# Carbon Neutral Electricity Production from a Fractured Granite Geothermal Reservoir with Organic Rankine Cycle: The United Downs Deep Geothermal Power Project

**Marta Giudici[1], Stefano Selva[1] and Rand Hazel Farndale[2]**

**[1]Exergy International srl**
**[2]Geothermal Engineering Ltd**

**Keywords**

*Binary Geothermal Power Plant, Organic Rankine Cycle, Radial Outflow Turbine, Hot Dry Rock Geothermal System, Total Reinjection*

## ABSTRACT

The United Downs Deep Geothermal Power (UDDGP) project near Redruth, Cornwall, is owned and operated by Geothermal Engineering Ltd (GEL) and represents the first integrated deep geothermal project in United Kingdom (UK). The plant will start construction at the end of 2023 and aims to deliver around 1.6 MWe of baseload renewable electricity by the end of 2024. Analysis of the geothermal fluid has also identified concentrations of more than 260ppm of lithium in the deep resource.

This paper presents the technical features and technologies adopted to develop this project. To develop the geothermal power plant, two deep, directional wells were successfully drilled in 2018-19 and subsequently tested in 2020-21. The production well was drilled first, to a depth of 5,275m Measured Depth (MD) – the deepest onshore well in the UK - and the injection well to 2,393m. The power plant, currently under development by Exergy, will be a 1.6 MWe net geothermal binary system equipped with Radial Outflow Turbine technology exploiting the geothermal brine of the reservoir with a total reinjection of the resource. The system will be delivered in 18 months, with start-up expected in 2024. Once in operation, this installation will save around 6,500 tons of CO2 emissions per year - Exergy et al. (2023) compared to an equal production of conventional fossil fuel power generation.

## 1. Introduction

The increase in global energy consumption and CO2 emissions have led 195 countries to define a global action plan to not exceed 1.5°C global warming compared to the preindustrial level - United Nations (2016). In order to respect this agreement, in recent years, governments, investors, companies, and private citizens have been directed towards the development of alternative energy systems to fossil fuels. The reduction in carbon intensity of the energy sector is one of the most relevant issues, not only in the electricity generation section, but also in other activities like transportation, which is responsible for a large share of the emissions, and heating and cooling. The exploitation of geothermal energy for power generation can significantly contribute to the decarbonization of the energy sector thanks to its constant availability and low emission. Unlike wind and solar power, which are dependent on weather conditions, geothermal energy provides a consistent and reliable source of power. Geothermal power plants can operate around the clock, generating electricity consistently, regardless of weather or time of day. This stability contributes to grid reliability and reduces the need for backup power sources.

## 2. Geothermal State of the art

Geothermal energy is a clean renewable energy source with a maximum capacity factor of 95% - Sullivan et al. (2010). According to theoretical calculations, the energy reserves in the upper 10 km of the earth's crust are approximately $1.3 \times 10^{27}$ J. Using the 2012 global energy consumption rate of approximately $6.0 \times 10^{20}$ J/ year as a benchmark, these geothermal reserves could supply the global energy use for approximately 217 million years - Shyi-Min et al. (2017).

Geothermal systems are often categorized into two main types: traditional geothermal (hydrothermal) systems and enhanced geothermal systems (EGSs). Traditional geothermal power systems have been in development for approximately a century, resulting in mature power generation technologies. On the other hand, EGS offers a distinct advantage by accessing more abundant heat sources through the creation of artificial fractures in hot rocks and subsequent injection of fluids.

Stefansson (2005) inferred a total electricity generation potential from traditional hydrothermal geothermal resources of 200 GWe. Based on a statistical analysis of heat distribution, Goldstein et al. (2009) concluded that there is a 70% chance that EGS systems have a potential of 1000 GWe. Thus, the technically exploitable geothermal potential is up to 1200 GWe.

For policy and investment decisions, it is the economic potential that matters. The economic hydrothermal potential for year 2050 is about 70 GWe – Bertani (2011). To assess the economic value of EGS, it is crucial to note the lack of any commercial experience to-date for EGS systems. To achieve a successful EGS installation, specific requirements must be met: a heat exchange surface area of at least 1 million m2, a reservoir volume of several cubic kilometers, a maximum flow impedance of a few MPa/l/s, and a water loss of no more than 10%. Goldstein et al. (2009), suggests that there is an 85% probability of producing at least 70 GWe of EGS power by year 2050. Thus the technically exploitable geothermal potential is up to 140 GWe for the year 2050.

Geothermal energy exhibits immense potential as a clean and sustainable energy source, with significant reserves that can meet global energy demands for millions of years. The established conventional geothermal systems, along with the emerging enhanced geothermal systems, contribute to the realization of this potential by efficiently tapping into the Earth's heat resources.

### *2.1 Conventional Geothermal Systems*

Conventional Geothermal Systems are typically found in areas where higher geothermal gradients allow hot water to flow within permeable rocks at depth. In conventional geothermal applications, a thermal anomaly alone is not sufficient for a productive geothermal resource; a reservoir is also required. The reservoir consists of a large body of permeable rocks containing significant amounts of fluid, such as water or steam, which carry heat to the surface. Cooler rocks surrounding the reservoir, connected by fractures and fissures, act as channels for rainwater to penetrate underground. Impermeable cap-rocks often prevent fluid escape, maintaining pressure within the reservoir – Barbier et al. (2002).

The conjunction of these particular characteristics is uncommon, resulting in a notable constraint on exploiting the energy reserves in the upper 10 km of the Earth's crust, confining the utilization to a limited number of locations worldwide - Moeck (2014).

### *2.2 Unconventional Geothermal Systems - Enhanced Geothermal Systems (EGS)*

The currently used term ‘enhanced or engineered geothermal system’ (EGS) has its roots in the early 1970s when a team from Los Alamos National Laboratories began the hot dry rock (HDR) project at Fenton Hill. - Breede et al. (2013)

High-temperature HDR (Hot Dry Rock) geothermal systems enable the extraction of significant amounts of thermal energy from specific areas of the Earth's surface that are characterized by abnormally high temperatures but lack substantial naturally occurring steam or hot water. These regions, accessible through conventional drilling methods, consist of dry rock formations. In contrast to conventional (wet) geothermal energy sources, which rely on the presence of naturally available steam or hot water for economic viability, HDR geothermal systems make use of the thermal potential stored within these dry-rock reservoirs - U.S. DOE (2019)

The main steps for the development of HDRs are:

1. resource exploration and assessment
2. drilling of production/reinjection wells
3. creation of a reservoir (either through stimulation of existing fractures or hydrofracturing to create new fractures)
4. the injection/production cycle for extracting heat
5. power plant operation
6. maintenance of the reservoir

Shyi-Min et al. (2017)

According to the US Department of Energy - US DOE (2019), Enhanced Geothermal Systems (EGS) offer several key advantages over Conventional Wet Geothermal Systems:

- Contribution to the energy portfolio: EGS holds the potential to become a significant contributor to the global energy mix as a clean and renewable energy source.
- Low Greenhouse Gas Emissions: EGS demonstrates minimal to no greenhouse gas emissions. Most EGS geothermal power plants employ closed-loop binary cycle technology, which results in negligible greenhouse gas emissions.

- Expansion of Geothermal Energy Production: EGS has the capability to facilitate geothermal energy development beyond the limitations of traditional hydrothermal areas. By leveraging EGS technology, geothermal energy production can be extended to regions that were previously considered unsuitable for conventional geothermal systems.
- Baseload Energy Supply with Reduced Intermittency: EGS can provide baseload energy, ensuring a consistent and stable power supply without significant intermittency. This characteristic eliminates or minimizes the need for additional energy storage technologies, simplifying the integration of geothermal energy into existing power grids.

The primary challenging aspect of EGS technology lies in the initial high risk associated with resource exploration and assessment, as well as the substantial upfront investment required for establishing the artificial reservoir. Over the past four decades, advancements in creating fractures in hot and dense rock formations have been made through the knowledge gained from oil and gas production experiences. The feasibility of EGS implementation relies on the specific conditions present at the demonstration site. With the maturation of hydraulic fracturing technology, the success rate of EGS projects has progressively improved, as evidenced by achievements recent projects such as Desert Peak - Akerley et al. (2021), Utah FORGE project - Norbeck et al. (2023) and Fervo wells at the Blue Mountain geothermal field in Nevada - Fercho et al. (2023). The early stages of EGS development have highlighted the critical importance of selecting suitable sites for optimal project outcomes, complementing the advancements in mining technologies. If the development of today's conventional geothermal technology continues, more than 70 GWe of EGS will be exploited in 2050, at an estimated probability of 85%. After 2050, the global installed geothermal capacity is expected to focus on EGS - Shyi-Min et al. (2017).

## 3. Case Study - Geothermal Exploitation in Cornwall

For decades, it has been established that the heat-generating granites in Southwest England hold significant potential as a geothermal resource. Evidence from historical records, measurements in deep tin and copper mines, and firsthand accounts from miners have consistently indicated elevated temperatures, findings which were corroborated by heat flow studies and geothermal assessments conducted in the 1970s and 1980s (e.g., Francis (1980), Downing and Gray (1985)). Notably, the heat flow in the Cornish granite is almost double the United Kingdom (UK) average, exceeding 120mW/m2 - Ledingham et al. (2021).

A Hot Dry Rock (HDR) geothermal research program was conducted at Rosemanowes Quarry, near Penryn in west Cornwall, from the late 1970s to the early 1990s - Parker (1999). This project significantly contributed to the understanding of HDR reservoir development, specifically emphasizing the importance of naturally occurring joints and fractures aligned in favorable orientations, parallel to the regional maximum stress.

In 2009, a comprehensive study was undertaken within a data-rich 400km2 region of west Cornwall, encompassing the Carnmenellis granite outcrop, the original HDR research site, and numerous abandoned mines. From the study, the Porthtowan fault zone emerged as the optimal host for a geothermal reservoir (Figure 1 – Map of South Cornwall (UK): Granite Outcrop, Porthtowan Fault Zone and United Downs.Figure 1). Its considerable length and linear nature suggest a near-vertical orientation and persistence at depth, as evidenced in certain mining operations. Several sites were evaluated, and the chosen location was a brownfield site situated within the United Downs Industrial Estate, approximately 2 miles east of the town of Redruth - Ledingham et al. (2021).

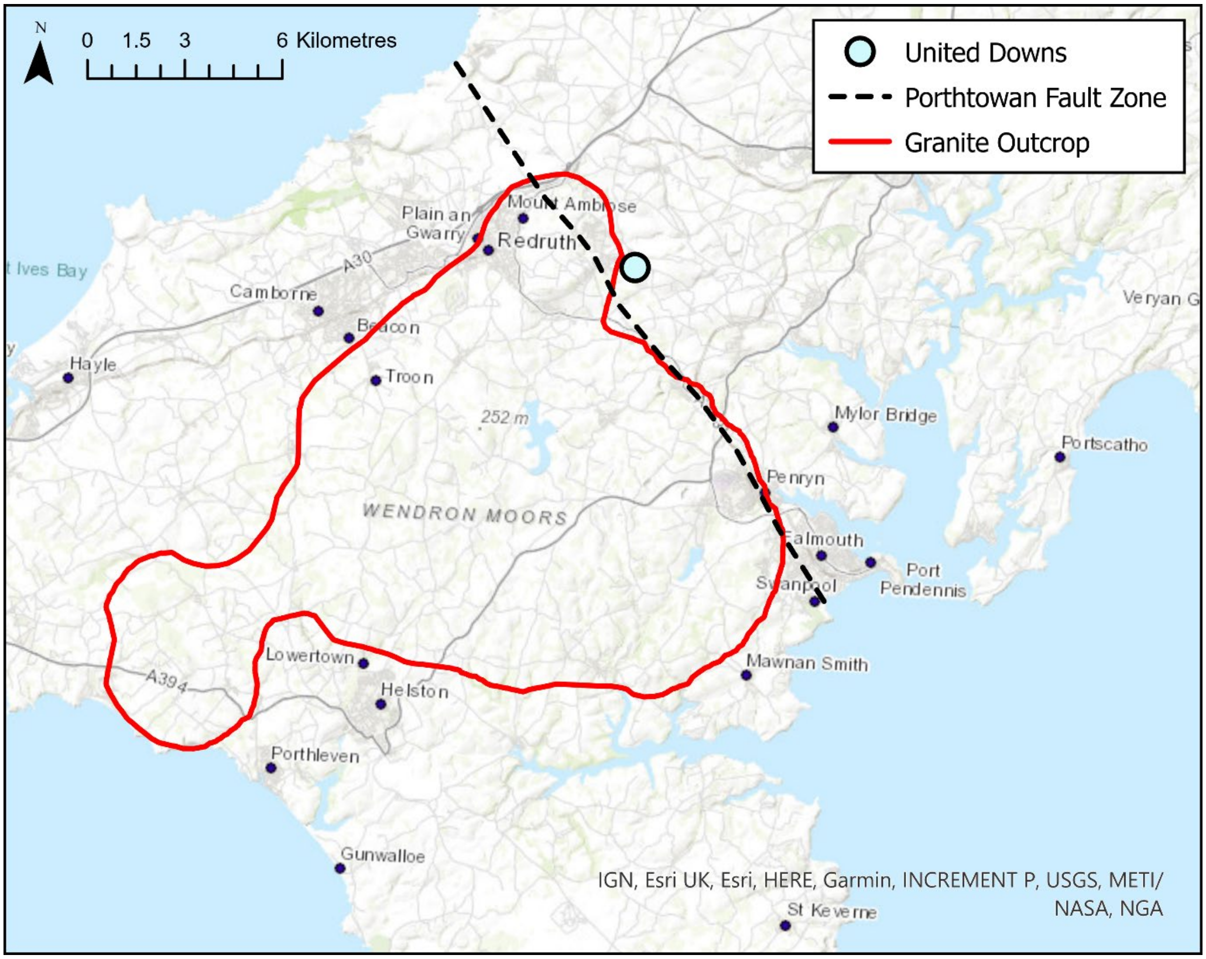


**Figure 1 – Map of South Cornwall (UK): Granite Outcrop, Porthtowan Fault Zone and United Downs.**

### *3.1 United Downs Deep Geothermal Power (UDDGP) project*

The UDDGP concept is an innovative approach to geothermal development that relies on several key factors. One important factor is the utilization of large spacing between the production and injection wells, which helps overcome the risks associated with closely spaced wells in systems like HDR (Hot Dry Rock) and EGS (Enhanced Geothermal Systems). These risks include short-circuits and poor long-term temperature performance. However, by targeting fractures or fault systems with high natural permeability, larger well spacing becomes feasible.

Lessons learnt from the previous Rosemanowes research project – Parker (1999) and Richards et al. (1994) influenced this design. At Rosemanowes, the injection well was placed beneath the production well, with the expectation that injected water would migrate upwards driven by injection pressure. However, it was observed that the injected water migrated downwards through shear stimulation on favorable joints, resulting in significant water loss. The UDDGP system addresses this issue by implementing a downhole pump in the production well to create a pressure sink. This pump will draw water not only from the injection well but also from the far-field, aiming for low-pressure operation and 100% recovery. Prior to development, it was anticipated that shearing on natural fractures could occur at relatively low pressures. Given the similar stress regime to the Rosemanowes HDR site, downward migration of the injected fluid was also expected, with increasing injection pressure temporarily could further drive the fluid downwards if needed - Ledingham et al. (2021).

Geothermal Engineering Ltd (GEL) acquired the United Downs Project in 2010, with the project now entering the final stage of development. The procurement and drilling phases took place between 2018 and 2019 resulting in the realization of directional wells UD-1 and UD-2 of 5,275m and 2,393m measured depth, respectively.

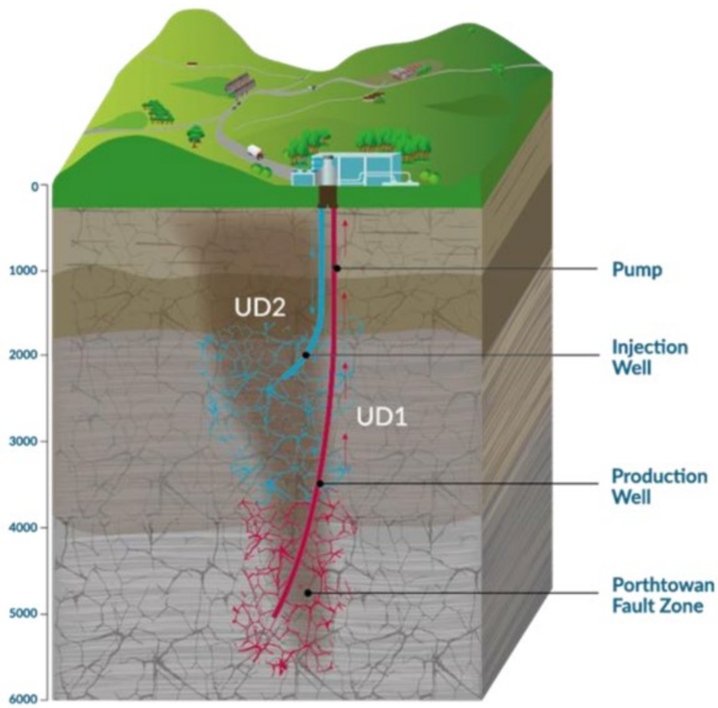


**Figure 2 - Schematic of the geothermal doublet at United Downs, drilled into the Porthtowan Fault Zone - Ledingham et al. (2021)**

Between August 2020 and July 2021, injection tests were conducted on both wells to analyze the hydraulic environment of the reservoir and enhance productivity. These tests aimed to understand the characteristics of the granite reservoir, improve flow rates for sustained power plant operation through hydraulic stimulation, monitor injection-induced seismicity, determine safe flow rate levels, and alleviate reservoir stress - Farndale et al. (2022).

In July 2021, a seven-day reservoir testing period was conducted. An Electrical Submersible Pump (ESP) was deployed into UD-1 and connected to injection pumps on UD-2 to simulate power plant operation and evaluate overall reservoir performance. The methodology and results of reservoir testing is described in detail in Farndale et al. (2023).

**Figure 3 - United Downs Deep Geothermal Power Plant wells UD-1 and UD-2**

The final phase of the project, started in 2023, involves the construction of a binary power plant with a closed loop gathering system. This design entails the complete reinjection of the geothermal resource, resulting in a zero-emission geothermal power system. Exergy International srl has been entrusted with the design and construction of the plant that is expected to be operational in 2024.

### *3.2 United Downs Deep Geothermal Power Plant: Exergy's Customized ORC Solution*

Exergy's UDDGP ORC power plant will be supplied by the brine coming from the production well UD-1. The brine will enter the ORC at a temperature of 170°C, then cooled down to ~50°C in the duplex tubes of the shell and tube heat exchangers. The thermal power which derives from the brine is used first to preheat and then to evaporate and superheat the organic fluid typically adopted in ORC geothermal applications. In the selected cycle configuration, the organic fluid enters in the Radial Outflow Turbine in superheated conditions and is expanded down to the condensation pressure. Before entering the condenser the valuable heat of turbine exhaust is recovered in a recuperator to enhance cycle efficiency. The condenser is an induced air-cooled condenser. After the condenser, two feed-pumps are used to increase the pressure up to the maximum value, to close the loop. After the last ORC heat exchanger the cold brine is sent to the reinjection system where two multistage centrifugal pumps give the geothermal fluid the necessary head to be reinjected.

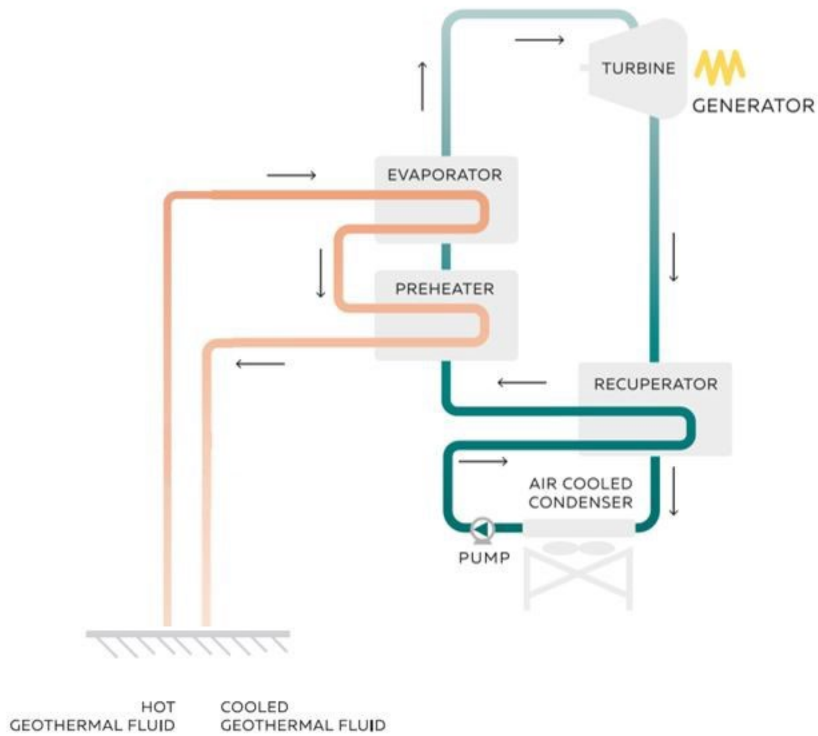


**Figure 4 - Simplified diagram of an air-cooled Organic Rankine Cycle, with heat delivered from a geothermal system.**

Starting from the working fluid selection that has been tailored to optimize heat source compatibility and enhance overall efficiencies, the entire cycle configuration has been optimized according to Exergy's know-how and experience. The optimization of the thermodynamic cycle in combination with the design of major equipment (such as pump, heat exchangers and turbine) have been carried out to reach the technical-economic optimum for the system. At the core of the power plant there is the Radial Outflow Turbine (ROT) technology, which represents a pioneering advancement in the field. This innovative turbine design, protected by current and pending patents, marks the first utilization of its kind within an Organic Rankine Cycle (ORC) system. The Radial Outflow Turbine, different from the axial and radial inflow configuration, is able to convert the energy contained in the fluid into mechanical power, with higher efficiency than any competing technology present on the market.

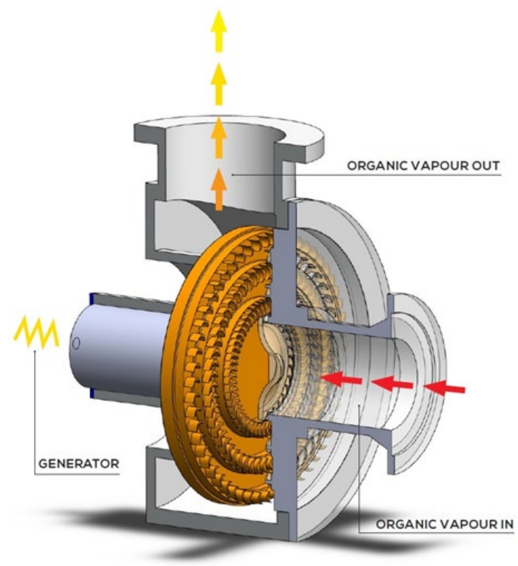


**Figure 5 - Exergy's Radial Outflow Turbine**

Thanks to cycle optimization and the utilization of highly efficient technologies, Exergy design of the Organic Rankine Cycle enables the efficient utilization of brine thermal energy to achieve a gross power production of approximately 3MWe. Considering the ORC auxiliaries power consumption of ~ 500kWe and the expected production and reinjection pump consumption of ~ 580 kWe and ~ 320 kWe respectively the net electric power production of the plant will be approximately 1.6 MWe.

**Figure 6 - Rendering of United Downs Deep Geothermal Power Plant**

## 4. An incoming opportunity – Lithium extraction from brine

Lithium was discovered in Cornwall in 1864 in the hot underground (geothermal) fluid when was taken from a tin mine for analysis - Miller (1864). During geothermal well testing at the United Downs site, GEL also took samples of the fluid from circa 5km below the surface. Analysis of these samples found globally significant lithium concentrations of more than 260ppm.

Global lithium production has tripled between 2010 and 2020, indicating its growing importance. However, the demand for lithium is projected to increase significantly further by 2050, potentially 18-20 times higher than present if current extraction policies continue - Vera et al. (2023). Presently, lithium extraction is predominantly done from hard-rock ores and continental brines. The traditional method of extracting lithium from continental brine deposits involves open air evaporation, which concentrates the brine but results in the loss of large volumes of water. This evaporation-based process raises concerns about its overall sustainability. As the demand for lithium continues to rise, there is a need to develop sustainable and efficient extraction methods. To address these challenges and diversify lithium production, researchers are urgently exploring economically viable technologies for extracting lithium. This new approach, called direct lithium extraction (DLE), encompasses various technologies, including thermal and electrochemical processes. DLE technologies have overcome many limitations of conventional lithium extraction, particularly in terms of water usage.

## 5. Conclusions

The development of hot dry rock technology has the potential to boost geothermal power generation. The United Downs Deep Geothermal Power Project is a pioneering project in this field and its success will contribute significantly to the wider adoption and spread of this technology. Since the successful testing of the United Downs wells in July 2021, GEL have secured planning permission for two further geothermal sites within Cornwall, with a number of additional sites also in the planning pipeline.  further advancing the utilization of geothermal energy for sustainable power generation. The United Downs site has therefore catalyzed a new UK industry, further advancing the global utilization of geothermal energy for sustainable power generation.

## REFERENCES

Akerley, J.H., Robertson-Tait, A., Zemach, E., Spielman, P., and Drakos, P., “Near-field EGS: A review and comparison of EGS demonstration projects at Desert Peak and Bradys”. *Proceedings World Geothermal Congress 2020+1*, Reykjavik, IS (2021).

Barbier, E., “Geothermal energy technology and current status: an overview”, *Renewable and Sustainable Energy Reviews,* 6, (2002), 3–65.

Bertani, R., “Geothermal power generation in the world 2005–2010 update report”, *Geothermics,* 41, (2012) 1–29

Breede, K., Dzebisashvili, K., Liu, X. and Falcone, G., “A systematic review of enhanced (or engineered) geothermal systems: past, present and future”, *Geothermal Energy*, (2013), 1-4.

Downing, R.A., and Gray, D.A., “Geothermal Energy The Potential in the United Kingdom”, *H.M.S.O.*, Norwich, UK (1986).

Exergy International Srl, Geothermal Engineering Ltd, "Exergy and Geothermal Engineering Ltd. (GEL) Sign Contract for UK's First Deep Geothermal Power Plant", (2023).

Farndale, H., and Law, R., "An Update on the United Downs Geothermal Power Project", *Proceedings: 47th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA (2022), 7-9.

Farndale, H., and Law, R., "The Effects of Soft Stimulation on Reservoir Growth and Injectivity at the United Downs", *Proceedings: 48th Workshop on Geothermal Reservoir Engineering* Stanford, CA (2023), 6-8.

Fercho, S., Norbeck, J., Mcconville, E., Hinz, N., Wallis, I., Titov, A., Agarwal, S., Dadi, S., Gradl, C., Baca, H., Eddy, E., Lang, C., Voller, K., and Latimer, T., "Geology, State of Stress, and Heat in Place for a Horizontal Well Geothermal Development Project at Blue Mountain, Nevada", *Proceedings: 48th Workshop on Geothermal Reservoir Engineering*, Stanford, CA (2023), 6-8.

Francis, M.F., "Investigation Of The South West England Thermal Anomaly Zone", PhD Thesis, Imperial College, London, UK (1980).

Goldstein, B.A., Hill, A.J., Long, A., Budd, A.R., Ayling, B., Malavazos, M., "Hot rocks down under – evolution of a new energy industry", *Geothermal Resources Council Transactions 33*, (2009), 185–198

Ledingham, P., and Cotton, L., "The United Downs Deep Geothermal Power Project", *Proceedings: World Geothermal Congress*, Reykjavik, IS (2021).

Miller, W.A., Treas, M.D., "Chemical Examination of a Hot Spring containing Cesium and Lithium in Wheal Clifford, Cornwall", *Chemical News*, X (1864), 181-182

Moeck, I.S., "Catalog of geothermal play types based on geologic controls", *Renewable and Sustainable Energy Reviews,* 37 (2014), 867–882.

Norbecka, J.H., and Latimera. T.M., "Commercial-Scale Demonstration of a First-of-a-Kind Enhanced Geothermal System", (2023).

Parker, R. "The Rosemanowes HDR project 1983-1991", *Geothermics*, 28, (1999), 603-615.

Richards, H.G., Parker, R.H., Green, A.S.P., Jones, R.H., Nicholls, J.D.M., Nicol, D.A.C., Randall, M.M., Richards, S., Stewart, R.C., Willis-Richards, J., "The performance and characteristics of the experimental hot dry rock geothermal reservoir at Rosemanowes, Cornwall (1985–1988)", *Geothermics,* 23, (1994), 73-109.

Shyi-Min, L., "A global review of enhanced geothermal system (EGS)", Renewable and Sustainable Energy Reviews, Industrial Technology Research Institute, Taiwan, ROC (2017).

Stefansson, V., "World geothermal assessment", *Proceedings: World Geothermal Congress,* Antalya, TR (2005), 24–29.

Sullivan, J.L., Clark, C.E., Han, J., and Wang, M. "Life-Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems", (2010).

United Nations, "Paris Agreement", Le Bourget, FR, (2016).

U.S. Department of Energy, "Geovision: Harnessing the Heat Beneath Our Feet", (2019).

Vera, M.L., Torres, W. R., Galli, C.I., Chagnes, A., and Flexer, V., "Environmental impact of direct lithium extraction from brines", *Nature reviews earth & environment*, 6, (2023), 149-165.