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The United Downs Geothermal Power Plant, Cornwall, UK: combining the generation of geothermal electricity and heat, with the extraction of critical raw materials.

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ABSTRACT

The United Downs Geothermal Project, developed by Geothermal Engineering Ltd (GEL), is nearing completion, with commissioning of the power plant scheduled to complete in early 2025. The plant will produce the first geothermal power in the UK and is an important case study for the development of geothermal projects both in Cornwall, and across the country.

The United Downs site consists of a geothermal doublet with a 5,275m production well and a 2,393m injection well within a faulted and fractured granitic reservoir. The concept, developed by GEL in 2008, builds upon the results of the 1970/1980's Hot Dry Rocks Programme. Site selection/acquisition and a period of fundraising and permitting occurred between 2010 and 2018. Drilling, testing and stimulation of the wells took place between 2018 and 2021. Testing highlighted some natural permeability within the reservoir and bottomhole temperatures greater than 180 °C. Furthermore, high lithium concentrations (> 300 ppm) were identified in the geothermal brines. Construction of the power plant was undertaken throughout 2024 and export to the grid is scheduled to begin in early-2025.

In addition to development of the United Downs power plant, GEL has explored the potential for the extraction of lithium from deep geothermal brines. The first two phases included a pilot study of direct lithium extraction and a technical and economic feasibility study for the development of a demonstration plant. GEL are completing a third phase of this work, the design and construction of a 100 tonnes per annum (Lithium Carbonate Equivalent) demonstration scale lithium extraction plant (part funded by the Automotive Transformation Fund). Construction of the demonstration plant will complete in early 2025. The results will feed into a commercial scale plant at the site.

1. INTRODUCTION

Construction of the United Kingdom's first geothermal power plant, located in United Downs, Cornwall, is set to complete in Q1, 2025. The United Downs Geothermal Project has been developed from conception by Geothermal Engineering Limited (GEL). The project utilises a fractured granitic reservoir via a deep geothermal doublet. Once online, the United Downs Power Plant will demonstrate the potential for geothermal power generation in the region and mark a large step forward for the geothermal industry in the UK. This paper builds on previous reports (including, but not limited to, Cotton et al., 2021, Farndale and Law, 2022 and Farndale and Law, 2023), which provide detail on early development phases, the drilling of the geothermal wells and reservoir testing and stimulation.

2. GEOLOGICAL CONTEXT

The UK's geothermal potential is underutilised. Only a small number of shallow, heat-only projects are currently active, with no geothermal electricity projects online. With widespread Pre-Permian and Permian-Mesozoic sedimentary basins as well as Ordovician-Devonian (Southwest England) and Carboniferous-Permian Granites (Northern England, Northern Ireland, and Scotland) (Abesser et al., 2023), the opportunity is significant. The near-surface granitic deposits in Cornwall provide some of the most accessible geothermal resources with the potential for both electricity and heat production via both hydrothermal reservoirs (in areas of natural permeability) or engineered/enhanced geothermal systems (EGS). Elevated heat flows and geothermal gradients are driven by enriched concentrations of radiogenic isotopes including potassium, uranium, and thorium.

The granites in the southwest of the UK, the Cornubian Batholith, possess the highest measured heat flows (> 120 W/m^2) (BGS, 2019) and geothermal gradients (33 – 35 °C/km) (Ledingham et al., 2019) (Figure 1). During planning for the United Downs Geothermal Project, modelling using surface heat flow measurements and subsurface data from a 2,600 m deep well at Rosemanowes Quarry estimated temperatures between 180 and 220 °C at 4,500 m depth. Furthermore, Cornwall is divided by two series of broad fault/fracture zones, a NNW-SSE orientated series referred to as 'cross courses' and an ENE-WSW orientated series referred to as 'lodes'. Both series underwent a phase of extension-driven reactivation after the Variscan orogeny. Whilst the ENE-lode structures are often infilled with hydrothermally driven mineralisation, the NNW-trending cross courses, are aligned with the regional maximum horizontal stress and are typically associated with enhanced permeability (Heath, 1985; Brereton et al. 1991).

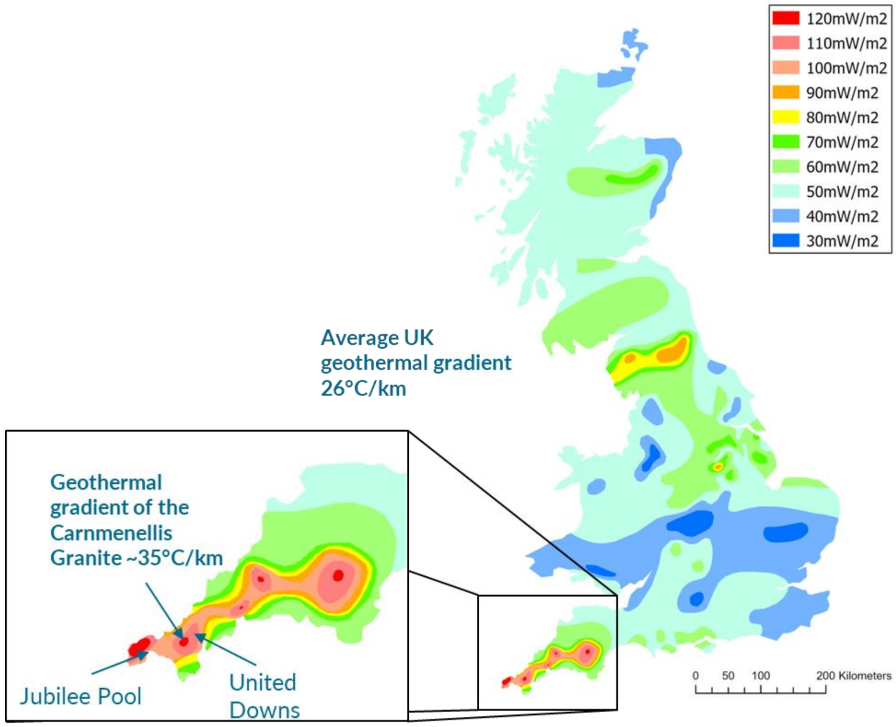

Figure 1: Schematic Diagram of heat flow beneath (A) the United Kingdom and (B) Cornwall and Devon (after Busby et al., 2011).

2. PROJECT DEVELOPMENT

2.1 Previous Geothermal Development in Cornwall

Interest in the production of geothermal power in Cornwall has existed since the late 1970's. The Hot Dry Rocks (HDR) programme, located in Rosemanowes Quarry, aimed to demonstrate the feasibility of the 'commercial exploitation of HDR in the UK' (MacDonald et al., 1992).

The HDR programme demonstrated the circulation of water between two directional wells within the Carnmenellis Granite (a body of granite in the southwest of the Cornubian Batholith), following hydraulic stimulation of natural fractures. The development of the fractured reservoir during stimulation was monitored. During testing of circulation however, ~70 % of water was lost, driven by the downward growth of fractures, following the direction of minimum stress (Batchelor, 1983; CSM, 1984; CSM, 1985; Parker, 1999). After demonstrating the circulation of water through the granite and the enhancement of naturally permeable structures through shearing, funding for the project ceased in the early 1990's.

2.2 Project Concept and Site Selection

Interest in the development of a geothermal power project in Cornwall was reignited by GEL in 2008. Building on the results of the HDR programme, GEL aimed utilise and enhance geological structures within the granite which possess inherent permeability. In 2009, GEL completed a study to identify and evaluate suitable geological structures and potential site locations proximal to the previously studied Carnmenellis Granite. Not only had the Carnmenellis Granite been previously drilled during the HDR programme, and elevated temperatures measured at depth, but extensive historic mining in the area also provides a wealth of shallow subsurface data not available around other granitic bodies in the region. The Porthtowan Fault Zone (PFZ) was selected as the target structure due to its extension from coast to coast, horizontal width at surface (200 – 500 m), proximity to outcropping granite and near vertical dip. Furthermore, the PFZ is extensively mapped at the surface and to 500 m depth in historic mine plans. Reports from mine workers describe 'hot' inflowing water in underground springs suggestive of permeable subsurface structures.

A semi-rural, brownfield site on the United Downs Industrial Park was identified 2010. Proximity to the PFZ (< 1 km), size (large enough to accommodate a drill rig and the development of a power plant), road access and availability of a pre-existing grid connection were all considered, as well as the levels of support in surrounding communities.

The conceptual design of the geothermal system was built on the outcomes of the HDR programme. A geothermal doublet was designed to intersect the same geological structure (PFZ), yet with a large vertical spacing between the bottom of the production and injection wells (Figure 2). This spacing is intended to increase the residence time of re-injected brine before any re-interaction with the production well. Establishing circulation between the wells is dependent on the interconnectivity and development of fractures and other permeable structures, however, with the HDR project highlighting the downward enhancement of fractures upon injection, increased circulation may develop with time.

Once all the relevant permits were secured for site development, a period of fundraising began. The United Downs Power Plant was ultimately funded through a combination of the European Regional Development Fund, Cornwall Council and private investors (Kerogen Capital and Thrive Renewables).

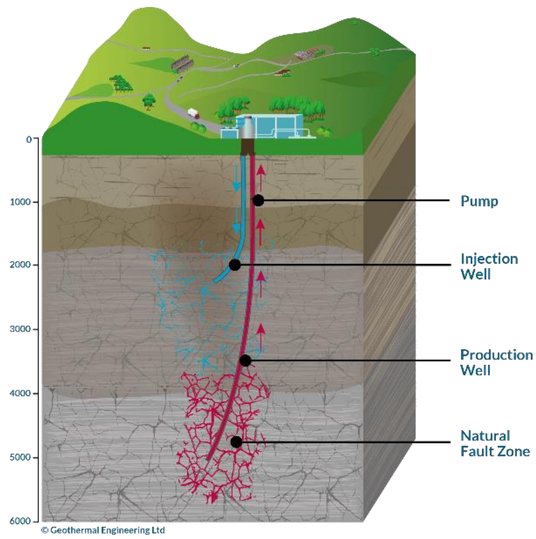

Figure 2: Schematic Diagram of the geothermal doublet design at United Downs. The production well was drilled to a measured depth of 5,275 m and the injection to a measured depth of 2,393 m.

2.3 Drilling

Procurement and drilling of the geothermal doublet took place throughout 2018 and 2019. The fault zone was intersected between 4,100 m and 4,700 m, in the 8 ½" open-hole section of the 5,275 m MD production well. A 2,393 m MD injection well was subsequently drilled into the same structure.

During drilling, data was collected and interpreted in real-time to identify intersections of the target structure. Comprehensive open hole wireline logging suites were performed in the 12.25" and 8.5" intervals of UD-1, including ultrasonic and micro-resistivity (12.25" interval only) image logs and full waveform sonic for the identification of fractures. In the 17.5" interval, caliper, temperature, and gamma logging was carried out. Cuttings were taken every 10 m until the PFZ was intersected, and sampling frequency increased to every 5 m. An analysis of the lithologies identified during drilling is presented in Farndale and Law (2022).

2.4 Testing and Stimulation

Testing and stimulation took place between August 2020 and July 2021. The purpose was to define the injectivity of the fractures, to improve the injectivity of the reservoir through hydraulic stimulation, to monitor any injection-induced seismicity to map growth of the reservoir during stimulation, to understand safe flow rate levels (pressure and volume) to inform future well treatment and to 'destress' the reservoir to prevent microseismic events occurring during long term operation (Farndale and Law, 2022).

Initial testing highlighted permeability within the natural, unstimulated fractures adjacent to the open hole section of the production well and temperatures of 180 °C at 5,275 m MD, aligning with modelled estimations. Upon analysis of the brine compositions, lithium concentrations > 300 ppm were identified.

During hydraulic stimulation of the production well > 6,200 m^3 of fresh water was injected with gradual variations in volume and injection rates. Well pressure, flow rate and induced microseismicity were continuously monitored. Analysis of well pressure changes and migration of microseismic events suggest that the low-pressure stimulation successfully improved the hydraulic conditions of the reservoir, with gradual expansion of fractures above and below the open hole, across an area > 50,900,000 m^3 (Farndale and Law, 2023).

In July 2021, full reservoir testing was undertaken for seven days. An Electrical Submersible Pump (ESP) was lowered to a depth of ~1 km into the production well and coupled to injection pumps on the injection well to simulate operation. These final test results informed procurement and design of the power plant.

A full description of testing and analysis of stimulation conducted at United Downs is presented in Farndale and Law (2022) and Farndale and Law (2023), respectively. Drilling and testing provided a large amount of data, contributing to research projects including but not limited to; 'Science for Clean Energy'/'S4CE' (Horizon 2020), 'Geothermal Power Generated from UK Granites'/'GWatt' (NERC), 'Multi-sites EGS Demonstration'/'MEET' (Horizon 2020) and OptiDrill (Horizon 2020).

2.5 Construction of the Power Plant

In mid-2023, GEL signed a turnkey EPC contract with Exergy International SRL for the supply and installation of a 3 MWe gross capacity Organic Rankine Cycle (ORC) power plant. The contract included the design and engineering of the binary plant, as well as the manufacturing and installation of plant equipment. Exergy's 'Radial Outflow Turbine' has been utilised in the design (Exergy, 2023). Air-cooled condensers are included in the design to avoid water consumption, and the closed loop design avoids vapour loss from the brine.

Construction primarily took place throughout 2024 (Figure 3, Figure 4) and is set to finalise in Q1 2025. Where possible, local contractors have been engaged throughout the entire process. The electrical submersible pump (ESP), provided by Baker Hughes differs from a standard oil and gas pumps, being designed to work at temperatures up to 225 °C (designed for high temperature application of steam flooding for heavy Canadian Oil) and flow rates up to 60 l/s. The ESP was installed in Spring 2024, to a depth of 1,400 m (Figure 3b, Figure 3e).

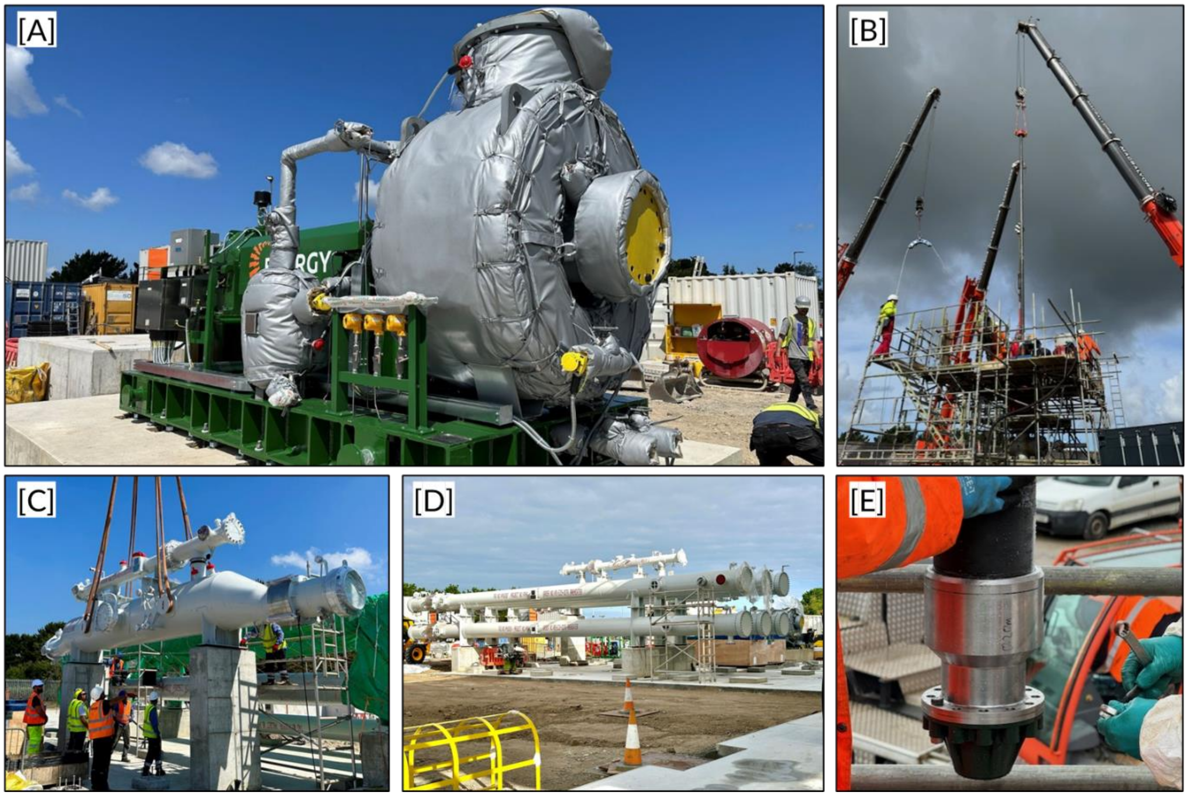

Figure 3: Photographs from the power plant construction and ESP installation at the United Downs Geothermal Project. [A] The generation turbine installed on site, [B] the installation of the pump with three cranes, [C] the installation of the evaporator and superheater, [D] the installed heat exchangers and [E] the head of the ESP.

Construction of the powerplant has allowed GEL to maintain the high levels of stakeholder engagement that have taken place throughout all phases of the project, with the visitor centre being retained onsite. Visits ranging from primary schools to high profile political figures has aided in raising the profile of the geothermal sector both locally and nationally and maintained a strong link to local communities. Furthermore, nearing completion of the United Downs plant has aided in the engagement around future sites, with a ready example to refer to if any concerns are raised.

Once construction is complete, the commissioning phase will begin, a process overseen by both GEL and Exergy. Commissioning has been designed as a stepped test of all electrical components, prior to commissioning of the production well, the doublet, and finally multiple sections of the ORC plant itself.

Figure 3: An aerial photograph of the United Downs Power Plant taken during the final stages of construction in Q4 2024.

3. LITHIUM EXTRACTION AT UNITED DOWNS

Beyond development of the power plant at United Downs, GEL has explored the potential for the extraction of lithium from the deep geothermal brines. Enriched lithium contents have long been identified in subsurface mine waters in Cornwall (e.g., Miller, 1864) and the testing of the deep brine compositions the from production wells at United Downs confirmed significant concentration at depth. The United Downs deep geothermal brines possess high lithium concentrations relative to a number of key lithium-rich brines globally (Table 1).

Globally, lithium production is dominated by hard rock mining in Australia and China, and evaporation from Salar brines in South America (Energy Institute, 2024). Processing of lithium compounds and downstream products largely takes place in China, before shipping worldwide (IEA, 2024). Both methods are associated with high carbon emissions, pollution, and waste, as well as the large consumption of reagents, land, and water (e.g., United Nations 2020). Furthermore, the subsequent intercontinental transit of lithium products further increases the net carbon emissions.

Increases in the forecasted demand for lithium has driven the extractive industry to evaluate other potential sources of lithium, including geothermal brines. Geothermal brine compositions are driven by the geological setting and source of fluid and therefore be complex and vary widely. Extraction of lithium directly from solution (‘direct lithium extraction’, DLE) would reduce the land use and water consumption associated with Salar brines evaporative extraction and allow for reinjection of spent brine back into the system, maintaining reservoir pressure. Coupled with the generation of geothermal power, carbon emissions owing to the power required during extraction are negated and a low- or zero-carbon product can be generated. Furthermore, use of geothermal electricity and heat onsite reduces the OPEX associated with lithium extraction. With evolving regulations shifting towards ‘green’, zero-/low-carbon lithium and audit trails for lithium-ion batteries (e.g., European Parliament, 2022), the low carbon aspect of geothermally produced lithium becomes more beneficial. In addition, the onshoring of lithium production is seen as a potential route to avoidance of future geopolitically driven supply issues and as the first step in development of a downstream industry in the country.

Despite several notable geothermal brines being identified as lithium-rich globally (e.g., Sanjuan et al., 2022), to date, extraction of any notable scale is limited. There are a range of DLE technologies under development, however, overcoming the complex compositions of geothermal brines and low technology readiness level (TRL) of many methods has been a challenge for many projects. Despite this, a number of projects have either implemented or are approaching on-site implementation of DLE technologies at small scale, and a smaller number produce lithium from brines in commercial quantities (e.g., Nicolaci et al., 2023).

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. This project is part funded by the UK Department of Business and Trade’s Automotive Transformation Fund (Scale Up Readiness Validation scheme). 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.

Table 1: Comparison of United Downs deep geothermal brine composition with notable geothermal brines globally. International brine compositions were compiled by Sanjuan et al. (2022), and the sources of each data for each line are noted within the table.

Location	Reservoir type	Temperature (°C)	TDS fluid (g/l)	Li (mg/l)	References
United Downs, Cornwall, UK	Fractured granitic reservoir	180	31 – 42	290 - 330	This study.
Campi Flegrei, Mofete, Italy	Volcano-sedimentary reservoir.	380	516	480	Pauwels et al. (1991), Buonasorte et al. (1993), Sanjuan et al. (2022)
Cesano Geothermal Area, Italy	Carbonate reservoir adjacent to young alkaline-potassic volcanic centre	350	230 – 290	220 – 380	Pauwels et al. (1991), Buonasorte et al. (1993), Sanjuan et al. (2022)
Salton Sea, Southern California, USA	Series of deltaic sediments adjacent to young volcanic area.	340 – 360	260 – 265	200 – 215	Elders and Cohen (1983), Williams and McKibben (1989), Sanjuan et al. (2022)
Groß Schonebeck, North German Basin, Germany	Rotliegend, Lower Permian sandstone and volcanic units.	220	212 – 269	180 – 237	Regenspurg et al. (2010, 2015), Sanjuan et al. (2022)
Groß Schonebeck, North German Basin, Germany	Upper Muschelkalk fractured and karstified limestone/dolomite reservoir	210	55 – 62	143 – 162	Stober (2014), Sanjuan et al. (2022)
Upper Rhine Graben, Germany/France	Triassic Buntsandstein red sandstone overlying granitic basement.	190 – 250	104 - 121	1159 – 210	Pauwels et al., 1993, Sanjuan et al. (2016), Sanjuan et al. (2022)
Soultz-sous-Forets	Granitic basement.	200 – 250	93 – 107	161 – 190	Sanjuan et al. (2016), Sanjuan et al. (2021), Bosia et al. (2021), Sanjuan et al. (2022)

4. FUTURE DEVELOPMENT

The geothermal concept at United Downs is repeatable across similar structures in Cornwall and the wider Southwest. With extensive faulting (cross courses) across the region and the favourable alignment with the background tectonic stress, similar reservoir behaviour is expected across the county. By selecting sites with granite at the surface, or at very shallow depths, drilling of the geothermal wells is relatively constrained. Furthermore, as proved at United Downs, flow rates can be mechanically engineered through low-pressure hydraulic stimulation.

Beyond United Downs, GEL has gained planning permission for two further sites in Cornwall, Manhay and Penhallow, which sit ready for drilling and development. An additional site is currently undergoing permitting, and a number of prospective sites are in earlier phases of development. Manhay and Penhallow will build on learnings from United Downs, employing a geothermal doublet to each produce a forecasted gross output of 4.9mW. Both additional sites have had successful bids for Contracts for Difference which provide a guaranteed price for power outputted to the grid. Both sites have a grid connection offer in place.

As well as the expansion of geothermal power production across further sites in Cornwall, upon completion of the power plant and 100 tpa lithium extraction plant at United Downs, testing will begin to inform the upscaling of lithium extraction. GEL are targeting production of 1000 – 1500 tpa of lithium carbonate equivalent (LCE) at United Downs. High lithium concentrations are anticipated in the planned sites across Cornwall due to similar reservoir geology. Upon confirmation of high lithium concentrations, expansion of lithium extraction to these sites will follow.

In addition to lithium, GEL are involved in research and development to explore the potential for low-carbon extraction of additional critical minerals from the deep geothermal brines in Cornwall.

GEL are targeting a production capacity of 20 MWe and ~23,000 tpa lithium carbonate by 2030.

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