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Geoscience and decarbonization: current status and future directions



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Abstract: At the 2015 United Nations International Climate Change Conference in Paris (COP21), 197 national parties committed to limit global warming to well below 2°C. But current plans and pace of progress are still far from sufficient to achieve this objective. Here we review the role that geoscience and the subsurface could play in decarbonizing electricity production, industry, transport and heating to meet UK and international climate change targets, based on contributions to the 2019 Bryan Lovell meeting held at the Geological Society of London. Technologies discussed at the meeting involved decarbonization of electricity production via renewable sources of power generation, substitution of domestic heating using geothermal energy, use of carbon capture and storage (CCS), and more ambitious technologies such as bioenergy and carbon capture and storage (BECCS) that target negative emissions. It was noted also that growth in renewable energy supply will lead to increased demand for geological materials to sustain the electrification of the vehicle fleet and other low-carbon technologies. The overall conclusion reached at the 2019 Bryan Lovell meeting was that geoscience is critical to decarbonization, but that the geoscience community must influence decision-makers so that the value of the subsurface to decarbonization is understood.

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Background

Geoscience has long been understood as part of the solution to decarbonization. A paper in *Science* magazine ‘Stabilization wedges: Solving the climate problem for the next 50 years with current technologies’ by Pacala & Socolow (2004) established the important concept that a number of complementary technological fixes and behavioural changes could be used to bring about emissions reduction of a size that can make a difference for climate change. In short, Pacala & Socolow (2004) argued that the climate problem can be solved with present proven technology, and by being less wasteful of energy. Their concept visualized CO₂ emissions reduction as a set of ‘stabilization triangles’ illustrating the ‘current path’ (with rising carbon emissions) and a ‘flat path’ (showing what could be achieved by lowering emissions). Pacala & Socolow (2004) saw the stabilization triangle between the two paths as being made up of ‘wedges’ that might make the task of decarbonization more manageable; each wedge being an activity that, if executed alone between now and 2055, could stop a billion tonnes per annum of extra carbon from getting into the atmosphere by 2055. Several of the wedges have a geoscience aspect including the geological controls on nuclear waste disposal in increased nuclear scenarios and the increased supply of gas to allow a switch of power generation from coal to gas in thermal power stations. Perhaps the purest geological solution named by Pacala & Socolow (2004) in their wedge concept was carbon capture and storage (CCS) – suggesting that if it were applied to coal power stations totalling 800 GW capacity (about 200 large coal power stations) and the CO₂ was stored underground, then this would achieve a wedge of emission abatement.

Moving on 15 years from Pacala & Socolow (2004), the range of decarbonization solutions has increased and the commitment made by nations to reducing emissions has become stronger. Internationally, the Intergovernmental Panel on Climate Change (IPCC 2018), the International Energy Agency (IEA 2018), the Energy Transitions Commission (ETC 2017) and, in national contexts, policy advisory groups (e.g. the UK Climate Change Committee 2019) have produced a range of models and projections on how these emissions reductions might be achieved. However, real progress has been slow. Figure 1 illustrates how some slowing of global CO₂ emissions has occurred over the last decade (notably growth in renewable energy and switching from coal power to gas), but significant further emissions reductions are still required if the world is to approach the objectives of the Paris agreement. Ringrose (2017) provided a review of how these reductions might be achieved, focusing on the three essential actions: renewable energy, natural gas and CCS. Deployment of renewable energy has grown dramatically over the last decades. Globally, the world produced c. 5900 GWh of renewable energy in 2016 (<https://ourworldindata.org/>), with hydropower representing almost 70% of this, and the rest being a mix of power generated from solar, wind and geothermal sources. This represents a six-fold increase since the 1960s. Future projections anticipate that electricity (rather than fossil fuels) will become the main global energy carrier by 2050, with renewable power sources able to provide the bulk of global electrical power demand (IRENA 2019). Global demand for fossil fuels, which currently provide around 80% of global energy, is expected to peak some time in the next decade (Goldthau *et al.* 2019), although there are many different opinions on how soon these changes will occur and what the future energy mix will look like. During the coming

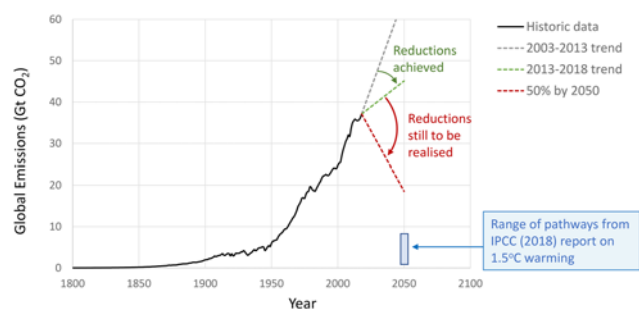


Fig. 1. Historical record of global CO₂ emissions compared with various projections (data sources: carbon emissions data up to 2013 from <https://cdiac.ess-dive.lbl.gov/> with 2014–2018 years estimates from www.wri.org).

decades, energy supply systems are likely to change rapidly and new concepts such as gas-based power generation complementing fluctuating renewable energy sources may well become mainstream. Ways of using fossil-fuel-based energy with reduced (or net zero) levels of CO₂ emissions to the atmosphere will also be in focus.

The IPCC (2018) describe four 'illustrative model pathways' to limit global warming to the Paris COP21 1.5°C objective (Fig. 2). All pathways require some level of carbon dioxide removal (CDR), but the amount varies across pathways, as do the relative contributions of bioenergy with carbon capture and storage (BECCS) and removals in the agriculture, forestry and other land use (AFOLU) sector; the model pathways also involve energy storage. Pathway P1 involves social, business and technological innovations that result in lower energy demand up to 2050 and rising living standards, especially in the developing world. P2 focuses on sustainability and international cooperation, as well as shifts towards sustainable and healthy consumption patterns, low-carbon technology innovation, and well-managed land systems with limited societal acceptability for BECCS. In P3, societal as well as technological development follows historical patterns and emissions reductions are mainly achieved by changing the way in which energy and products are produced, and to a lesser degree by reductions in demand. In P4, which involves a slower response to decarbonization efforts, there is consequently a need for more subsequent use of negative emissions technology with extensive deployment of BECCS (Fig. 2).

The Sustainable Development Scenario of the IEA (2018) *World Energy Outlook* would also achieve the long-term objectives of the Paris agreement, and assumes increases in wind and solar energy, expansion of the electric car fleet, increased energy productivity, and deployment of carbon capture utilization and storage (CCUS) technologies. The Energy Transitions Commission (ETC 2017) looks more broadly across the finance and policy landscape, and sees decarbonization as being achieved by four transition strategies

running simultaneously (Fig. 3) facilitated by finance- and policy-enablers. These are: (1) decarbonization of power combined with extended electrification; (2) decarbonization of activities which cannot be cost-effectively electrified; (3) acceleration in the pace of energy productivity improvement; and (4) optimization of fossil fuel use within overall carbon budget constraints.

The ETC suggest that decarbonization of power combined with extended electrification could account for the largest share of emissions reductions between now and 2040, with zero-carbon sources (mainly renewables) accounting for up to 80% of the global power mix by 2040.

The ETC's second strategy, involving decarbonization of activities like transport or industrial activities such as cement manufacture which cannot be electrified at reasonable cost, is more of a technical challenge. The third looks at efficiency improvements in building insulation, household appliances, transport equipment and industrial processes; and the fourth looks at optimization of fossil fuel use within overall carbon budget constraints.

Decarbonization can also be seen within the framework of global development and the United Nations Sustainable Development Goals (SDGs). Despite the huge rise in demand and supply of energy for electricity and transport, its distribution is still very uneven across the world. In 2016 sub-Saharan Africa and South Asia had *c.* 590 million and 255 million people, respectively, with no access to electricity (Our World in Data: <https://ourworldindata.org/> accessed March 2019), while in the developed world this figure was negligible. Approximately 800 million Indians and 600 million sub-Saharan Africans use traditional biomass as their primary cooking fuel (Stephenson 2018). Thus, a central industrial and social challenge of the twenty-first century is to satisfy growing energy demand while reducing emissions related to energy production, but also to ensure that energy is available to all.

The Sustainable Development Goal 7, 'Ensure access to affordable, reliable, sustainable and modern energy', will attempt to achieve this. It aims at improving energy access, increasing renewables in the energy mix, energy efficiency, and enabling a low-carbon transition with international cooperation. Many of the targets are closely associated with geoscience: for example, the need for exploration and feasibility studies for subsurface renewables such as geothermal, as well as the development of technology for sustainable use of fossil fuels within strict carbon budgets (Table 1).

Themes of the conference

It was within this background of the urgent need for global emissions reductions that 100 geoscientists, social scientists and policy-makers met at the 2019 Bryan Lovell meeting to offer geological solutions to the 'well below 2°C' objective agreed at the COP21 conference in Paris. The Bryan Lovell meeting was held on

Breakdown of contributions to global net CO₂ emissions in four illustrative model pathways

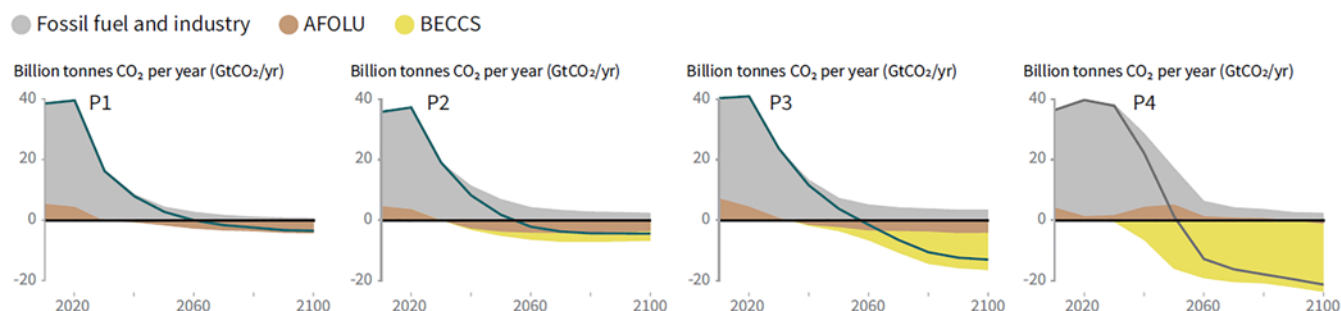


Fig. 2. The four IPCC illustrative model pathways (IPCC 2018). BECCS, bioenergy with carbon capture and storage; AFOLU, emissions removals related to agriculture, forestry and other land use.

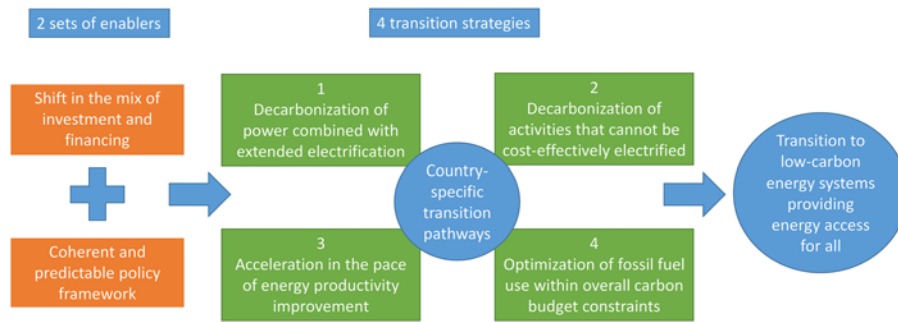


Fig. 3. Four transition strategies of the Energy Transitions Commission (2017).

21–23 January 2019 (<https://www.geolsoc.org.uk/GSL-Bryan-Lovell-2019>) bringing delegates from across the world to discuss geological decarbonization of energy – or ways that geoscience and the subsurface can contribute to the international efforts to keep global warming well below 2°C. The main scientific themes were: (1) thermal storage; (2) compressed air energy storage; (3) hydroelectric storage; (4) conventional CCS and BECCS; (5) minerals for the energy transition; (6) siting of offshore wind turbines; (7) geothermal energy; and (8) hydrogen economy. More general themes at the conference included: (a) science policy; (b) social science insights on energy transitions; (c) public views on geoscience options for energy decarbonization; and (d) the availability of geological skills for the geoscience decarbonization future.

Science themes

Thermal storage

Thermal storage is a surprisingly important technology for geoscience; decarbonization being critical for the decarbonization of energy used in domestic heating and cooling. Toby Peters of the University of Birmingham was one of the first speakers to introduce the challenge of cooling; noting that more than a billion people are facing risks due to a lack of access to cooling, with consequential lack of access to nutritious food and to vaccines essential for health, and the inability to find respite from temperatures beyond limits for human survival. Ensuring cooling is affordable and accessible to all who need it is essential to

alleviating poverty in many parts of the world and to achieving the SDGs for 2030. Peters said that by 2050, we could require 14 billion cooling appliances globally, which is four times as many as are in use today and 4.5 billion more than the current global projections for 2050. This would see the air conditioning and refrigeration sector consume more than five times the amount of energy than it does today. Later talks looked creatively at geoscience solutions that could provide cheap cooling (as well as heating) using the subsurface in urban areas.

Sebastian Bauer and Andreas Dahmke, from Christian-Albrechts-University in Kiel, noted that in Germany, about 50% of total energy demand is from heating and cooling systems, with only a small fraction of that demand being satisfied by renewable sources to date. As part of the energy transition, a significant increase of renewable energy is therefore required to counter climate-change effects. They described the possibility of seasonal storage of large amounts of heat from solar or industry. Technical options for subsurface heat storage include aquifer and borehole thermal energy storage, which in principle enable heat storage in most subsurface geological formations. Using temperatures of up to 90°C allows an increase in storage rates and capacities. To enable the implementation of large-scale urban subsurface heat storage, however, methods for dimensioning the storage systems in terms of achievable heat injection and extraction rates, as well as storage capacities, are required. Also, methods for predicting induced thermal, hydraulic, mechanical and chemical effects need to be able to assess the environmental impact of these storage sites. Bauer and Dahmke also showed that subsurface space demand for possible

Table 1. Targets to 2030 and indicators for the United Nations Sustainable Development Goals (SDGs)

Targets	Indicators	Geoscience link
7.1. By 2030, ensure universal access to affordable, reliable and modern energy services	<ul style="list-style-type: none"> Proportion of population with access to electricity Proportion of population with primary reliance on clean fuels and technology 	Geoscience for the exploration and sustainability of renewable and appropriately used fossil energy sources
7.2. By 2030, increase substantially the share of renewable energy in the global energy mix	Renewable energy share in the total final energy consumption	Geoscience to support the expansion of renewable (e.g. geothermal, wind-turbine ground conditions)
7.3. By 2030, double the global rate of improvement in energy efficiency	Energy intensity measured in terms of primary energy and GDP	Holistic planning involving the subsurface
7.A. By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency, and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology	Mobilized amount of United States dollars per year starting in 2020 accountable towards the \$100 billion commitment	Improved links between geoscientists/geoscience institutions and other energy specialists
7.B. By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing states, and land-locked developing countries, in accordance with their respective programmes of support	Investments in energy efficiency as a percentage of GDP and the amount of foreign direct investment in financial transfer for infrastructure and technology to sustainable development services	Improved links between geoscientists/geoscience institutions and energy system specialists, including energy distribution specialists and finance sector

storage sites needs to be considered as part of subsurface spatial planning.

Ingo Sass from the Technische Universität of Darmstadt considered low-enthalpy geothermal systems as heat sinks, which can be used to get rid of excess heat. Such systems are already used in cooling applications, which become more and more important in the context of global warming. Furthermore, excess heat from industrial processes, cogeneration power plants or solar thermal collectors can be transferred through a borehole heat exchanger array to the subsurface during the summer months and then be extracted in the winter for heating purposes. Such seasonal storage systems relying on *in situ* subsurface heat to maintain injected fluid temperature are especially efficient when applied on a district heating level.

Roy Baria, Technical Director of EGS Energy, discussed the importance of hot dry rock and the advances that engineered geothermal systems will provide without the need for naturally convective hydrothermal resources. Until recently, geothermal power systems have exploited only resources where naturally occurring heat, water and rock permeability are sufficient to allow energy extraction. However, EGS technologies enhance geothermal resources in hot dry rock through hydraulic stimulation.

Also looking for high enthalpy heat was Thomas Driesner (ETH Zurich), who described the potential of 'superhot' geothermal in Iceland at a depth of 2 km immediately above a magma body, producing superheated steam reaching 450°C and 140 bar at the wellhead. At the Larderello Field in Tuscany, described by Adele Manzella of CNR Italy, two European projects are also looking at deep chemical-physical conditions in an area characterized by very high heat flow in one of the most productive hydrothermal systems in the world.

Charlotte Adams of Durham University described a geothermal opportunity in relation to the legacy remaining from over two centuries of intensive coal mining, which has left a flooded underground asset that is estimated to contain some 2.2 million GWh of available geothermal heat from two billion cubic metres of water at temperatures which are constantly around 12–16°C. Using heat pumps and exchangers, these temperatures can be increased to 40–50°C and the mine waters kept away from the surface. Adams

pointed out that over one-quarter of UK homes overlie worked coalfields and could access this source of geothermal energy and seasonal heat storage.

Compressed air energy storage

The challenge of intermittency raises the problem of being able to store excess energy when it is fed into the grid on windy and sunny days, and being able to use it later when demand rises above supply. Seamus Garvey of the University of Nottingham explained that compressed air energy storage (CAES) could be a solution. Compressed air has long been used to store energy: for example, pressurized air tanks are used to start diesel generators and to propel underground mine railways. In CAES, the idea is to store large amounts of compressed air in underground caverns – mainly in salt layers – for extraction through a turbine later.

The challenge can be reduced to two variables – the capacity of storage and the speed at which the stored energy can be made available to the grid. This is conceptualized in Figure 4. A few technologies provide grid-scale capacity (or 'bulk power management'), including pumped hydroelectric storage and CAES, even though the speed at which the power can be accessed is slower, for example, than that from large batteries.

One of the engineering challenges for CAES is that air heats up when compressed from atmospheric pressure, and in an industrial CAES situation a storage pressure of about 70 bar is envisaged. Heat must be controlled to avoid damage to compressors and caverns.

Salt caverns are favoured because, being impermeable, there are no pressure losses, and because there is no reaction between the oxygen in the air and the salt. The UK has relatively large onshore areas underlain by salt, some of which are already used for natural gas storage. CAES is also feasible in natural aquifers, although oxygen may react with minerals in the host rock, and microorganisms in an aquifer can deplete oxygen and alter the character of the stored air; similarly bacteria can act to block pore spaces in the reservoir. Depleted natural gas fields could also be used for CAES, although any mixing of residual hydrocarbons with compressed air would have to be considered.

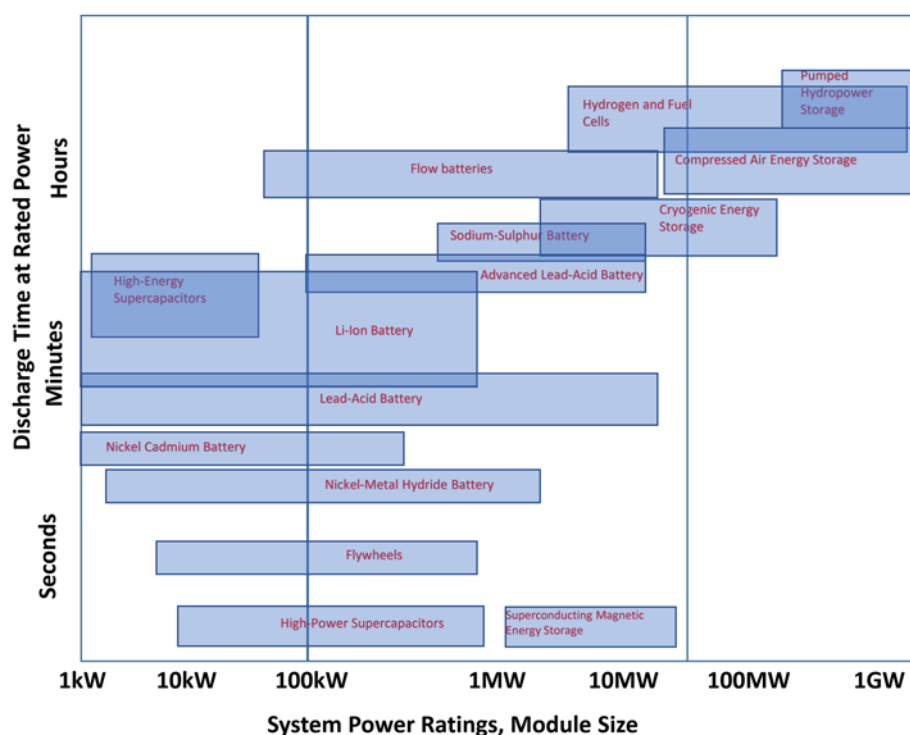


Fig. 4. The suitability of different energy storage technologies for grid-scale applications. Modified after the Centre for Low Carbon Futures website (<http://www.lowcarbonfutures.org/pathways-energy-storage-uk>).

CAES has advantages over grid-scale batteries including longer lifetimes of pressure vessels and lower material toxicity. However, cavern design and construction are expensive.

Hydroelectric storage schemes

As indicated in [Figure 4](#), pumped hydroelectric schemes (PHSs) are very suitable for rapid response, grid-scale energy storage. Martin Smith of the British Geological Survey explained that in the UK there are four such schemes located in Scotland and North Wales providing a maximum power output of 2.8 GW to the UK electrical grid. The main challenges for any PHS site include the topography, water availability and geology. Located in areas of predominantly ancient hard crystalline basement or volcanic rock, the geology is often assumed to be stable and predictable, but this is not always the case, necessitating in-depth geotechnical feasibility and mitigation studies. Smith described the detailed fault studies that were required following the failure of a tunnel due to fracturing and faulting, following stress release, at the Glendoe Hydroelectric Scheme. This resulted in the requirement of the construction of a bypass tunnel and a lengthy court action on the liability for the costs.

CCS and BECCS

Carbon capture and storage (CCS), and the related concept of bioenergy with carbon capture and storage (BECCS) which enables negative emissions, took up a good part of the conference with talks from Jon Gibbins (University of Sheffield), Martin Blunt (Imperial College) and Clair Gough (University of Manchester). The details of the technology are well known and reviewed elsewhere (e.g. [Gibbins & Chalmers 2008](#)). However, both Blunt and Gibbins expanded the arguments for the widespread implementation of CCS, concluding that safe, long-term storage of carbon dioxide in the subsurface is possible with careful site characterization, injection design and monitoring. They also noted that current commercial arrangements, not technical difficulties, are holding back large-scale implementation. Whatever the financial framework, it is likely that the expertise and knowledge of the oil and gas companies will be central to commercial-scale CCS roll-out.

Clair Gough of the Tyndall Centre described how bioenergy with carbon capture and storage (BECCS) has become central to achieving the goal of limiting global average temperature rise to 1.5°C. BECCS is a variant on CCS that uses biofuels rather than fossil fuels as the combustion material. The choice of combustion material is crucial because it improves the balance of energy and emissions such that BECCS could result in ‘negative emissions’: in other words, the process would result in a net extraction of CO₂ from the atmosphere. Gough concluded though that bringing together modern biomass energy systems with CCS at scales large enough to contribute to negative emissions at a global level go well beyond technical and scientific challenges. As a young and untested group of technologies, there are many uncertainties associated with BECCS and a there is strong imperative to understand the conditions for, and consequences of, pursuing them. Nonetheless, BECCS is seen as a key part of the pathways outlined by the [IPCC \(2018\)](#) for global warming to 1.5°C ([Fig. 1](#)).

Raw materials for the energy transition

Karen Hanghøj of EIT Raw Materials described the raw materials we will need to power and facilitate decarbonization (e.g. materials for electric car batteries). She explained how the key will be better understanding of the ‘circular economy’: bringing materials into the loop in a sustainable way, keeping materials in the loop for a long as possible, and minimizing waste at all stages. This theme was continued by Frances Wall (Camborne School of Mines), Lluís Fontboté (University of Geneva) and Tracy Shimmield (British

Geological Survey), who pointed out that however hard we try to recycle materials, we will still need to mine greater quantities of raw materials, and a greater range of elements, than ever before in order to build and sustain low-carbon technologies. Much of this will be sourced from conventional mines, but some may be mined from the seabed. Solar cells, wind turbines, electric cars, lithium batteries, fuel cells and nuclear power stations are all complex technologies with equally complex raw materials needs. Despite their necessity, clean-technology raw materials are often required only in small quantities and are quite cheap to buy. Having only a few mines worldwide might be sufficient, but these are vulnerable to supply disruption. The family of 17 rare earth elements (REEs) is, perhaps, the epitome of these critical raw materials, and these REEs are used in wind turbines, solar photo-voltaic panels, direct-drive motors in electric vehicles, low-energy lighting, all computers and many other applications all around us. Potential supplies are diverse – ranging from high-grade igneous rocks to low concentrations in clays, muds on the seafloor, and as by-products from fertilizer and aluminium production.

Hydrogen economy

The term ‘hydrogen economy’ was first coined by the physicist John Bockris as an alternative to the present hydrocarbon economy. The hydrogen economy encompasses fuel for transport (road vehicles and shipping), stationary power generation (for heating and power in buildings) and an energy storage medium feeding from off-peak excess electricity. A large-scale change from hydrocarbons to hydrogen as the ‘prime energy carrier’ requires a radical rethink of infrastructure and storage: for example, geological storage and pipelines for hydrogen are not unlike the infrastructure presently in place for natural gas and being discussed for CO₂ and CCS. Two talks at the conference explored the ‘hydrogen economy’.

James Dawson (Norwegian University of Science and Technology) discussed the main technical challenges of burning hydrogen and hydrogen-rich fuels, which include significant differences between the combustion properties of hydrogen and natural gas, such as flame speed and ignition delay times. He emphasized the importance of scale with the aim of demonstrating that, alongside the growth of renewable energy sources, hydrogen-fired gas turbines can play a crucial role in global CO₂ reductions and help provide a stable energy supply infrastructure.

Henrik Solgaard Andersen of Equinor described a possible way to implement a regional hydrogen economy through the H21 programme. The H21 project (www.northerngasnetworks.co.uk) presents a detailed engineering solution for converting the gas networks across the north of England to hydrogen between 2028 and 2035. This would provide deep decarbonizing of 14% of UK heat and be the world’s largest CO₂ emission reduction project achieving 12.5 million tonnes per year of CO₂ avoided. The scheme would involve, amongst other things, 8 TWh of interseasonal underground hydrogen storage based in 56 caverns of 300 000 m³, and a CO₂ transport and storage infrastructure with the capacity to sequester up to 20 million tonnes of CO₂ per annum by 2035 in deep saline formations in the Southern North Sea.

Nuclear

Finally, an energy source that has a strong, although indirect, connection with geoscience is nuclear power, mainly because waste produced will probably have to be disposed of in secure, deep geological repositories. Nuclear is widely considered to be a contributor to low-carbon power production, and nuclear power plants have made significant contributions to power supply globally, but also generate radioactive waste. Jonathan Turner of

Radioactive Waste Ltd explained that the UK has accumulated a substantial legacy of radioactive waste since the 1940s, and will continue to do so for many years into the future. By 2100, it is likely that 2.6 million tonnes of high-level radioactive waste in the UK will need to be safely managed, probably within deep caverns constructed specifically for the purpose. Essentially, a geological disposal facility (GDF) makes use of engineered materials and structures including concrete, metals and clays, as well as the surrounding geological environment, as containment barriers. Geoscientific expertise will play a central role in designing and siting the GDF (e.g. predicting the behaviour of groundwater systems in glacial periods), and in modelling the near-field response of the geosphere to a GDF (e.g. excavation damage zones, effect of heat flux and the extent of rock desaturation during the GDF operational period).

A big part of containment is the natural arrangement of the rocks that surround the engineered barriers. In some ways this is similar to underground disposal or containment of CO₂; however, the time frames are very different as radionuclides may be hazardous for up to hundreds of thousands of years into the future. Thus, a fundamental requirement of the geological environment is that its behaviour should be predictable enough to establish very long-term radiological safety. Amongst the factors that need to be assessed are present and future levels of seismic activity, effects of glaciation, uplift and erosion, and future effects of climate change including sea-level rise – because all of these processes could compromise the GDF. An assessment of risk involves a rather detailed study of geological processes occurring now and in the recent past in order to understand changes up to 1 myr into the future.

New nuclear power stations have been promoted as a relatively low-carbon solution to base-load power. Bob Holdsworth of Durham University explained that seismic hazard represents one of the most ‘geological’ external hazards that need to be considered when developing a new nuclear power plant. The primary seismic hazard and main cause of damage to structures and plant is strong shaking of the ground caused by the passage of seismic waves radiating from the earthquake source. This may be amplified by the local presence of unconsolidated sediments and can also trigger secondary hazards such as liquefaction or landslides. The characterization of strong ground motion is usually carried out via a probabilistic seismic hazard analysis. This analysis has been carried out on two UK new nuclear sites, and is in progress for two others.

General themes

Two speakers, Spencer Dale (BP) and Chris Stark (Committee on Climate Change), considered the landscape of world energy, climate change and decarbonization. Spencer Dale argued that the advent of electric vehicles and the growing pressures to decarbonize the transportation sector mean that oil is facing significant competition, but despite this, oil demand is projected to continue to rise, even with significant decarbonization trends. This is because population and living standards are set to rise. Major oil and gas companies, along with the IEA, expect that there will be a continuing role for oil and gas for several decades, but to be used strategically and within strict carbon budgets. Chris Stark discussed decarbonization of transport and the role of hydrogen and biomass in a low-carbon economy, along with the need for managing coastal areas and changing land use.

An interesting social science insight on energy transitions was provided by Benjamin Sovacool. He explained to delegates the historical context of energy transitions, setting it in context with previous transitions such as the industrial revolution. Sovacool’s message was that transitions can be excruciating slow, but that if you get conditions right they can be faster. Perhaps geoscience can help to make the fossil to renewables transition faster?

Nick Pidgeon of Cardiff University, a well-known commentator on public views on energy, outlined what we know about public views on exploitation of ‘the underground’ for energy applications – starting with the lessons learned from earlier unsuccessful attempts to site radioactive waste repositories in the many countries that have tried. Radioactive waste remains the paradigm case in risk associated with site failure, and highlights the importance of taking seriously public and societal acceptability over and above simply technological or economic factors. In more recent times some of these lessons can be seen to apply to technologies such as geological carbon capture, large-scale energy storage, geothermal energy and bioenergy with carbon capture or BECCS.

The question of having the right skills for the geoscience decarbonization future was addressed by Philip Ringrose (Equinor/NTNU) and John Underhill (Heriot Watt University). Underhill argued that decarbonization places a responsibility upon academic trainers, educators and researchers to equip the next generation of geoscientists with the right technical skill sets. This may be perceived as a threat to well-established and long-running geology and environmental science courses, but it also represents a new opportunity to tailor undergraduate and postgraduate training to address the increasing need. Philip Ringrose presented a history of the role of oil and gas companies in the energy sector, but asked the question – what will the commercial energy sector look like under decarbonization? He concluded that a modified oil and gas energy sector is most likely to play a significant role because of its ability to undertake large projects, and because decarbonization is likely to require activity on industrial scales, using the same rock formations exploited for oil and gas resources and subsurface resource management tools developed in the oil and gas sector.

Synthesis

Common challenges

One aim of the conference was to understand some of the geological and scientific questions that are common to geological decarbonization technologies. Perhaps the most fundamental of these emerged quickly during the proceedings: the need to characterize rock geochemically and geomechanically. An example is the need to understand the composition and properties of deep rock salt when it is used to store hydrogen as part of a large-scale regional hydrogen fuel and heating system (a ‘hydrogen economy’). Salt will be subjected to repeated pressurization and depressurization during storage, and must maintain its ability to contain the hydrogen safely. Without this understanding, the vital role that hydrogen could play in a low-carbon economy might not be realized.

Similarly, the geochemical and geomechanical character of other rock formations, from unconsolidated sediment to sedimentary, metamorphic and igneous rocks, needs to be understood to predict the performance of these materials in hosting energy-related systems such as low-enthalpy geothermal reservoirs or ‘hot-dry-rock’ reservoirs, the storage of CO₂ and other gases, and tunnelling for pumped storage construction.

Rock characterization will mean the systematic gathering of data on the properties of rocks like rock salt or sandstone for carbon dioxide storage in areas that are likely to be developed for decarbonization. Geological sites for permanent storage of CO₂ or for seasonal storage of gas will require detailed rock characterization (Fig. 5). A combination of core data, wireline log data and seismic image data are routinely used to characterize subsurface reservoirs, and forms the basis for economic decisions on how to use those subsurface stores.

This will need strategic investment and a realization that aspects of decarbonization will take place in geographical clusters and



Fig. 5. Geological studies in storage-site characterization: (left) example core samples from a tidal delta lithofacies from the Carboniferous storage unit at Krechba, Algeria; and (right) outcrop analogue of tidal deltaic sedimentary architecture from the Middle Jurassic Neill Klinger Formation, Greenland. (Photographs courtesy of Phil Ringrose.)

development corridors where geological and infrastructure conditions are most suited (Stephenson 2018).

An example is the hydrogen economy – the idea that hydrogen can provide a fuel for cells to drive vehicles, heat houses and power industry. Hydrogen production may, in the longer term, be through electrolysis of water using excess (renewable) electricity, but in the short term is more likely to be produced by steam methane reforming from natural gas which produces CO₂ and hydrogen. While hydrogen from electrolysis provides an attractive low-carbon fuel, hydrogen from natural gas reforming can offer significant scale-up potential, but requires the CO₂ by-product to be disposed of geologically. The key point here is that geological disposal of CO₂ cannot be done everywhere, because only specific geologies are suitable. This means that hydrogen-energy systems will be likely work to best in regions with geology suitable for seasonal hydrogen storage in salt caverns and CO₂ storage in saline sandstone aquifers. An example is the H21 project introduced earlier in this article. The project seeks to convert the existing natural gas network in Leeds – used mainly for heat – to 100% hydrogen. A batch of four steam methane reformers on Teeside will produce the hydrogen needed, while the waste CO₂ will be captured and disposed of offshore in the Southern North Sea. CO₂ capture is a well-established technology and CO₂ disposal in geological formations has been demonstrated at scale for over 20 years at the Sleipner Gas Field. Salt cavern storage in the Tees and York areas will be needed for ‘intra-day’ and ‘intra-seasonal’ swings in demand as heating is turned on and off by consumers. Beyond the heating solution, the availability of low-cost bulk hydrogen in a gas network could revolutionize the potential for hydrogen vehicles in the NE of England and, via fuel cells, support a decentralized model of combined heat and power and localized power generation.

Geological science will also have to step up to understand the origin and genesis of geological materials for electric vehicle batteries and wind turbines. A second common challenge recognized by scientists at the Bryan Lovell conference concerned the need to understand better the flow of fluids in the deep subsurface, whether they be warm or hot water, steam, carbon dioxide, natural gas or hydrogen. This is not a trivial task given the presence in the subsurface of several fluid phases, reactive rock, fractures and rock heterogeneity. Flow is important because in technologies like geothermal we want to encourage the flow of useful fluids (hot water), while in other technologies we want to contain fluids, such as in carbon dioxide capture and storage. An

ability to monitor and verify through sophisticated imaging and detection will also be needed.

A similar challenge is that of scale up from small laboratories to full scale. Many technologies are well understood at the small scale but need testing at scales approaching their final industrial deployment. This implies that demonstrations and pilots are required, and thus an increased level of funding and commitment on the part of government, and creative public–private partnerships. It was acknowledged at the conference that the right government intervention could address market failure and rapidly move forward some subsurface decarbonization technologies such as district low-enthalpy geothermal heating.

A final challenge, perhaps recognized as the most pressing, is to understand public attitudes to subsurface decarbonization technologies. Research has been done on the way that the public view CCS, but there are few studies of technologies such as compressed air energy storage or hydrogen storage. In densely populated countries in Europe and elsewhere, it is clear that very high levels of environmental assurance will be needed to gain a social licence to operate.

The opportunity for geoscience research

Notwithstanding these challenges, the conference attendees agreed that the UK and Europe are very well placed to develop subsurface decarbonization technologies. The UK has excellent subsurface capability in its research base of world-class universities, research institutes, and oil and gas companies, and is also developing its experimental and pilot-scale infrastructure: for example, the new £31 million British Geological Survey UKGEOS test sites (<https://www.ukgeos.ac.uk/>).

Germany has significantly stepped up its efforts in renewable energy, with a growing geoscience focus on seasonal storage (hydrogen, air), while Norway has often taken the lead in developing CCS technology, operating the world’s largest CO₂ capture test centre (TCM Mongstad). EU research funding commitments in clean energy are very substantial, spearheaded by the Horizon Europe programme. These geoscience research and technology developments will certainly be required to enable us to decarbonize the present world energy system in tandem with surface renewables such as solar and wind (Stephenson 2018). Indeed, the apparently ‘hidden subsurface’ may offer the only solution to hard-to-decarbonize parts of the system including heavy industry such as steel, cement and refineries, via CO₂ capture and storage technologies. Furthermore, bioenergy and carbon capture and storage (BECCS) is currently the only practical way to achieve large-scale negative emissions, which may be vital if our efforts in other areas fall short.

Conclusions

In order to progress geoscience in decarbonization, the findings of the Bryan Lovell conference were that the geoscience community needs to:

- secure funding to deliver pilot schemes scaled-up from successful experimental or laboratory-based projects;
- encourage the development of regulatory and licensing frameworks to deliver technologies such as geothermal energy for heat and a regulatory system that supports the valuation and use of the subsurface, along the lines of fossil fuel licensing, incorporating management of conflicting interests;
- raise awareness of the key role of geoscience in achieving decarbonization and engage communities with field-scale projects for various subsurface technologies, including CCS and geothermal heating schemes;

- highlight the importance of critical subsurface resources (mined metals and minerals) in delivering decarbonization through technologies such as wind turbines (e.g. neodymium, cobalt) and batteries for electrification (e.g. lithium and cobalt);
- undertake high-quality, independent environmental monitoring to ensure confidence in project safety – in densely populated areas, very high levels of environmental assurance will be needed to gain a social licence to operate;
- characterize the physical and mechanical properties, chemistry, and structure of the subsurface to determine the feasibility of various subsurface storage and infrastructure projects;
- develop and design effective and cost-efficient monitoring techniques for various uses of the subsurface;
- improve scientific understanding of how potentially reactive fluids flow in the subsurface as they pertain to decarbonization technologies such as underground thermal energy storage and characterization of geothermal resources.

Critical to the success of the decarbonization initiative is knowledge and data-sharing across geographical borders, between industries and by all stakeholders of the subsurface – ensuring that competing interests are well managed.

A successful and innovative set of subsurface decarbonization technologies developed in Europe will be an exportable asset in the years to come, leading to jobs, investment and economic growth, and we expect to see geoscience playing a vital role.

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