AADE-23-NTCE-039

A Summary of Lessons Learned from European Geothermal Applications

Ahmed Amer, Vance Smith, Lucio Bussaglia and Alessandro Cascone, Newpark Fluids Systems

Abstract

The number of geothermal wells drilled throughout the world is growing as countries work to transition to cleaner energy. Energy companies are looking to leverage the production of energy and heat from these high-temperature reservoirs. However, progress has been with caution as a degree of uncertainty existed in the well designs with respect to downhole losses and related budgets when drilling these types of reservoirs. The hostile operating environment requires an engineered geothermal drilling fluid design to satisfy the operational drilling objectives of these types of wells.

This paper will showcase histories from various European geothermal wells and the suitability of these to North American geothermal fields. Although the US and many other countries have been drilling geothermal wells for decades, there is always room for improvements and lessons learned from other fields. This implementation of "best technology" becomes more critical as geothermal energy takes on new importance in the clean energy era.

Key design criteria for the engineered geothermal fluid includes adequate rheological properties for cuttings transport and thermal integrity to prevent gelation and flocculation at extreme temperature conditions. Each candidate product has been evaluated to determine efficacy with properties tested to allow time for tripping operations without impacting fluid properties, as the static condition has been recognized to be the most critical in many geothermal wells. The drilling fluids service provider conducted extensive testing of the fluid design at their research center in Rome, where the fluids are static aged at temperatures of 200°C (392°F), the upper temperature limit of the test equipment.

Introduction

The demand for energy has been steadily increasing over time and the need for non-hydrocarbon-based resources has focused on renewables like solar and wind with an added focus on geothermal power where the United States has been leading. Figure 1 shows the consumption of geothermal energy measured in installed generation capacity.

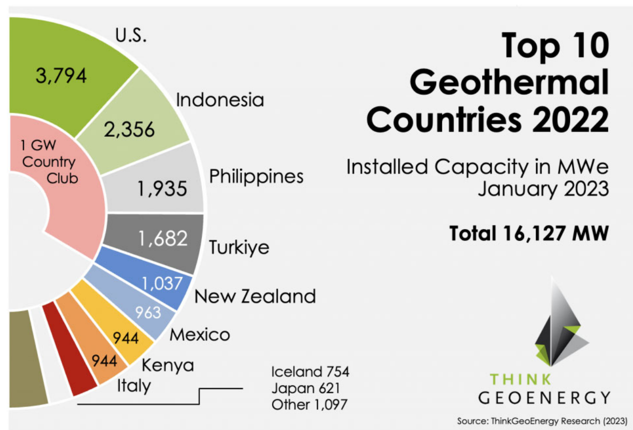

Figure 1 – Top Geothermal Countries in 2022 based on installed generation capacity (Mwe) (Think Geoenergy, 2023b)

The above information combined with the expected increase in geothermal demand (Figure 2) explains the industry's focus on how to make geothermal more economic and compete with other sources in the energy mix.

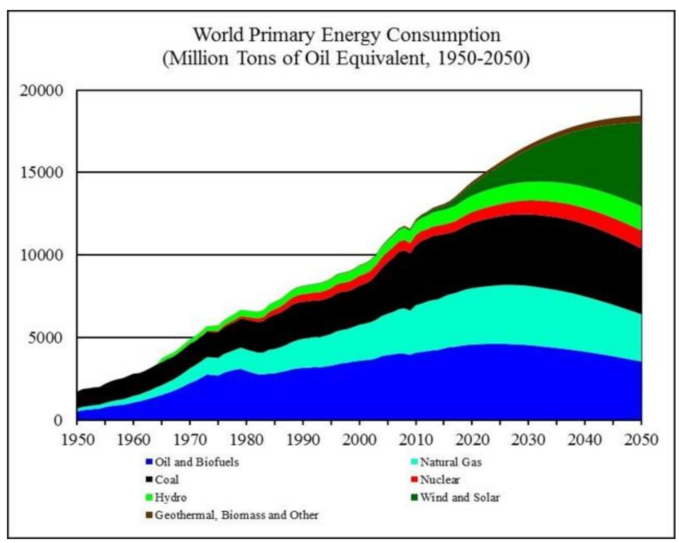

Figure 2 – World energy consumption by source shown historically from 1950 and predicted to 2050 (Li, 2017).

That said, the energy industry seems to typically bundle the various types of geothermal systems in one category while the reality is there are more ways to classify and differentiate based on the temperature and type of rock as shown in Figure 3 and Figure 4 below.

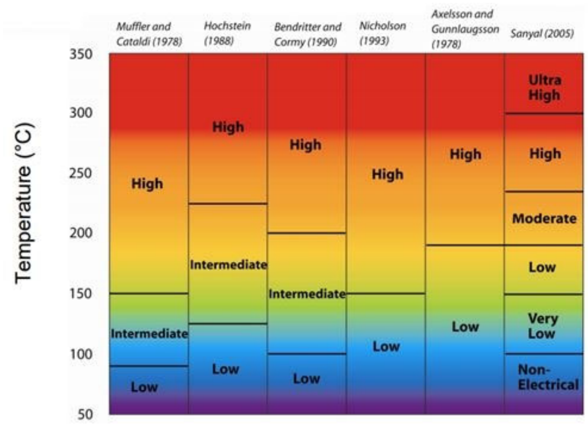

Figure 3 – Classification of geothermal operations by temperature (Williams et al., 2011).

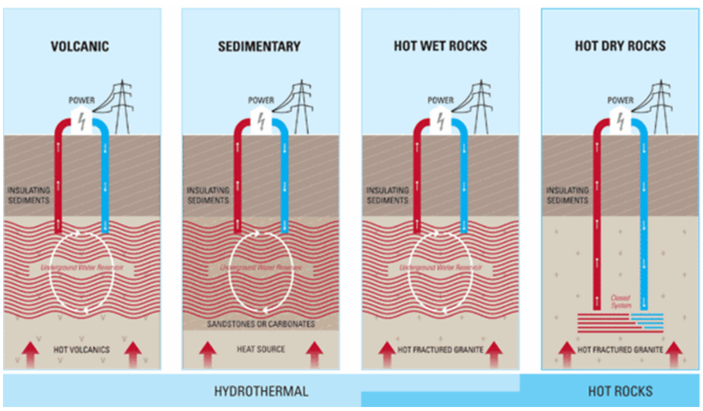

Figure 4 – Classification of geothermal operations by rock type (Think Geoenergy, 2023).

A study done by the National Renewable Energy Lab and Colorado School of Mines showed that the key cost factors in a geothermal project are both the drilling costs in general and specifically the cost allocated to lost circulation which accounts for $2 to 28 million US dollars in the capital cost of an average geothermal plant (Figure 5).

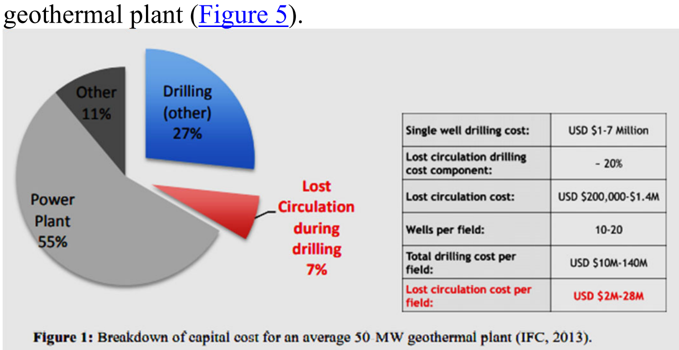

Figure 5 – Cost breakdown of geothermal drilling highlighting the lost circulation cost as a significant percentage of the overall cost (Cole et al., 2017)

Further analysis shows that the chances of failure in curing these losses is much higher than chances of success across the various loss rates as illustrated in Figure 6.

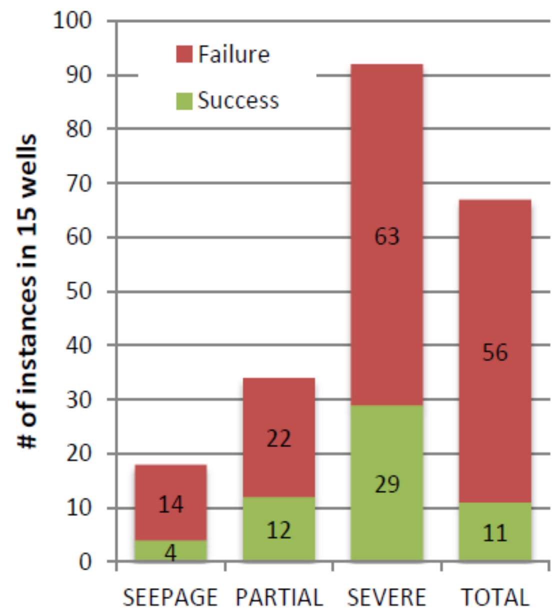

Figure 6 – Seepage severity vs failure/success rates for 15 wells (Cole et al., 2017).

This can be attributed to several factors around the fluid selection and the suitability of the lost circulation material (LCM) to the loss zone, the size of the fractures, and the extreme temperatures at which some of the conventional LCM carried over from oil and gas drilling activity break down.

Experience From Global Applications

Case History 1 (Tuscany, Italy)

Italy is one of the most renowned country worldwide in the geothermal sector (Pallotta et al, 2020). Geothermal energy is used in Italy to satisfy general heating requirements. The hottest geothermal areas in Italy are located in the tectonically active regions of Southern Tuscany (Figure 7). These areas host all the national geothermal plants for electricity production and most of the geothermal district heating networks.

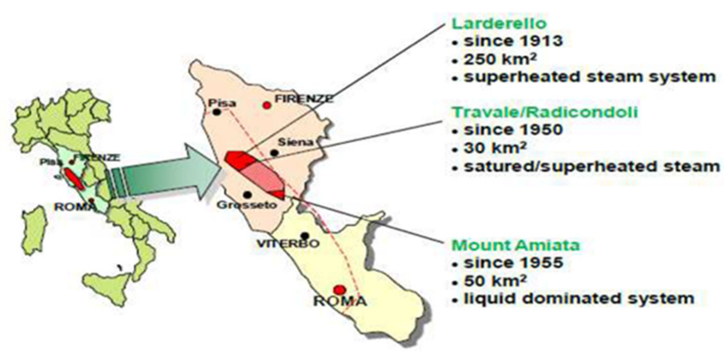

Figure 7: Traditional geothermal areas in Italy (Manzella et al., 2019).

Geothermal resources are abundant in Italy, ranging from resources for shallow applications (mostly heat pump technology), through to medium (>90°C) and high (>150°C) temperature systems at depths accessible only by wells (usually within 3-4 km). High temperature systems tend to be in tectonically active regions either in volcanic and intrusive or fault-controlled systems (Santilano et al., 2015). Many direct applications of geothermal heat are also located in Tuscany, however thermal uses are widespread in the national territory, with district heating systems mostly localized in the north and other direct uses and ground source heat pumps distributing on a much larger territory (Bargiacchi et al, 2020).

From 1989 to 2022, we have serviced nearly 100 wells (Figure 8) in this area using unweighted dispersed system formulated with commercial bentonite, synthetic polymer viscosifier, and thinners to deflocculate the drilling fluid to adjust to the high temperature environment. In some cases, the mud cooler was installed at the rig site to cool the drilling fluid at surface.

On the majority of the wells, the low-pressure gradient does not require the use of any weighting additives. However, in some areas, due to the development of abnormal overpressure gradient, a weighted drilling fluid is needed with the mud weight (MW) up to 14.2 lb/gal. The approach is to drill all sections with drilling fluid and switch to treated water across the reservoir section when total losses occurred. Due to the high temperature environment, high rate of water evaporation is seen that causes operational challenges such as drilling fluid thickening and flocculation. The continuous addition of water stream into the circulating system and treatment with thinners to re-establish the drilling fluid parameters is the standard treatment. Centrifuges are run to clean drilled solids from the drilling fluid. H_2S and CO_2 are present in some fields at concentrations of <100 ppm and <6% respectively. A recap of wells drilled in Tuscany is showed on Table 1.

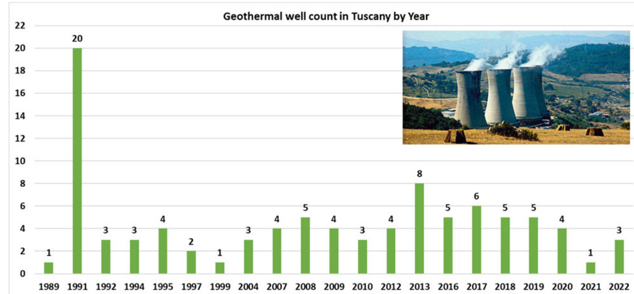

Figure 8: Geothermal well count in Tuscany region, Italy.

Table 1: Summary Recap of Wells Drilled in Tuscany Region, Italy	
Well count	94
Max MD (ft)	15,184
Min MD (ft)	928
Average MD (ft)	4,422
Max MW (lb/gal)	14.19
Min MW (lb/gal)	8.51
Average MW (lb/gal)	10.67
Max BHST (°F)	864
Min BHST (°F)	62
Average BHST (°F)	325
Max deviation (°)	33

Case History 2 (Germany)

Germany is another country in Europe characterized by extensive geothermal activities. The heated water is used as steam to turn turbines, produce the power, and the secondary application is the extraction of lithium. If the bottomhole static temperature (BHST) is high enough, the water is used as steam to turn turbines and generate electricity or use the hot water for direct heating. Some geothermal wells don't produce hot water, but they are used as a massive heat exchanger to generate electricity by pumping cold water in then circulating it from the depth (as much as over 24 laterals at 26,247 ft) to the surface. Other wells are used to extract lithium from the geothermal water that is later used for the batteries in electric vehicles (EV's).

One of the drilling challenges is the presence of reactive clay while drilling the surface and intermediate sections. Based on lithology, surface section can be drilled with high-performance water-based drilling fluid (HPWBM) using biodegradable polymers for rheology control, filtration, and shale encapsulation with less than 3% polyamine shale inhibitor or with bentonitic spud mud. Intermediate sections are drilled with HPWBM with the use of potassium carbonate as shale inhibitor as a substitution for potassium chloride for environment reasons. The reservoir section is drilled using a high-temperature reservoir drilling fluid (HT RDF) to minimize formation damage. In some wells total losses occur while drilling the reservoir section. In this scenario, water is used as a substitution for RDF.

The main challenge for drilling geothermal wells is the environmental aspect. Some wells are drilled in very sensitive areas very close to the urban centers. All products utilized must be non-water hazardous or at least classified as Water Hazard Class of 1.

Another challenge is to minimize the liquid waste for environment limitations. To reduce the volumes of waste, dewatering technology is used to treat the circulating drilling fluid "on the fly" and reuse the generated water to mix new drilling fluid or dilute the active system. Dewatering is the process of removing the majority of colloidal size solids by the addition of chemicals to coagulate and flocculate the solids in the drilling fluid; then this blended, chemically enhanced fluid is pumped to a decanting centrifuge that mechanically separates the solids from the water (Figure 9). A summary of wells drilled in Germany is shown on Table 2.

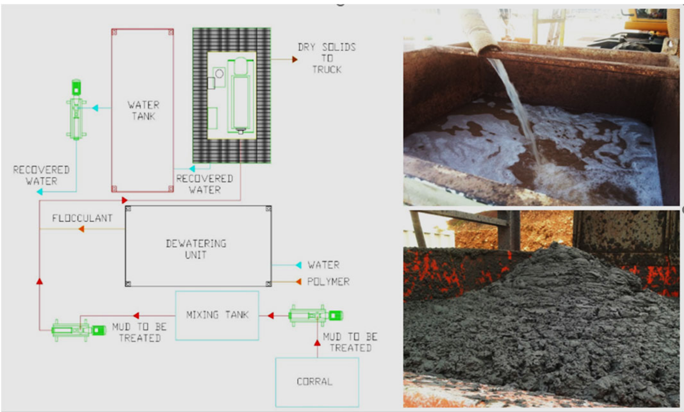

Figure 9: Dewatering process

Table 2: Geothermal Well Summary in Germany

Year	Well Name	MD (ft)	Deviatio n (°)	Max BHST (°F)	Max MW (lb/gal)
2005	Well #01	,,7,516	45	320	9.4
2006	Well #02	10,958	Vertical	320	9.5
2008	Well #03	11,309	25	320	9.9
2009	Well #04	12,654	35	320	9.7
2010	Well #05	12,654	35	302	9.2
2017	Well #06	16,975	70	329	16.0

Case History 3 (Iceland)

In April 2009 drilling started on a geothermal well through a basaltic formation in a remote zone in Iceland characterized by very low ambient temperature in the range of -32 and -18°C (Figure 10). Due to the location of the well, distances from supply centers, and extreme weather conditions; logistics and lead time for shipment of products were critical for the success of the project. Although the original plan called for TD at 16,404 ft, due to the extreme high bottom temperature and volcanic activity, the final depth was anticipated at 6,890 ft (2,100 m). A mud cooler was installed to cool the drilling fluid.

The well was drilled with the use of a dispersed fluid whose formulation is showed on Table 3. During drilling, formation losses were recorded with a loss rate of 10 to 20 m^3/hr. Losses were partially cured by pumping LCM pills using different materials. At the depth of 1,907 m, a logging tool was run downhole registering a BHST of 160°C. Due to the severe formation losses, the operator decided to continue drilling with water until 2,101 m where it was not possible to continue due to the high temperature and seismic activity.

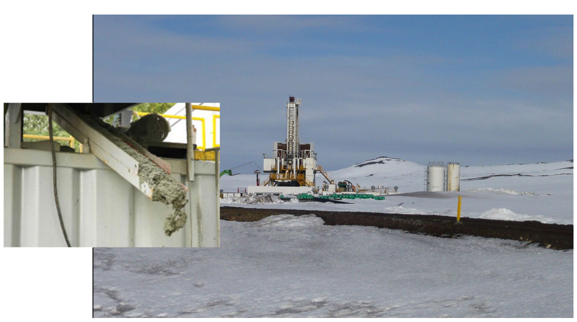
Figure 10: Well Site in Iceland.

Table 3: Iceland Drilling Fluid Composition

Product	Function	Conc. (lb/bbl)
Resinated Sodium Lignosulfonate	HT fluid loss and rheology stabilizer	3.5
API Bentonite	Viscosifier and fluid loss reducer	26
Synthetic Polymer	Thinner and HT fluid loss reducer	1.8
Humic Granule	Thinner and HT fluid loss reducer	5.3
Chrome-Free Lignosulfonate	Thinner	3.5
Liquid PHPA	Shale stabilizer and Viscosifier	1.0

Case History 4 (Azores-Portugal)

In November 2020, drilling started on a one-year geothermal campaign in Azores islands in Portugal comprised of 8 wells (Table 4). The main challenge was to drill in very sensitive and touristic areas that strictly required the utilization of products with low environmental impact.

The Azores are located above an active triple junction between three of the world's major tectonic plates. The volcanic geology, associated with the occurrence of many springs in the foothills, resulted in a basin with high geothermal gradient. The Ribeira Grande geothermal field lies on the northern flank of the Fogo Volcano.

The permeability of this geothermal reservoir is associated with fractures in the volcano's geology. The project scope was to drill 4-5 new wells (1,100 – 1,200 m true vertical depth (TVD) to develop the current field in the Island of Sao Miguel, followed by 3-4 wells (30° deviated, 2,000 m TVD / 2,229 m measured depth (MD) to develop production on the island of Terseira.

Drilling in basalt rocks with high geothermal gradient (250°C at 1,000 m TVD) generates natural challenges associated with high temperature, including:

- Product degradation
- Abnormal drilling fluid water evaporation
- Abnormal physical behavior of the drilling fluid
- Drilling fluid total losses at various depth (up to 2.895 m^3/well)

High temperature is a root cause for product degradation, negatively affecting the performance of the drilling fluid. At the same time, evaporation in conjunction with product degradation results in abnormal physical behavior of the drilling fluid which requires dilution of compensation water and fluid products to be carefully controlled. Maximum mud weight required was expected to reach 1.1 SG. Additional challenges often associated with thermal basins include the nature of the geology and stratigraphy which can result in total losses at various depths, starting in this particular field from the top section (60 – 70 m). Continuous management of the drilling fluid was essential to proactively adjust the formulation and maintain dilution rates, including reacting immediately to major downhole total losses such as encountered as early as the top

Table 4: Geothermal Well Summary in Azores Islands

Year	Well Name	MD (ft)	Deviation (°)	Max BHST (°F)	Formation losses (bbl)	Max MW (lb/gal)
2020	Well #1	3,281	Vertical	482	467,778	9.60
2021	Well #2	3,455	Vertical	482	181,896	9.02
2021	Well #3	3,455	Vertical	482	141,669	9.18
2021	Well #4	3,527	Vertical	482	467,778	8.85
2021	Well #5	3,527	Vertical	482	609,765	8.68
2021	Well #6	3,527	Vertical	482	694,035	9.02
2021	Well #7	7,635	30.5	N/A	363,792	8.76
2021	Well #8	5,249	3.5	N/A	86,178	8.68

section. The company's supply chain planning was essential to the project success, establishing a continuous supply of product which enabled the drilling fluid to be constantlyy built and maintained throughout the well. Table 5 recaps the successful drilling campaign that achieved a 24-day average drilling time which was a significant improvement over the 30-day drilling time anticipated.

Table 5: Azores Geothermal Field by the Numbers

Temperature and depth	250 °C at 1000 m
Expected time to drill each well (average per well)	30 days
Actual time to drill each well (average per well)	24 days
Rate of dilution (average excluding mud loss compensation)	2.5 to 4 (m^3/m^3)
Total Downhole losses (average)	1,254 m^3 / well
Total Downhole losses (maximum recorded)	2,895 m^3 / well

Successful drilling in extreme environments, such as those in the Azores geothermal field, requires extensive experience and expertise in drilling fluids technology. The decision to leverage, a high-performance water-based drilling fluid specifically designed for geothermal drilling and our extensive operational success in geothermal drilling were key to the success of the project.

Differences between Geothermal in Europe and the United States

There are several key differences between the United States and Europe in geothermal energy:

- **Resource availability**: Europe has more accessible geothermal resources than the United States due to its location along the active tectonic plate boundaries. The western part of the United States, particularly California, has some of the best geothermal resources in the country.

- **Capacity and utilization**: Europe has a higher installed capacity and utilization of geothermal energy compared to the United States. According to the International Geothermal Association, Europe has an installed capacity of 2,705 MW, while the United States has an installed capacity of 3,927 MW as of 2020. However, the utilization rate of geothermal energy in Europe is much higher, with some countries generating over 20% of their electricity from geothermal sources.

- **Policy support**: European countries have generally provided more policy support for geothermal energy compared to the United States. In Europe, governments have implemented feed-in tariffs, tax incentives, and other policies to encourage geothermal energy development. The United States has fewer national policies to support geothermal energy, but some states such as California and Nevada have implemented policies to promote geothermal development.

- **Market structure**: The geothermal energy market in Europe is more developed and mature compared to the United States. In Europe, there are more established companies and technologies that specialize in geothermal energy, and the market has a longer history of development. In contrast, the geothermal market in the United States is still relatively young and developing, with fewer companies and technologies focused solely on geothermal energy.

Conclusions and Lessons Learned

- Geothermal energy is a growing source of renewable energy, and its demand is expected to increase in the coming years.

- There are various ways to classify and differentiate geothermal systems based on temperature and rock type.

- While the utility of geothermal varies from Europe to the US in terms of direct use vs power-generation, many of the drilling challenges are common across US and Europe.

- Italy and Germany are examples of countries with extensive geothermal activities, and their experiences can provide valuable insights for geothermal projects in other regions.

- Many of the wells in Europe are conventional hydrothermal while the new initiatives in the US are around Enhanced Geothermal systems which would also require stimulation.

- Many of the challenges faced while drilling geothermal wells are the same around the world.

- Non-Productive Time and unscheduled events likelihood increases as the depth and/or temperature increases.

- Drilling challenges in geothermal projects include high temperatures, the presence of corrosive and abrasive fluids, and wellbore instability.

- The key cost factors in a geothermal project are drilling costs in general, and specifically, the cost allocated to lost circulation, which can account for a significant percentage of the overall cost of a geothermal plant.

- The chances of success in curing lost circulation losses in geothermal drilling are much lower than the chances of failure, and this is due to several factors related to fluid selection, the suitability of lost circulation material, and extreme temperatures.

- Due to gas influxes potential and use of water as a fluid; corrosion management is key.

- Despite the challenges, geothermal energy has significant potential as a renewable energy source, and ongoing research and development efforts are focused on making it more economical and competitive with other sources in the energy mix.

References

Bargiacchi, E., Conti, P., Manzella, A., Vaccaro, M., Cerutti, P., and Cesari, G. 2020. "Thermal Uses of Geothermal Energy: Country Update for Italy." World Geothermal Congress, Reykjavik, Iceland, April 20 - May 2, 2020. http://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01082.pdf

Cole, P., Young, K., Doke, C., Duncan, N., and Eustes, B. 2017. "Geothermal Drilling: A Baseline Study of Nonproductive Time Related to Lost Circulation." 42nd Workshop of Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 13-15, 2017. SGP-TR-212. https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2017/Cole.pdf

Li, M. 2017. "World Energy 2017-2050: Annual Report." Seeking Alpha website. https://seekingalpha.com/article/4083393-world-energy-2017minus-2050-annual-report

Manzella, A., Serra, D., Cesari, G., Bargiacchi, E., Cei, M., Cerutti, P., Conti, P., Giudetti, G., Lupi, M., and Vaccaro, M. 2019. "Geothermal Energy Use, Country Update for Italy." European Geothermal Congress 2019, Den Haag, The Netherlands, June 11-14, 2019.

Pallotta, D., Dei, A., Bussaglia, L., and Cascone, A. 2020. "Application of an Engineered Drilling Fluid System for Drilling an Ultra HT Geothermal Well in Central Italy." World Geothermal Congress, Reykjavik, Iceland, April 26 - May 2, 2020.

Santilano, A., Manzella, A., Gianelli, G., Donato, A., Gola, G., Nardini, I., Trumpy, E. and Botteghi, S. 2015. "Convective, Intrusive Geothermal Plays: What About Tectonics?" *Geothermal Energy Science* vol. 3 (September 15, 2015) 51-59. https://www.geoth-energ-sci.net/3/51/2015/gtes-3-51-2015.pdf

Think Geoenergy. 2023. "An Overview of Geothermal Resources." https://www.thinkgeoenergy.com/geothermal/an-overview-of-geothermal-resources/

Think Geoenergy. 2023. "ThinkGeoEnergy's Top 10 Geothermal Countries 2022: Power Generation Capacity (MW)." https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2022-power-generation-capacity-mw/

Williams, C.F., Reed, M.J., and Anderson, A.F. 2011. "Updating the Classification of Geothermal Resources." 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, January 31 – February 2, 2011. SGP-TR-191. https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2011/williams.pdf