothermal plants with an installed capacity of 47.6MWe feed into the German grid. Total geothermal power production in 2020 was 196.6 GWh.[35] The technical potential of geothermal power is estimated to be 15,000–132,000 GWh per year.[36] Most of the major combined heating and electricity plants are operating in the state of Bavaria.[36] With the advancements in deep drilling technology and the improved probability of creating engineered reservoirs alongside the implementation of improved thermodynamic cycles, the country has also taken several initiatives in recent decades to increase its reliance on geothermal energy. Besides, the federal plan to transition to renewable energy by 2050 has further boosted its quest for Geothermal power to add to its national grid.[37]

Turkey

Turkey achieved 4th position in 2020 with 1.69GW_e installed geothermal capacity.[18] In 2019, 55 geothermal power plants and 17 geothermal city heating plants were operational. 450 geothermal fields have been discovered. Geothermal direct-use applications were 3.49GW_t. Exploration for deep geothermal resources resulted in the discovery of a reservoir with a temperature around 240°C. The Manisa-Alasehir geothermal field contains geothermal fluid of around 287°C, while 295°C was recorded at Nigde province in Central Anatolia. The production capacity in Turkey by 2025 is estimated at 2.6GW_e. Turkey also has a very high EGS potential estimated at around 400 GW_e.[38]

Romania

Coal and gas are the main sources of power in Romania with 14002 GWh and 10258 GWh produced respectively in 2018. [39] 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.[40]

Italy

[32] Orkustofnun, The Iceland deep drilling project https://nea.is/geothermal/the-iceland-deep-drilling-project/
[33] Ari Stefánsson et al., The IDDP-2 DEEPEGS Drilling Experience and Lesson Learned, Proceedings World Geothermal Congress 2020+1
[34] Geothermal energy – Germany's largely untapped renewable heat source, https://www.cleanenergywire.org/factsheets/geothermal-energy-germanys-largely-untapped-renewable-heat-source
[35] Josef Weber et al., Geothermal Energy Use in Germany, Country Update 2019-2021, in *European Geothermal Congress 2022*, https://www.researchgate.net/publication/369061715_Geothermal_Energy_Use_in_Germany_Country_Update_2019-2021
[36] Opportunities geothermal energy in Germany, https://www.nortonrosefulbright.com/en/knowledge/publications/3e005a80/opportunities-geothermal-energy-in-germany
[37] Thomas Klaus at el., Energy target 2050: 100 % renewable electricity supply, https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/energieziel_2050_kurz.pdf
[38] Orhan Mertoglu et al., Geothermal Energy Use, Country Update for Turkey, European Geothermal Congress 2016, September, https://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-30-Turkey.pdf
[39] The Energy Sector in Romania, https://bankwatch.org/beyond-coal/the-energy-sector-in-romania
[40] Four Areas for Potential Geothermal Power Generation Discovered in Romania, https://www.thinkgeoenergy.com/four-areas-for-potential-geothermal-power-generation-discovered-in-romania/

In 2018, Italy's primary source of power production was thermal, with a contribution of 66%. Geothermal provided only 2% of total generation. Tuscany contains all the major geothermal fields in Italy, with thermal energy applications widespread all over Italy. 30% of total production in the region of Tuscany was from geothermal. To date, the geothermal electricity installed capacity is 915.5MW$_e$. As for thermal use, the total installed capacity at the end of 2017 was 1.42GW$_t$. Total installed capacity is expected to reach 975.5MW$_e$ by 2025.[41]

France

Primary application of geothermal in France is for heating and cooling purposes. Installed geothermal capacity for heating and cooling reached 2.5GW$_t$ in 2016. Though one third for that is in deep Dogger reservoir in the Paris area, but it is mainly due to recent and strong development of shallow geothermal resources in the whole country. Direct uses are concentrated mainly in Ile de France with more than 20 deep wells drilled. It is expected to reach 3GW$_t$ installed. At Soultz-sous-Forêts a 1.7 MW$_e$ ORC plant has been established with temperature around 150°C. Soultz-sous-Forêts was also one of the earliest EGS based plants. The capacity of Bouillante geothermal power plant located in Guadeloupe archipelago will be upgraded from 15 to 45 MWe in the next years.[42]

3.3 Global Scenarios

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 for geothermal heat, there is a need for the development of enhanced geothermal systems (EGS) technologies to tap into these resources on a 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 developing novel technologies to try to reduce EGS investment costs. [43] The installed capacity of global geothermal electricity generation plants reached 16 GW$_e$ in 2021, with an average growth rate of 3.5% since 2000. In addition, the utilization of geothermal energy for heating and cooling has experienced a steady expansion, with an approximate annual growth rate of 9% from 2015 to 2020, reaching a total capacity of 107 GWe by the end of 2020.[44] 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 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 online 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, are now exploring the potential geothermal energy. The installed capacity of global geothermal electricity generation plants reached 16 GW$_e$ in 2021, with an average growth rate of 3.5% since 2000. In addition, the utilization of geothermal energy for heating and cooling has experienced a steady expansion, with an approximate annual growth rate of 9% from 2015 to 2020, reaching a total capacity of 107GWe by the end of 2020.[44] 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,

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[41] Adele Manzella et al., Geothermal Energy Use, Country Update for Italy, European Geothermal Congress 2019, http://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-16-Italy.pdf

[42] Christian Boissavy et al., Geothermal Energy Use, Country Update for France, European Geothermal Congress 2019, https://europeangeothermalcongress.eu/wp-content/uploads/2019/07/CUR-11-France.pdf

[43] JRC Geothermal Power Plant Dataset, https://publications.jrc.ec.europa.eu/repository/bitstream/JRC113847/kjna29446enn_jrc113847.pdf

[44] https://www.irena.org/Publications/2023/Feb/Global-geothermal-market-and-technology-assessment

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[45], with the biggest capacity additions expected in Indonesia, Turkey, the Philippines, and Mexico[46]. 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. OPTIDRILL technology will enhance the growth of geothermal energy by enabling us to reach high enthalpy resources at greater depths cost-effectively, thereby reducing the cost and environmental impacts of geothermal power. Recent innovations in the geothermal sector carried by the European industry, particularly EGS and binary turbine technologies, enable a great and sustainable future development of geothermal power globally. In both cases, the applications of OPTIDRILL technology for geothermal components can expedite the growth and sustainability of geothermal power globally.

USA

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. As of 2022, USA is the largest geothermal power-producing country with a 3.79GW production capacity. [47] Geothermal power generation in the country is spread across seven states, yielding a total output of 17,000 GWh in the same year. The states producing geothermal power are a) California, b) Hawaii, c) Idaho, d) Nevada, e) New Mexico, f) Oregon and g) Utah. California and Nevada generate most of the geothermal power, 69.5% and 24.2%, respectively.[48] Recently, conventional fossil fuel-based power generation has shown a decline in production. The main reason to this phenomenon is the retirement of coal-based power plants. Hydro and nuclear plants have shown a stable rate of production along with geothermal plants. Wind and solar have shown the largest growth among renewable energy sources. Through December 2018, renewable energy provided 17 % of total power in USA, whereas geothermal was 2 % of renewable and 0.4 % of total generation. A large amount of coal and nuclear retirements was expected. Gas, wind, and solar would be the main source of the upcoming demand. A study by the United States Geological Survey (USGS) showed the potential of known undeveloped hydrothermal resources to be approximately 9GW_e and undiscovered resources to be 30GW_e. Besides electricity generation, geothermal energy is used in various direct-use applications, including district heating, heating pools, spas, greenhouses, and aquaculture and fish farming facilities. [49] The potential for geothermal power in the United States is projected to be around 530 GW, with a direct usage potential of 231 GW by 2050, including up to 17,500 district heating and cooling systems.[50]

Mexico

With 963MWe installed capacity, Mexico ranked 6th as the top geothermal power-producing country in 2020**.** 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 570MW_e in operation. In 2019, fossil fuels accounted for more than four-fifths of total electricity generation (81.7%) (262.6 TWh), with hydroelectric facilities contributing 5.9%, nuclear 3.4%, wind 4.8%, geothermal 1.7%, and solar 2.5%. The country has increased its geothermal capacity up to 1005.8MWe in the same year. After 2014, CFE (Comisión Federal de Electricidad) awarded exploration permits on 13 geothermal zones. The energy ministry envisions that by 2030, 1.67GW_e of geothermal

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[45] Annual U.S. & Global Geothermal Power Production Report, https://www.eesi.org/files/2016_Annual_US_Global_Geothermal_Power_Production.pdf
[46] IEA: Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations, DOI:10.1787/energy_tech-2017-en
[47] https://www.baseloadcap.com/2022-in-review-what-happened-in-geothermal-energy
[48] Use of Geothermal Energy - U.S. Energy Information Administration (EIA), https://www.eia.gov/energyexplained/geothermal/use-of-geothermal-energy.php
[49] The United States of America Direct Utilization Update 2019, https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01011.pdf
[50] https://www.energy.gov/eere/geothermal/articles/now-available-iea-2020-us-geothermal-report

power will be generated through conventional hydrothermal sources and an additional 3.8GW_t of direct-use applications from geothermal energy. [51]

Philippines

With 1.94GW capacity in 2022, the Philippines ranked 3rd position in the top geothermal energy-producing countries.[52] In 2017, geothermal provided 11 % of total generation, and it was 8% in 2018. The most recent estimation of geothermal potential is 4.06GW_e, of which 50% has been developed. Three main geothermal fields are the main sources: Visayas, Luzon, and Mindanao.[53] Around 18 locations are being explored, with 91MWe estimated to be added between 2021 and 2026. The Philippines' geothermal resource development potential is projected to be around 4.02GWe. **[54]**

Indonesia

Indonesia is ranked 2nd among the largest geothermal power installed countries with 2.36GW_e capacity.[52] Indonesia has the world's largest geothermal reserves, accounting for up to 40% of global reserves, which amounts to roughly 27GW to 29GW. However, the country's present geothermal energy development accounts for only 4.2% (1.23GW) of the total reserves.[55] The largest number of geothermal resources are in West Indonesia. Sumatra, Java, and Bali are the 3 main islands containing this resource. North Sulawesi province is the most advanced in terms of geothermal energy usage, with approximately 40% of electricity demand fulfilled from geothermal resources.[56]

New Zealand

New Zealand is the 5th ranked geothermal energy-producing country with a capacity of 1005 MW_e.[18] Geothermal energy provides approximately 18% of its electricity and about 7-8PJ directly as heat.[57] The Taupo volcanic zone contains the largest geothermal resources of the country, with a small amount in Ngawha in Northland. As of 2018, there was an additional 350MW_e generation**.** **[58]** 129 geothermal zones have been identified in New Zealand with varying temperatures. With an addition of 31.5 MW_e by 2020, the total installed capacity is expected to reach 1.06GW_e**.**

Kenya

With 861MW_e, Kenya has the 8th largest installed geothermal power capacity.**[Error! Bookmark not defined.]** Geothermal resources in Kenya are located within the Rift Valley, with an estimated potential of greater than 2GW. 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

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[51] José M Romo-jones et al., 2019 Mexico Country Report, https://www.researchgate.net/publication/343111483_Geothermal_energy_in_Mexico_update_and_perspectives
[52] https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2022-power-generation-capacity-mw/
[53] Ariel D Fronda and others, Geothermal Energy Development: The Philippines Country Update, http://large.stanford.edu/courses/2016/ph240/makalinao1/docs/01053.pdf
[54] Gerald W. Huttrer, Geothermal Power Generation in the World 2015-2020 Update Report, https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01017.pdf
[55] Hadi Setiawan, Geothermal Energy Development in Indonesia: Progress, Challenges and Prospect; https://www.researchgate.net/publication/291106700_Geothermal_Energy_Development_in_Indonesia_Progress_Challenges_and_Prospect
[56] Geothermal Energy in Indonesia, https://www.indonesia-investments.com/business/commodities/geothermal-energy/item268
[57] Geothermal energy in New Zealand, https://www.eeca.govt.nz/insights/energys-role-in-climate-change/renewable-energy/geothermal/
[58] Geothermal Energy Generation, https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-generation-and-markets/geothermal-energy-generation/

fast-tracking the potential resources.[59] As part of the Kenya Vision 2030 objective, Kenya aims to build up to 5.53GW of geothermal power by 2030.[60]

Eastern African Rift System

The East African Rift System, one of the largest rifts in the world, stretching from Mozambique to Djibouti, has a significant untapped geothermal potential [61] with the capability to produce over 15GW of geothermal power.[62] Geothermal heat can also be used for low-temperature heat, as required by the manufacturing industry, making it a suitable substitute for fossil fuels. The Geothermal Risk Mitigation Facility (GRMF), launched in 2012, awards grants to cover part of the investment costs associated with early-state geothermal power projects in East Africa. As of May 2020, 14 surface studies and 16 drilling programs were supported in 6 countries. GRMF is playing a critical role in establishing geothermal as a strategic option in power expansion planning. Of the countries in the East African Rift System, Kenya is the 8th largest geothermal energy producer. Other nations in the region, Ethiopia, and Rwanda, are exploring geothermal resources for the future.

3.4 Different Regions with Underdeveloped or Unexploited Geo-resources

The Spanish Canary Islands have enormous untapped geothermal potential for air conditioning and power plants in all islands. Geothermal has the potential to generate 30% of its energy needs. Not far from Canary Island, the archipelago of the Azores is deriving 22% of its energy demand from geothermal.[63] The geothermal potential of the Gran Canaria region in the Canary Islands found that the temperature of hot underground water is around 150°C at a depth of 2.5 km and it is estimated that enough geothermal energy is present in Gran Canaria to generate electricity.[64] Although geothermal resources are abundant on Caribbean islands, apart from Guadeloupe, which has a 4.5MW_e binary plant, geothermal development is still in the early stages. Guadeloupe has an estimated 3.5GW_e of geothermal power potential. Guadeloupe has the only geothermal power plant in the Caribbean, a 4.5MW_e plant at Bouillante. There are plans to expand the Bouillante plant. The very active Mt. Pele comprises an obvious locus for geothermal resources. Martinique has an estimated 3.5GW_e of geothermal power potential. There are plans to set up a geothermal plant in Martinique. The Netherlands Antilles has an estimated 3GW_e of geothermal power potential. Dominica has an estimated 1.39GW_e of geothermal power potential. Grenada has an estimated 1.11GW_e of geothermal power potential. High enthalpy resource in Mount Saint Catherine was confirmed in 1992. Montserrat has an estimated 940MW_e of geothermal power potential. St. Vincent and the Grenadines have an estimated 890MW_e of geothermal power potential. St. Lucia has an estimated 680MW_e of geothermal power potential. St. Kitts and Nevis have an estimated 50MW_e of geothermal power potential.[65] 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

[59] Kenya Energy Situation, https://energypedia.info/wiki/Kenya_Energy_Situation
[60] https://en.wikipedia.org/wiki/Geothermal_power_in_Kenya
[61] https://www.irena.org/news/articles/2020/Nov/The-East-African-Rift-Realising-the-Regions-Geothermal-Potential
[62] Peter Omenda et al., overview of geothermal resource utilization in the east African rift system, https://orkustofnun.is/gogn/unu-gtp-sc/UNU-GTP-SC-11-41.pdf
[63] https://www.thinkgeoenergy.com/spanish-canary-islands-with-enormous-geothermal-potential/
[64] https://www.thinkgeoenergy.com/studies-indicate-sufficient-geothermal-resources-to-power-all-gran-canaria/
[65] https://sustainabledevelopment.un.org/content/documents/3339energy_joseph.pdf

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 increasing worldwide. Study has shown that geothermal power could be sold to the utilities for less than the 12 -15¢/kWh cost of generation now estimated by the various Caribbean utility companies. Considering all these factors, OPTIDRILL will encourage investors in geothermal power production in these regions which will lower the dependency on fossil fuels and reduce electricity cost.

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

A feed-in tariff (FIT) guarantees that renewable energy producers can sell the electricity they generate at a price set in advance by the government under a long-term contract. Countries use FIT to promote renewable sectors by compensating for the higher LCOE of renewable sources. In most EU countries and other countries around the world, the feed-in-tariffs instrument plays a vital role in boosting 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/kWh. By comparison, in neighbouring Poland, residents paid half as much, while households in the USA 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 FIT aims to promote renewable energies to increase the share of renewable energy in the electricity mix and produce no greenhouse gases (GHGs) for a sustainable environment for future generations. Currently, FIT is determined based on 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 FIT schemes, investors are eligible for payment of additional bonuses due to innovative applications such as enhanced geothermal systems.[66] The future of FIT is uncertain. Some countries are reducing or phasing out FIT for certain renewable sources, including geothermal. In Germany, the feed-in tariff guarantee ran for 20 years. The guaranteed price is now too expensive, and lowest-bid auctions are taking over, making some of the smaller plants unviable.[67] [68] In this scenario, LCOE reduction from OPTIDRILL technology can make geothermal plants more competitive, expediting the growth of geothermal energy in Europe and beyond.

[66] Feed-in Tariffs (FIT), https://energypedia.info/wiki/Feed-in_Tariffs_(FIT)
[67] https://energypost.eu/germany-will-the-end-of-feed-in-tariffs-mean-the-end-of-citizens-as-energy-producers/
[68] https://www.dentons.com/en/insights/alerts/2020/november/26/retroactive-cuts-for-solar-feed-in-tariffs

4. CONCLUSION

In this report, OPTIDRILL's impacts on the sustainability of geothermal power and the potentialities for improving the growth of geothermal power in European and global countries were discussed. The main points were:

- Due to its baseload capability, geothermal power will be in high demand as fossil fuel plants are going offline for grid stability.
- An increasing number of deep wells will be drilled to access high-temperature geothermal resources.
- OPTIDRILL will contribute to the reduction of high drilling and completion costs.
- The potentialities of OPTIDRILL in different regions of the world where geothermal power is operational, with unexplored and underdeveloped geothermal resources, and with high energy costs and low feed-in tariff was discussed.
- Exploiting the huge untapped potential of geothermal energy will require drilling many wells, where OPTIDRILL can contribute towards reducing the drilling costs.
- Large number of geothermal power plants projected to come online by 2050. In each of them OPTIDRILL can contribute towards reducing the drilling costs
- OPTIDRILL contributes to increasing the competitiveness of geothermal power
- OPTIDRILL provides environmental reduction compared to existing drilling technologies