

The United Downs Project: The UK's First Integrated Deep Geothermal System Harnessing an EGS Reservoir with advanced Organic Rankine Cycle

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ABSTRACT

This paper explores the application of Exergy's Organic Rankine Cycle (ORC) using Radial Outflow Turbine technology to tap into geothermal energy at United Downs UK's first deep geothermal project. Located in Cornwall, the project utilizes an Enhanced Geothermal System (EGS) that harnesses heat from the granite rocks beneath the United Downs site near Redruth. 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 significant lithium concentrations of approximately 340 parts per million. With direct zero-carbon lithium extraction techniques GEL aims to produce as much as 12,000 tonnes of lithium carbonate equivalent per year by 2030.

The installation of the ORC power plant, currently completed and expected for commissioning in June 2025, is expected to produce around 2.5 MWe of carbon-neutral electricity. Additionally, the project will supply 10 MWth of zero-carbon heat to the Langarth Garden Village housing development, led by Cornwall Council. Once operational, it is estimated to reduce CO₂ emissions by over 6,500 tonnes annually compared to traditional fossil fuel power generation.

1. INTRODUCTION

The rise in global energy consumption and CO₂ emissions has prompted 195 countries to adopt a coordinated action plan to limit global warming to no more than 1.5°C above pre-industrial levels (United Nations, 2016). Reducing the carbon intensity of the energy sector remains a critical priority—not only in electricity generation but also in high-emission sectors such as transportation, heating, and cooling. Geothermal energy offers a valuable pathway for

decarbonization due to its continuous availability and low greenhouse gas emissions.

According to the International Energy Agency (2024), geothermal power plants achieved an average global capacity factor exceeding 75% in 2023, significantly outperforming wind and solar PV technologies. Despite this high reliability, conventional geothermal energy accounted for only 0.8% of global energy demand in 2023, with approximately 15 GW of installed capacity. However, under the IEA's Announced Pledges Scenario, geothermal capacity could surpass 80 GW by 2050, supported by enhanced technological competitiveness, next-generation systems, and improved policy frameworks enabling faster project execution and expanded drilling authorizations.

2. GEOTHERMAL SYSTEMS

According to theoretical calculations, the energy reserves in the upper 10 km of the earth's crust are approximately 1.3×10^{27} J. Using the 2012 global energy consumption rate of approximately 6.0×10^{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.

2.1 Conventional Geothermal Systems

Conventional geothermal systems are typically located in regions with elevated geothermal gradients, where hot water circulates through permeable rocks at depth. In such systems, a thermal anomaly alone is insufficient to constitute a productive geothermal resource; the presence of a reservoir is also essential. A geothermal reservoir comprises a substantial volume of permeable rock saturated with fluids, such as water or steam, which transport heat toward the surface. Surrounding cooler rocks, intersected by fractures and fissures, serve as conduits for rainwater infiltration. Impermeable cap rocks commonly overlay the reservoir, preventing fluid escape and helping to maintain pressure within the system (Barbier et al., 2002).

The combination of these specific geological conditions is relatively rare, posing a significant limitation on the exploitation of geothermal energy within the upper 10 km of the Earth's crust and restricting viable development to a limited number of locations globally (Moeck, 2014).

2.2 Unconventional Geothermal Systems - Enhanced Geothermal Systems (EGS)

High-temperature Hot Dry Rock (HDR) geothermal systems enable the extraction of substantial thermal energy from regions of the Earth's crust that exhibit anomalously high temperatures but lack significant naturally occurring steam or hot water. These systems target dry rock formations that are accessible through conventional drilling techniques. Unlike conventional (wet) geothermal systems, which depend on naturally available fluids for energy extraction, HDR systems utilize the thermal potential stored within impermeable, fluid-deficient rock formations (U.S. DOE, 2019).

The primary steps in HDR system development include:

1. Resource exploration and assessment
2. Drilling of production and reinjection wells
3. Creation of a reservoir, either by stimulating existing fractures or inducing new ones through hydrofracturing
4. Implementation of the injection/production cycle for heat extraction
5. Power Plant Operation
6. Ongoing reservoir maintenance

(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.

One of the primary challenges of Enhanced Geothermal System (EGS) technology lies in the high initial risk associated with resource exploration and assessment, as well as the significant upfront investment required to establish an artificial reservoir. Over the past four decades, advancements in creating fractures within hot, dense rock formations have been driven by knowledge gained from oil and gas industry practices. The feasibility of EGS implementation is highly site-specific, depending on geological and operational conditions present at demonstration locations. With the continued maturation of hydraulic fracturing technology, the success rate of EGS projects has gradually improved, as demonstrated by recent developments such as the Desert Peak project (Akerley et al., 2021), the Utah FORGE project (Norbeck et al., 2023), and the Fervo wells at the Blue Mountain geothermal field in Nevada (Fercho et al., 2023).

Early-stage EGS efforts have underlined the importance of selecting geologically suitable sites, which is essential to complement advancements in reservoir engineering. If current trends in conventional geothermal development continue, projections estimate that over 70 GWe of EGS capacity could be exploited by 2050, with an associated probability of 85%.

3. GEOTHERMAL EXPLOITATION IN CORNWALL

For decades, the heat-producing granites of Southwest England have been recognized as a promising geothermal resource. Historical data, including temperature measurements from deep tin and copper mines, along with firsthand accounts from miners, have consistently indicated elevated subsurface temperatures. These observations were later confirmed 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 within the Cornish granite is nearly double the United Kingdom (UK) average, exceeding 120 mW/m² (Ledingham et al., 2021).

A pioneering Hot Dry Rock (HDR) geothermal research program was carried out at Rosemanowes Quarry, near Penryn in west Cornwall, from the late 1970s to the early 1990s (Parker, 1999). This project significantly advanced the understanding of HDR reservoir development, particularly highlighting the importance of favourably oriented natural joints and fractures aligned with the regional maximum stress direction.

In 2009, a comprehensive study was conducted across a 400 km² area of west Cornwall, encompassing the Carnmenellis granite outcrop, the original HDR research site, and numerous abandoned mines. From this study, the Porthtowan Fault Zone was identified as the most suitable host for a geothermal reservoir (Fig. 1): Granite Outcrop, Porthtowan Fault Zone, and United Downs). Its considerable length and linearity suggest a near-vertical orientation with depth continuity, as evidenced by historical mining operations. Multiple candidate sites were evaluated, and the selected location—a brownfield site within the United Downs Industrial Estate, approximately 2 miles east of Redruth—was chosen for its favorable geological characteristics and accessibility (Ledingham et al., 2021).

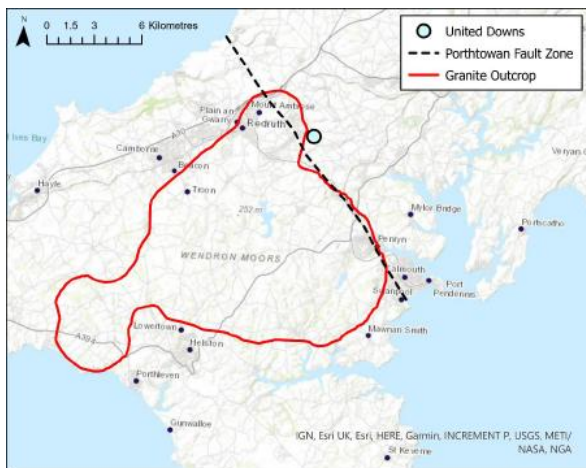


Figure 1: Map of South Cornwall (UK): Granite Outcrop, Porthtowan Fault Zone, and United Downs

3.1 The United Downs Deep Geothermal Power (UDDGP) project

The United Downs Deep Geothermal Project (UDDGP) represents an innovative approach to geothermal energy development, relying on several key design principles. One critical element is the use of wide spacing between production and injection wells to mitigate risks commonly associated with closely spaced wells in Hot Dry Rock (HDR) and Enhanced Geothermal Systems (EGS), such as short-circuiting and poor long-term thermal performance. By targeting fracture or fault systems with high natural permeability, greater well spacing becomes technically viable.

Lessons learned from earlier projects at Rosemanowes (Parker, 1999; Richards, 1994) significantly informed

the UDDGP design. At Rosemanowes, the injection well was drilled below the production well, with the expectation that injected water would rise due to injection pressure. However, it was observed that water migrated downward through shear stimulation along favourably oriented joints, leading to considerable fluid loss. To address this, the UDDGP system employs a downhole pump in the production well to create a pressure sink. This pump is designed to draw water from both the injection well and the surrounding formation, enabling low-pressure operation and targeting 100% fluid recovery (Ledingham, 2021).

Geothermal Engineering Ltd (GEL) acquired the United Downs site in 2010. The project is currently in the advanced stages of development, with the surface Organic Rankine Cycle (ORC) plant completed and nearing commissioning. Procurement and drilling activities took place between 2018 and 2019, resulting in the completion of two directional wells: UD-1 (5,275 m measured depth) and UD-2 (2,393 m). (Fig.2)

From August 2020 to July 2021, injection tests were conducted on both wells to characterize the hydraulic properties of the reservoir and enhance system productivity. These tests aimed to improve flow rates through hydraulic stimulation, monitor injection-induced seismicity, determine safe flow thresholds, and relieve reservoir stress (Farndale et al., 2022).

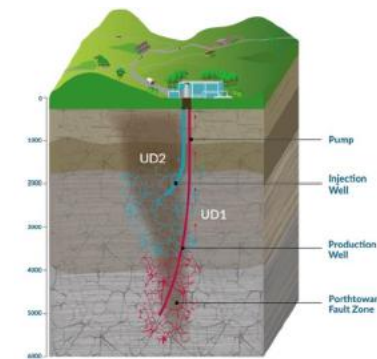


Figure 2: Schematic of the geothermal doublet at United Downs, drilled into the Porthtowan Fault Zone (Ledingham et al., 2021)

In July 2021, a seven-day reservoir test was performed using an Electrical Submersible Pump (ESP) installed in UD-1, which was connected to injection pumps on UD-2 to simulate full power plant operation and evaluate reservoir performance. (Fig.3) The methodology and outcomes of this testing campaign are detailed in Farndale et al. (2023)

The final phase of the project, initiated in 2023, involves the construction of a binary power plant with a closed-loop gathering system. This design ensures the complete reinjection of geothermal fluids, resulting in a zero-emission geothermal power generation process. Exergy International S.r.l. has been contracted to design and construct the plant, which is expected to become operational in 2025.



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

3.2 United Downs Deep Geothermal Power Plant: Exergy's Tailored ORC Solution

Exergy's Organic Rankine Cycle (ORC) power plant at the United Downs Deep Geothermal Project (UDDGP) will be powered by geothermal brine extracted from production well UD-1. The brine enters the ORC system at approximately 170°C and is cooled to around 50°C within the shell-and-tube heat exchangers, which utilize duplex tubes. The thermal energy from the brine is used to preheat, evaporate, and superheat an organic working fluid commonly used in ORC geothermal applications.

In the selected cycle configuration, the organic fluid enters the Radial Outflow Turbine (ROT) under superheated conditions and expands to the condensation pressure. Prior to condensation, residual heat from the turbine exhaust is recovered via a recuperator to increase overall cycle efficiency. Condensation occurs in an induced-draft air-cooled condenser. After condensation, two feed pumps pressurize the working fluid to complete the cycle. The cooled brine, after passing through the final heat exchanger, is directed to the reinjection system. Here, two multistage centrifugal pumps provide the necessary head for reinjection into the reservoir.

The entire cycle configuration has been optimized by Exergy based on proprietary experience and know-how. Optimization began with the selection of the working fluid to maximize compatibility with the heat source and enhance system efficiency. The thermodynamic cycle and major equipment components—including pumps, heat exchangers, and the turbine—were designed to achieve an optimal balance of technical performance and economic viability.

At the core of the system is Exergy's proprietary Radial Outflow Turbine (ROT) technology, a significant innovation in ORC systems (Fig. 4). This design—protected by current and pending patents—marks a unique application of a ROT within an ORC system. Unlike conventional axial or radial inflow turbines, the ROT converts thermal energy to mechanical power with superior efficiency.

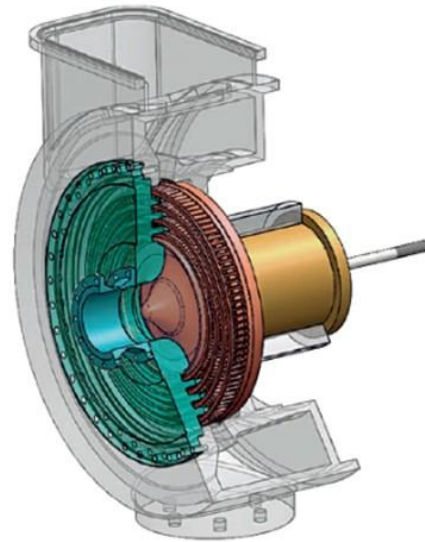


Figure 4: Exergy's Radial Outflow Turbine 3d section

When operating with organic fluids, the ROT offers multiple advantages:

- Natural accommodation of working fluid expansion through radial outflow turbine staging
- Low-speed operation for longer life of bearing and improved reliability
- Straight blades and radial geometry enabling a compact, flexible design and minimal 3D effects and turbulence
- Easily extractable mechanical group for simplified maintenance
- Capability for multiple pressure admissions on a single disk, enhancing performance and cost-effectiveness
- Up to nine stages on a single disk, enabling state-of-the-art efficiency

These features contribute to a compact, efficient machine that operates at low rotational speeds with reduced noise and vibration.

Thanks to cycle optimization and high-efficiency components, the ORC system is expected to generate a gross power output of approximately 3 MWe. Accounting for auxiliary power consumption—approximately 500 kWe for the ORC system, 580 kWe for the production pump, and 320 kWe for the reinjection pump—the estimated net electric power output of the plant is approximately 1.6 MWe.

The erection of the power plant has been completed. (Fig. 5) Commissioning and start up is planned for June 2025. Once in operation, this installation will save around 6,500 tons of CO₂ emissions per year (Exergy et al., 2023) compared to equal production of conventional fossil fuel power generation.



Figure 5: United Downs Geothermal Plant Construction Site

4. LITHIUM EXTRACTION FROM BRINE

Lithium was first identified in Cornwall in 1864, when geothermal fluid extracted from a tin mine was analyzed (Miller, 1864). During geothermal well testing at the United Downs site, Geothermal Engineering Ltd (GEL) collected fluid samples from a depth of approximately 5 km. Analysis of these samples revealed unexpectedly high lithium concentrations—among the highest recorded in geothermal wells in Europe—indicating strong potential for commercial extraction. (Fig. 6)

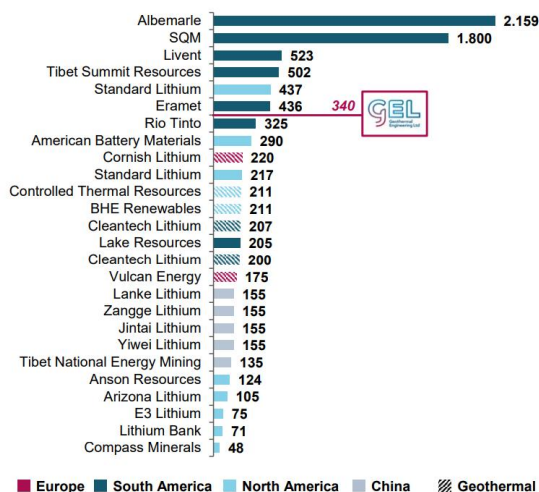


Figure 6: Lithium Concentration at United Downs Vs Other Projects (Law R. , 2025)

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.

The lithium extraction project at United Downs has focused on developing extraction in line with power plant development in order to target low-/zero-carbon lithium products. The first two project phases included partnering in a pilot study of ion exchange DLE using brine extracted during initial testing of the production well at United Downs, as well as a technical and economic feasibility study for the development of a demonstration-scale lithium extraction plant (part funded by the UK Department of Business and Trade’s Automotive Transformation Fund, Feasibility Study Round 3). The feasibility study included extensive testing of DLE technologies from a range of providers to identify suitable methods for installation on site, as well as the identification of an offtaker.

GEL are currently completing the third phase of development, the design and construction of a 100 tonnes per annum (tpa) demonstration scale lithium extraction plant. The project started in November 2023 and has included extensive testing of two selected DLE technologies and other technologies required for extraction (e.g., impurity removal), a thorough process design and procurement of selected technologies. Site preparation initiated in Q1 2025, and construction will complete in Q2. The plant has been designed to produce lithium carbonate and once complete, will be utilised for further testing. Outcomes of testing will feed into future scale-up.

5. CONCLUSION

The development of Hot Dry Rock (HDR) technology holds significant potential to enhance geothermal power generation. The United Downs Deep Geothermal Power Project is a pioneering initiative in this field, and its success represents a key milestone in the broader adoption of Enhanced Geothermal Systems (EGS). Since the successful well tests conducted in July 2021, Geothermal Engineering Ltd (GEL) has secured planning permission for two additional geothermal sites in Cornwall, with several more currently under review. The United Downs site has thus acted as a catalyst for a nascent geothermal industry in the UK, marking a

substantial step forward in the global effort to harness geothermal energy for sustainable power generation.

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