How a multidisciplinary, data-driven geoscience approach is required to help achieve the energy transition goals

David Gold[1*], Niklas Heinemann[1], Robert Porjesz[1], Rebecca Bolton[1], Greg Rhodes[1], Pierre Roy[1], Edward Bunker[1] and Matthew Booth[2] summarise multi-disciplinary projects that demonstrate the valuable role geoscience can play in the energy transition.

Introduction

The UN Climate Change Conference (COP21) Paris Agreement calls for global greenhouse emissions to be cut by half by 2030 and reach net zero by 2050 to keep global temperature rise well below 2°C above pre-industrial levels. These goals represent some of the largest and most complex global challenges we face. The energy transition will play a vital role in meeting the net zero target but must be balanced by both an increasing demand for energy from a growing global population and an increasing emphasis on energy security.

Hydrocarbon energy resources have been extracted from the Earth for many decades using in-depth technical knowledge of its subsurface. With the need to achieve net zero goals, many traditional hydrocarbon companies are reducing the carbon intensity of their operations and investing in renewable energy and carbon offsetting, repurposing existing hydrocarbon infrastructure and technology to support this transition. Subsurface technical specialists across the energy sector have decades of knowledge and skills that can help to accelerate decarbonisation.

In this article, we summarise some of our recent multi-disciplinary projects that demonstrate the valuable role geoscience can play in the energy transition, particularly when supported by data science, high performance computing (HPC) and other technologies. These examples span carbon and hydrogen storage screening, geothermal resource assessment and development, critical mineral exploration and site selection and monitoring for renewable energy.

Carbon capture, utilisation and storage

Carbon capture utilisation and storage (CCUS) contributes to both directly reducing emissions in key sectors and removing CO_2 to balance emissions that cannot be avoided. This is a critical part of reaching net zero targets. CCUS is one of the few technologies that can help to mitigate emissions from sectors like oil and gas and hard-to-abate industrial sectors like steel, cement, and chemicals and has a direct impact on achieving environmental, social, and corporate governance (ESG) targets. Subsurface storage and sequestration projects play a key role in climate change initiatives and will help companies working in the oil and gas and other industrial sectors to achieve decarbonisation. There are many different estimates as to the role that carbon capture and storage must play in limiting global warming to below 2°C, but in all the estimates there is a fundamental requirement to increase storage from around 40 Mtpa today to between 6 and 10 Gtpa by 2030 and 2070. This represents an increase of two orders of magnitude, which needs to be delivered in a relatively short span of time. To achieve this, a vast range of geoscience needs to be leveraged to develop workflows for CCUS projects. Support is required across the entire subsurface workflow from initial screening of potential storage sites, reservoir modelling, monitoring throughout injection and long-term storage operation, drilling and completion and economic optimization.

Screening methodologies, such as a recently developed storage play quality index (SPQI), allow reservoir play intervals across entire basins to be assessed in a reasonably short timeframe to better understand CO_2 storage potential (Booth et al., 2022). The key is to capture and fully comprehend the vast array of available discipline-specific data, including geology (Figure 1), geochemistry, petrophysics, geomechanics and reservoir engineering. The resulting data have been converted into a series of index maps which are combined within a weighted calculation to form a single SPQI map. These valuable tools can help CCUS operators to quickly identify suitable storage sites in depleted oil and gas reservoirs and deep saline aquifers.

Structural evaluation, assessment of storage capacity, reservoir rock fluid interactions, caprock integrity and risk, static and dynamic modelling including geomechanics, all require a very detailed understanding of the subsurface geology and reservoir properties supported by advanced seismic imaging and interpretation. Although specific to CCUS, this can clearly be repurposed from traditional oil and gas operations. This needs to be a dynamic understanding. For example injection will cause effects, such as pressure and temperature changes, geochemical reactions, and geomechanical changes, all of which need to be modelled as accurately as possible using multi-phase compositional simulations (Whittle et al., 2022). A good example of the

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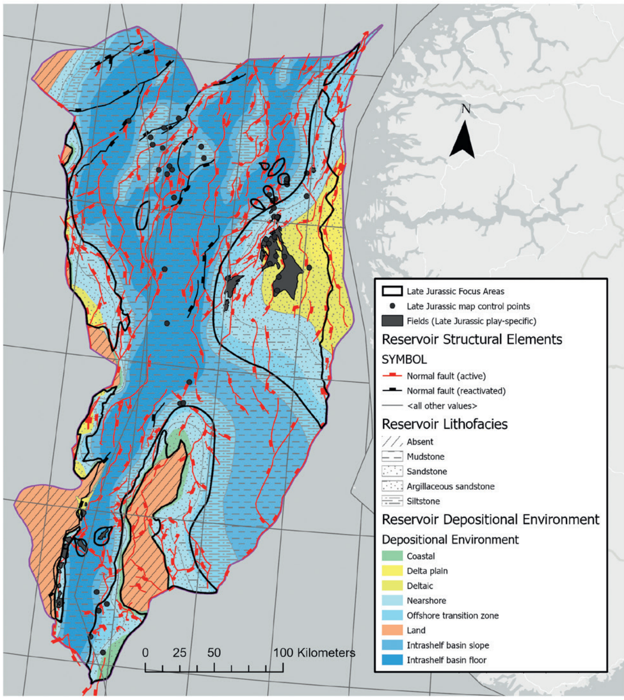


Figure 1 Example from CGG's GeoVerse Carbon Storage screening project undertaken in the UK and Norwegian Northern North Sea Basin showing a basin-scale map of gross depositional environment, lithology and faults for a potential upper Jurassic reservoir (image courtesy of CGG Earth Data).

advances in modelling that can be applied is integration of 4D imaging from seismic data to better assess the dynamic risk of storage sites, such as containment risk. Furthermore, there is a much greater focus on the seal characteristics and properties in CCUS projects than in traditional oil and gas extraction, where the primary focus has been on the reservoir shape, size, connectivity and its flow properties. However, the ability of the seal to hold back the volume (column height) of sequestered CO_2 and demonstrate the safe long-term storage capability is arguably much more important. Detailed technical studies of the seal involving mineralogy, petrophysics, geochemical reactivity, permeability and geomechanics are therefore vital.

This implies monitoring of the storage site is required, both during CO_2 injection and for decades afterwards to ensure that no leakage occurs, and that the operation is safe. Several methods, such as repeat seismic surveys, wellbore monitoring (using cables with distributed sensors for example), gravimetry and satellite imagery have been used or proposed for monitoring (e.g. Arts et al., 2008). New sensors are being investigated to reduce the monitoring cost over time or to improve spatial coverage. With a good understanding of the reservoir and calibrated dynamic reservoir models, and advanced feasibility modelling, monitoring methods can be optimized to provide real-time detection of CO_2 plume expansion in-line with the Measurement, Monitoring and Verification (MMV) plan for each site identified with the SPQI results.

Hydrogen energy

The UN, IEA, and many governments, including the UK in its 2021 Hydrogen Strategy, propose hydrogen as a viable clean energy sector that can help to decarbonise domestic heating, transport and power sectors and fuel-energy-intensive industries. Hydrogen has a density that is approximately ten times lower than that of natural gas and requires extremely high energy to compress and store it in surface infrastructure, making this type of storage a costly and currently impractical solution on a large scale. The only current feasible option for large-scale storage of hydrogen is in the subsurface, using first-hand hydrogen storage experience and from comparable subsurface operations such as cyclic underground storage of natural gas (Satterley et al., 2020) and, to a lesser degree, enhanced oil recovery and the permanent storage of CO_2.

Hydrogen can be stored in the subsurface, either in porous media sites such as depleted fields or saline aquifers, or in engineered caverns, such as salt caverns (Figure 2). The industry already has experience in storing hydrogen, either as pure hydrogen in salt caverns (e.g., Clemens, US; Moss Bluff, US and Teesside, UK) or as town gas, a 50% methane-hydrogen mix used mainly during the first half of the 20th century, and stored in porous media.

In porous media storage, hydrogen is injected into a reservoir, where it gathers at the top of the formation due to its low density until it is recovered. The three geological components of the cyclic storage operation, a suitable reservoir rock, a sealing cap rock and a trap structure to hold the stored resource close to the wells, are likely to be established in depleted gas fields, which makes them a preferable target for early projects that apply methodologies comparable to the exploration and development of hydrocarbon fields. Additionally, depleted gas fields are geologically well-understood and provide existing infrastructure in place, such as wells and pipelines, that could be repurposed for future hydrogen storage. Saline aquifers, basin-scale brine-containing reservoir formations that provide potentially large storage

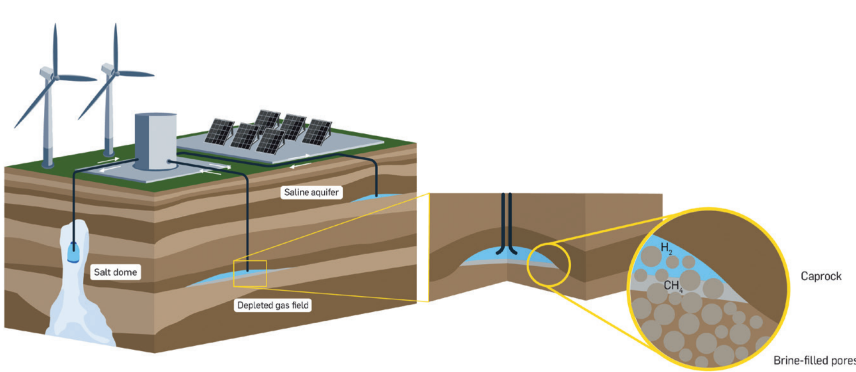


Figure 2 Schematic figure depicting seasonal hydrogen energy storage. 'Green' hydrogen produced by excess renewable energy (e.g. wind and solar) can be stored in subsurface salt caverns or porous reservoir formations for use at times of greater energy demand (image courtesy of CGG).

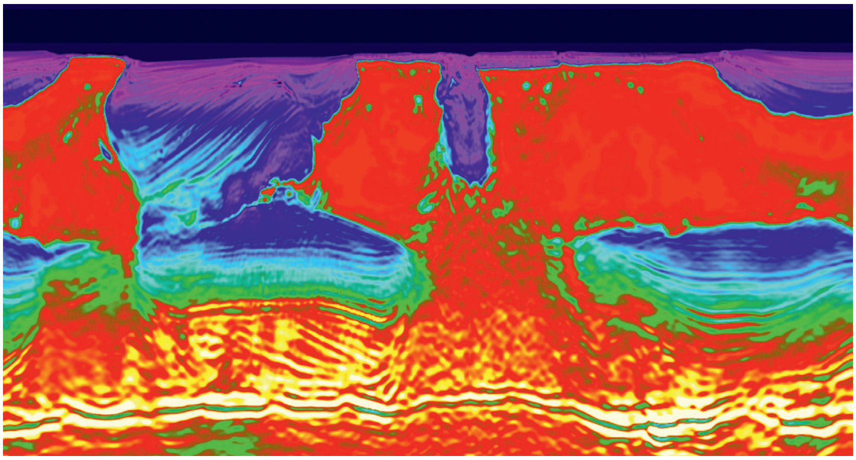


Figure 3 Elastic time-lag full waveform inversion (TL-FWI) velocity model clearly delineates massive salt bodies (high velocity indicated in red) and provides details on their internal structure. Walker Ridge, Gulf of Mexico (image courtesy of CGG Earth Data).

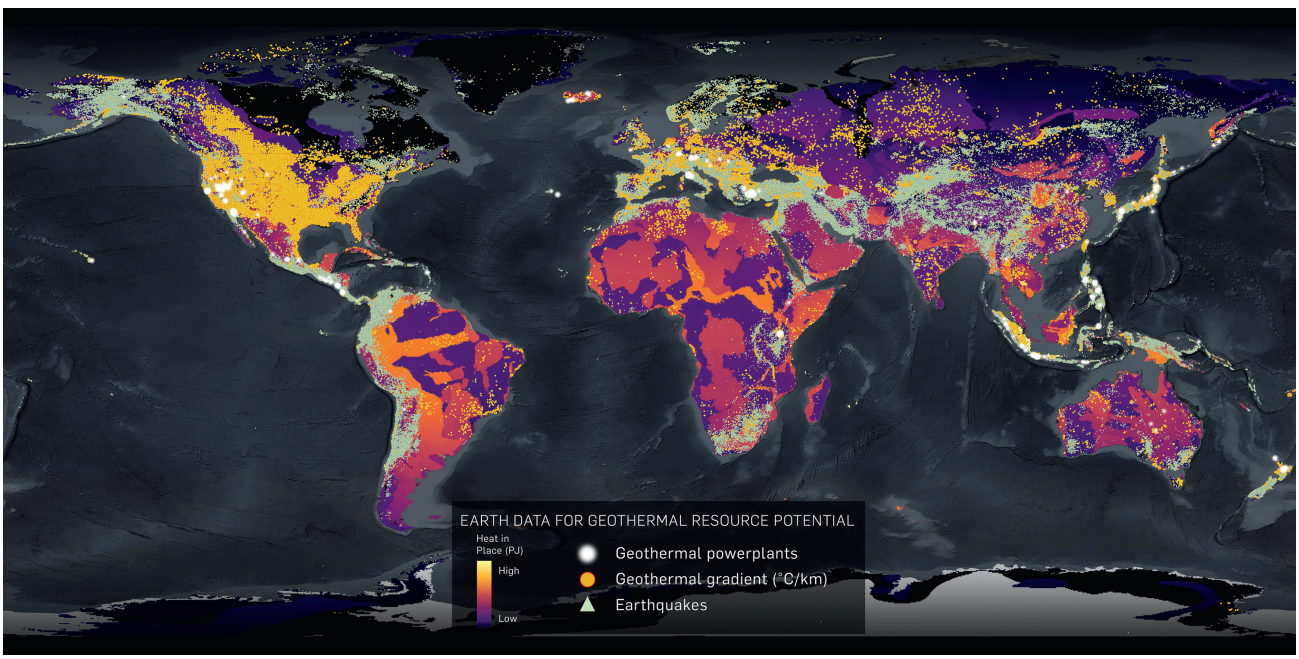


Figure 4 Global geothermal resource map produced through advanced analysis of geology, plate tectonic provinces and legacy oil and gas well data (image courtesy of CGG Earth Data).

capacities, have also been extensively used for cyclic gas storage. These have the potential advantage of being closer to centres of demand than gas fields e.g., the Midland Valley in Scotland (Heinemann et al., 2018)

The storage of hydrogen in salt caverns is a proven approach which allows several filling and emptying cycles per year and is therefore a flexible option for helping to balance energy supply and demand. Salt can be considered as impermeable, and its rheological properties allow for natural re-healing of fractures and supports the structural integrity of the cavern over the storage lifecycle. Salt caverns can be created in bedded salt, but mobilized domal structures, such as salt diapirs, are preferred due to their homogenous lithology and their relatively shallow location (Schulz, 2016). Characterisation of salt caverns relies on 1D well and 3D seismic data, but until recently it has been extremely difficult to seismically image beneath and within salt due to the dispersion and attenuation of the acoustic signal. Modern broadband seismic data coupled with new imaging technology such as time-lag full waveform inversion (TL-FWI; Wang et al., 2019) has significantly improved the velocity models and resulting seismic images in and around salt formations. Accuracy has been further enhanced through the extension to elastic TL-FWI (Ren et al., 2022), providing even clearer images of the salt boundaries. As one of many examples, high-quality broadband 3D imaged seismic data from the Gulf of Mexico (Figure 3) is being used to characterise the shape, size and internal structure of subsurface salt bodies to unprecedented degrees of accuracy.

Geothermal

Although the subsurface geoscience skills required for geothermal exploration and development differ slightly from those required for oil and gas, there are nevertheless existing skills and technologies that are highly transferable and are already being applied to geothermal projects. Moreover, as the shift to geothermal resources expands beyond high-enthalpy areas towards sedimentary basins, the transfer of oil and gas industry techniques, skills and data becomes increasingly beneficial to the geothermal industry by providing a fresh subsurface technical perspective and proven advanced drilling and completion techniques. Analysis of vast quantities of oil and gas subsurface datasets is shown to be effective in evaluating the potential for geothermal developments in sedimentary and offshore environments. This combined role of the data scientist and geoscientist in repurposing these data offers valuable new ways of exploring for geothermal energy.

CGG recently completed a global geothermal assessment drawing upon our well, seismic and interpretation database and experience in over 150 completed geothermal projects. A proprietary methodology was used to evaluate over 500,000 subsurface temperature data points to provide a baseline dataset and analytical resource evaluation aid for explorers, operators and investors to discover, assess and compare opportunities (Figure 4). This study used subsurface data to assess volcanic geothermal systems as well as lower-temperature but far more extensive sedimentary basin systems that represent a significant emerging resource opportunity.

Seismic data are increasingly being used to reduce the geological risk and uncertainty associated with geothermal projects. Recent collaboration with the Geological Survey of France (BRGM) in this area investigated whether legacy well and seismic data acquired for oil and gas exploration could be leveraged for geothermal exploration to avoid new data acquisition and therefore considerably reduce costs (Allo et al., 2021).

Several seismic lines acquired in France during the 1980s were reprocessed to allow quantitative characterization of a carbonate reservoir for geothermal production potential in the

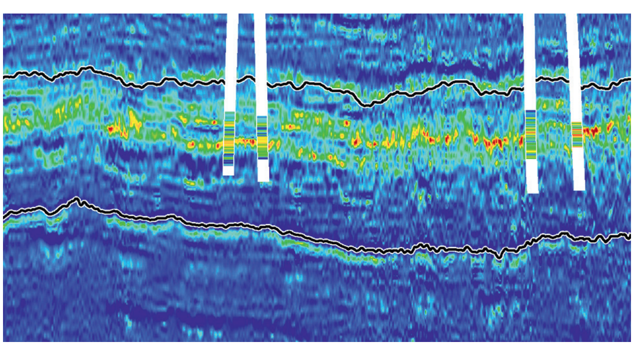


Figure 5 Effective porosity section through the study area, with well overlays, obtained directly from post-stack seismic amplitudes by application of a deep neural network trained on synthetic pseudo-wells. The extent of layers with high, connected porosity (in red and orange) encountered at existing wells is revealed in the top part of the reservoir interval (between black horizons). From Allo et al., 2021.

Dogger Formation northeast of Paris which is used for district heating. Although exploited for more than three decades, key reservoir properties of the producing layers such as porosity and permeability, are still very poorly known away from the well locations. Understanding these characteristics is vital for successfully targeting wells in areas capable of providing the exceptionally high fluid flow rates typical of geothermal wells, often in excess of 35,000 barrels of hot water per day. To reduce this uncertainty, techniques such as seismic inversion and recently developed rock physics-guided deep neural networks (DNN) were used to characterize carbonate reservoirs within the Dogger Formation. While both techniques can provide comparable results when applied to mature fields, the DNN approach is more practical for exploration as it can easily integrate synthetic data based on the extensive geological knowledge of the region. Statistical analysis of existing wireline logs and theoretical rock physics models are relied upon to simulate a large number of pseudo-wells used to train DNNs capable of translating seismic amplitudes directly into the reservoir rock properties of interest. This results in a model of porous and permeable layers encountered at existing geothermal wells that can be used to guide the location and design of future geothermal wells (Figure 5).

The significance of this technology extends far beyond this specific case study as it can be applied to any seismic reservoir characterization project for a range of different industry applications. It is especially effective for exploration cases where well data is limited or even absent, making machine learning a realistic alternative to conventional seismic inversion methods and a more efficient option to fully leverage legacy seismic data before considering the acquisition of brand-new data.

Critical minerals

Accelerated exploration for critical raw materials will be crucial to satisfy the demand arising from renewable energy technologies and the associated energy storage requirements of the energy transition. Conventional mining is an energy-intensive and environmentally impactful process; considerations of carbon intensity and other environmental and social impacts are likely to become increasingly important in mining projects.

As an example, let us consider lithium. Due to its high electro-positivity and low atomic mass, lithium is an ideal charge-carrying element for utilisation in high charge-density

Figure 6 A global lithium brine screening study provides a data-rich screening tool to enable explorers, operators, investors and extraction companies to discover, evaluate and compare opportunities (image courtesy of CGG Earth Data).

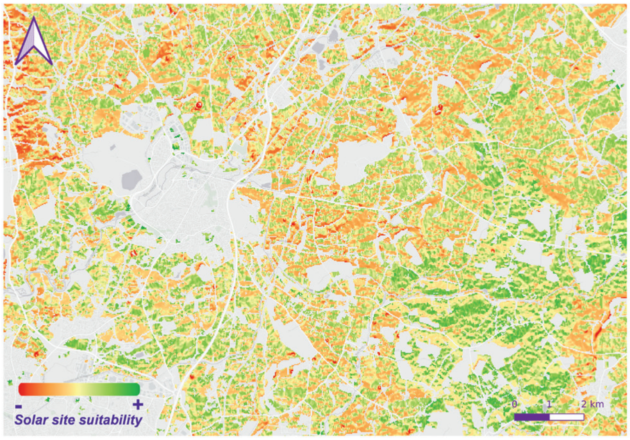


Figure 7 Example of a site suitability map for solar PV installations in the south of England using environmental, topographic, climate, land use, infrastructure, socio-economic, and cultural criteria (image courtesy of CGG).

batteries. These same properties dictate lithium's affinity to behave incompatibly within the Earth's crust and at its surface and dictate the diverse range of environments into which lithium becomes naturally concentrated at economic levels. While lithium occurs within both pegmatitic granite-hosted settings and volcanically associated clays, it also has an ability to occur in solution, leading to a diversity of lithium-bearing brine resources (Bunker et al., 2022). The most well-known lithium-brine resources are those occurring within endorheic evaporative basins such as the Salar de Atacama in northern Chile, although brines with potentially economic lithium concentrations have also been identified within unconventional settings, including granite-hosted systems, sedimentary aquifers, and oilfields.

Within this context, lithium-enriched brines likely have a geologically-long residence time, meaning that they may accumulate within basins and become buried through subsequent geological events. Such 'palaeo-brines', which represent a prospective exploration frontier, may be targeted by harnessing understanding of the lithium sources, pathways, sinks and concentration controls. This perspective is further enhanced through integrated knowledge of geology, geomorphology, palaeo-earth evolution and a holistic perspective on the lithium mineral system.

The increase in exploration for unconventional lithium brines is driven by the increasing lithium price, technical innovations for direct lithium extraction from brine, and the desire to produce lithium in environmentally responsible ways. Unconventional brines represent an attractive target, as many of the challenges associated with conventional lithium extraction techniques are reduced or avoided within these systems.

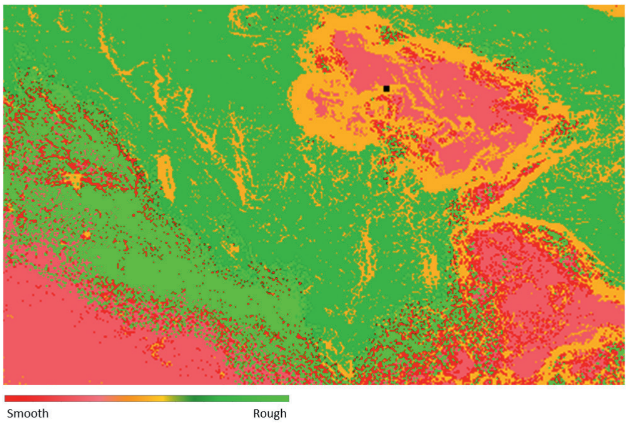
To assess lithium brine resources, a deep level of technical geoscience knowledge relating to exploration and extraction of geothermal resource must be combined with mineral system understanding. Detailed geothermal brine composition and flow rate characterization is an essential first step to guide investment and match brine properties to extraction techniques. It is necessary to compile, collate, analyse and QC numerous global geothermal and critical element data sets in order to build a structured array of data pertaining to water geochemistry, temperature, production information including flow rates, and hard rock geochemistry. These data facilitate global to regional screening and early exploration for both critical element extraction and geothermal resources including potential reservoir temperature prediction and identification of technical challenges related to brine properties (Figure 6).

Screening is, of course, just the start. We have used our experience with lithium to illustrate just one part of the overall workflow. A fully integrated combination of geo and data science is then required to support minerals and mining companies across exploration, production and monitoring. Critical minerals are becoming more challenging to locate, and the move to adopting and adapting the latest geophysical techniques will help with this growing challenge. High resolution and accurate data can help to improve subsurface understanding, providing far more confidence to the drilling operators. Our view here, as with all of the disciplines discussed, is that technology, data science and a fully integrated approach will be key to supporting more sustainable mining operations in the future.

Renewables

Expansion of renewable energy sources is required for reducing the impact of climate change and thus achieving net zero targets, but it must also be harnessed in an environmentally friendly and sustainable manner. Greater data-driven environmental insights can be gained for renewable energy projects through the deployment of advanced multi-disciplinary monitoring and analysis techniques. In recent years, expansion in the renewable energy sector has been driven mainly by the rapid acceleration of wind and solar photovoltaic (PV) development. To better assess and assist the expanding renewables sector, CGG has developed technology that can be used to reduce development risk for renewable energy operators by supporting the identification, planning and monitoring of renewable energy sites. This includes effective site suitability assessment tools using intelligence derived from large multi-disciplinary data volumes including environmental, topographic, climate, land use, infrastructure, socio-economic, and cultural criteria (Viner et al., 2022; Figure 7). Holistic suitability maps, derived from actual climate data and projected climate models, are complemented by integration of the potential impacts to natural capital (IPBES, 2019) and any associated ecosystem services present over the area of interest and its surroundings.

With the acceleration in deployment of marine renewable energy (MRE), such as wind and tidal turbines, selecting appropriate development sites will be critical in protecting the long-term interests of the surrounding environment and mitigating potential hazards. Ultra-high resolution seismic data combined with advanced seismic imaging (Davies & Rietveld, 2020) can be used to help understand the shallow near surface and potential hazards to better inform design of the placement of MRE infrastructure. Wind turbine foundation designs vary depending on substrate or bedrock, from gravity-driven through to complex piling and anchoring frameworks. Interpretation of the heterogeneity and consolidation of the shallow subsurface is key to choosing the right foundation, or combination of foundations, and fully costing the price of completing new windfarm sites. Analysis of the subsurface can be complemented by characteriza-



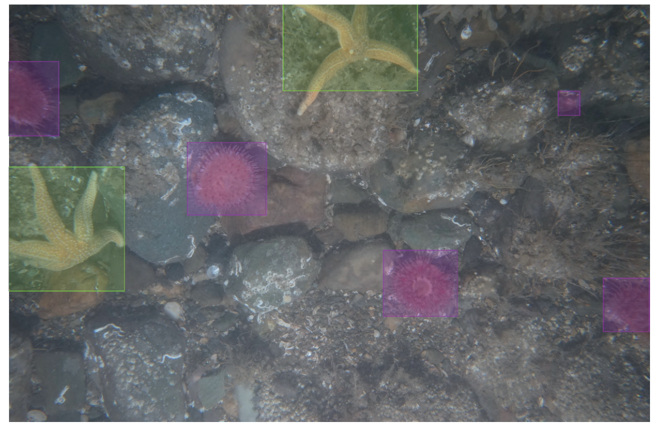


Figure 8 Left, Substrate classification based on multiple criteria including bathymetry, ruggedness and slope derived from multibeam dataset. Bright green areas indicate a higher variance of change signifying rugged terrain; orange areas represent the slope factor and/or change in gradient whereas red areas are deeper and flatter. Right) Example of automated species identification from benthic imagery using machine learning (image courtesy of CGG).

tion of the substrate through advanced data analytics and machine learning. Submarine tidal turbines are often mounted using ballast and gravity-based foundations requiring an area of relatively flat seabed. Clustering of multiple bathymetric features such as water depth, ruggedness and slope during analysis of geophysical data can be used to map areas of suitably level seabed and optimise placement of MRE devices (Figure 8).

Environmental interactions of MRE projects are challenging to predict and many questions remain about potential impacts. To predict and monitor environmental interactions, detailed information is required about ecosystem characteristics before, during and after a potentially impactful activity such as the installation of MRE infrastructure. Processing large volumes of geophysical and environmental data acquired from submarine surveys and use of machine learning to identify significant interactions between marine wildlife and potential changes to benthic habitats and biodiversity are powerful tools for assessing the environmental response to MRE infrastructure. Automated image analysis for species identification and enumeration to measure biodiversity using algorithms like convolutional neural networks (Figure 8) can vastly reduce the time required to extract usable data from imagery compared to manual expert processing (Vellappally et al., 2022). The change in biodiversity over time can be measured and compared to initial environmental baselines as part of ongoing environmental monitoring and measures can be put in place to achieve biodiversity net gain from new installations.

These approaches for onshore and offshore site suitability screening and monitoring are equally applicable to supporting the responsible development of other energy transition activities, such as deep-sea mining, and geothermal and carbon capture infrastructure projects.

Conclusion

Supporting the energy transition and its role in mitigating climate change requires effective collaboration, new technology and integration. This includes blending core and fundamental cultural aspects with new thinking to provide solutions to some of the toughest technical challenges. For CGG this has meant putting the right people and resources in a dedicated energy transition and environment group. As well as the geoscience activities referenced in this article, this group is supported by a range of other technical and business expertise including our earth observation group with satellite mapping expertise in deriving insights from optical and radar imagery and elevation data, our multiphysics group specialising in electro-magnetic, gravity and magnetic methods, and our reservoir development group with expertise in understanding and modelling subsurface reservoirs. Additionally, the existing core capabilities within the company are fully engaged – including seismic imaging, geology, equipment, data and high-performance computing (HPC), supporting our developments whilst continuing to improve and deliver for the oil and gas industry. For example, our HPC and AI capabilities provide data analytics-driven intelligence which, when coupled with geoscience expertise, help to uniquely understand the subsurface and natural environment and enhance the multiple ways it can be utilised, monitored and protected.

This article demonstrates some exciting ways in which geoscience professionals are coming together, aided by cutting-edge technology and data solutions, to address critical challenges in the energy transition. We feel that geoscience techniques and technologies are at the heart of the energy transition, and there are undoubtedly considerable opportunities for geoscientists across the industry to play a vital role. With this in mind, multi-disciplinary collaboration really is key – to be successful in these energy transition activities a truly collaborative mindset is needed both within individual companies but also, importantly across the industry.

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