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Geosciences and the Energy Transition

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A substantial and rapid decarbonisation of the global economy is required to limit anthropogenic climate change to well below 2°C average global heating by 2050. Yet, emissions from fossil fuel energy generation—which dominate global greenhouse gas emissions—are at an all-time high. Progress and action for an energy transition to net zero carbon is critical, and one in which geoscience sectors and geoscientists will play multiple roles. Here, we outline the landscape of the geosciences and the energy transition in the context of the climate crisis, and intergovernmental policies on climate and social justice. We show how geoscience sectors, skills, knowledge, data, and infrastructure, both directly and indirectly, will play a key role in the energy transition. This may be in the responsible sourcing of raw materials for low carbon energy technologies; in the decarbonisation of heating; and in the near-permanent geological capture and storage of carbon through novel technology development. A new and unprecedented challenge is to reach Geological Net Zero, where zero carbon emissions from geological resource production and consumption are achieved via permanent geological storage. We identify overarching and cross-cutting issues for a sustainable and fair net zero carbon energy transition, and the associated geoscience challenges and opportunities. Finally, we call for geoscience professionals to recognise and take responsibility for their role in ensuring a fair and sustainable energy transition at the pace and scale required.

Keywords: geological net zero, critical strategic metals, just energy transition, geoscience skills, low carbon geoenergy

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INTRODUCTION

Of all the energy transitions in human history, the present one, involving the decarbonisation of human activities globally and the drive towards a net zero carbon, sustainable world by 2050 or earlier, is the most pressing, arguably the most difficult, and uniquely the most global. In contrast to previous transitions that have been driven by the development of new technologies and subsequent market penetration and propagation (Sovacool, 2016), the current energy transition is driven by environmental and societal necessity (Fouquet, 2010; Slamersak et al., 2022).

The geosciences will play a key role in delivering a net zero energy future (Stephenson, 2018; Roberts and Lacchia, 2019). Nearly all forms of energy production require Earth resources, knowledge, and technologies underpinned by geoscience. Many geoscience job sectors relate to the energy industry—directly and indirectly. The energy transition thus mandates a geoscience transition.

In this article we outline and discuss the landscape of the geosciences and the decarbonisation of energy. We first introduce what is meant by the energy transition in the context of the climate crisis, and intergovernmental policies on climate and social justice. We then discuss, in turn, different areas in which the geosciences will, both directly and indirectly, play a key role in the energy transition—whether in the sustainable sourcing of raw materials extracted with a lower environmental footprint, or in the harnessing and storage of low-carbon energy, or in the disposal of energy-related wastes. We consider what the transition from carbon intensive industries means for geosciences, and the important role of CO_2 geological storage for balancing carbon budgets—including the concept of Geological Net Zero. We identify overarching and cross-cutting issues for a sustainable and fair net zero carbon energy transition, and the challenges and opportunities for future geosciences in the growing need for rapid incremental and/or transformative technologies and solutions. We close with a call to action for geoscience professionals: to both recognise, and to take responsibility, for their role in ensuring a fair and sustainable energy transition at both the pace, and scale, required.

The Energy Transition

A number of energy transitions have occurred through history, as individuals and communities have sought more efficient, powerful, or flexible solutions for heating, power, transport and lighting. These have historically driven by new discoveries and innovations, coupled with development of new markets. Examples of this can be explored as different communities have moved from biomass (e.g., wood, livestock), through fossil fuels (gas, oil, and coal), to alternative or renewable energy sources (e.g., wind, solar, wave, hydroelectricity, nuclear energy). These transitions have typically been measured, with differing rates of diffusion of technologies and practices through different geographies, communities and socio-economic sectors, and industries.

By contrast, the current energy transition is driven not by markets and innovations, but primarily by policy of Governments seeking an urgent response to anthropogenic climate change. To quote Smil (2016, p. 195):

> “The unfolding energy transition is not just about shifting from one set of primary energy sources to another: its fundamental raison d’etre is the prevention of excessive rise of average tropospheric temperature and that can be achieved only by the decarbonization of the global energy supply.”

The current energy transition can be further distinguished from its predecessors by its scale, breadth and impact. Globally, energy is still primarily generated by combustion of fossil fuels (gas, oil, coal) with minor, but increasing, contributions from renewables and nuclear (Ritchie et al., 2020). Energy—including electricity, heat, and transport—is responsible for 73.2% of global CO_2e[1] emissions (IEA, 2016). Energy combustion and industrial processes emitted 36.3 Gt CO_2 in 2021, an all-time high (**Figure 1**), 42% of which was sourced from coal alone (the International Energy Agency, IEA[2]). In addition to emissions from energy, resource extraction and processing including steelmaking contributes up to 10% of global greenhouse gas (GHG) emissions (Smith and Wentworth, 2022). As such, energy practices—including generation and demand—are currently driving climate change. In a matter of decades, these emissions must be eliminated, and a carbon balance of net zero CO_2e emissions to atmosphere achieved.

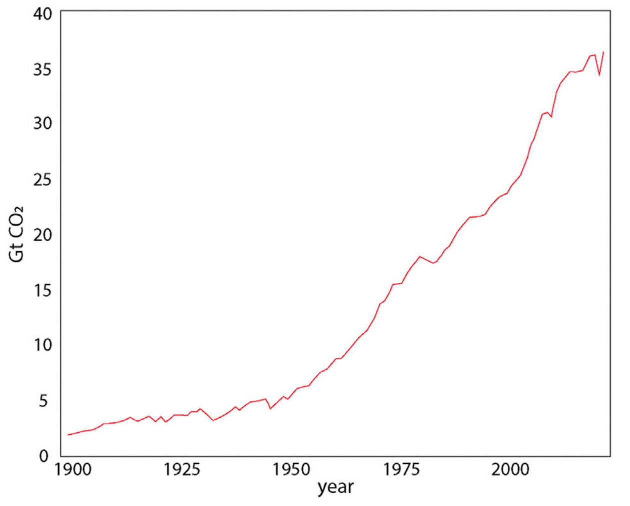

FIGURE 1 | Global annual CO_2 emissions from energy consumption and industrial processes 1900–2021 (IEA, 2022d).

TABLE 1 | CO_2e emissions associated with different power generation methods.

Generation method	kg (CO_2e)/MWhe
Deep geothermal*	6–1800
Onshore wind	7.8–16
Offshore wind	12–23
Solar PV	8–83
Solar CSP	27–122
Natural Gas	403–513
Natural Gas with CCS	49–220
Coal	751–1,095
Coal with CCS	147–469
Nuclear	5.1–6.4
Hydropower	6–147

*Data from UNECE (2021a) except *deep geothermal from McCay et al. (2019).*

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[1] CO_2 “equivalent”: a metric measure of used to compare combined emissions of greenhouse gases (with different Global Warming Potentials) by converting to the equivalent amount of CO_2.

[2] https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

There is a wide variation in emissions intensity of different power generation techniques that will depend on the region of deployment and resource development—e.g., natural gas production has variable CO_2e intensity depending on the region it is produced from[3]—and in the specifics of the supply chain as well as in plant operations, and in the boundaries of the assessment and available measurement and monitoring approaches at the time of the study. **Table 1** shows CO_2e intensity of energy produced by different technologies, calculated by Life Cycle Assessment which, amongst other factors, considered varying energy load, methane leakage rates and background grid electricity consumption across twelve global regions (UNECE, 2021a).

Table 1 demonstrates that no energy generation is zero carbon. Energy must be generated using low or lower carbon approaches than with fossil hydrocarbons, and technologies will require further innovation to reduce carbon emissions and other environmental impacts. From a scientific perspective "net zero" requires balancing the global release of GHG into the atmosphere by their removal into sinks (Fankhauser et al., 2021), and as a concept helps to address the concern that it is impossible to achieve "absolute zero" i.e., a wholesale elimination of greenhouse gas emissions by 2050. Further, the concept of "Geological Net Zero" means achieving zero carbon emissions from geological resource production and consumption, including from fossil fuels, cement production from limestone, and other industrial processes, via the safe and permanent geological capture and disposal of CO_2—i.e., locked up over geological timescales ($>10^4$ years; in effect, refossilisation) (Jenkins et al., 2021; Richards and Portolano, 2022).

Thus, the way that energy is generated and used must fundamentally change. There are different scenarios and pathways to achieve a net zero carbon energy system (IEA, 2021c) that meets demand. These scenarios feature: scale up of low carbon energy technologies (**Table 1**); scale down or scale out of high carbon intensity energy forms; decarbonisation approaches such as Carbon Capture and Storage (CCS); carbon budget balancing by carbon removals; waste reduction; and/or demand reduction. However, all pathways require an ongoing effort to phase out unabated fossil fuel usage, and it is probable that in the future new forms of energy generation and distribution will emerge. There is no "one size fits all" pathway: much like the energy transitions of the past, the nature and style of transition will be place and context specific, depending on differences in geographies, communities, practices, industries, and socio-economic factors. Key attributes have been identified that must be embodied for the concept of net zero to provide a successful climate change mitigation framework (Fankhauser et al., 2021). Regardless of the route taken, these pathways share a common goal: net zero emissions from energy. This requires action across a broad suite of industrial, governmental, economic, and domestic sectors: globally, simultaneously, and at an unprecedented rate.

The Paris Agreement and the Net Zero Target

The United Nations Intergovernmental Panel on Climate Change (IPCC) has concluded that it is "unequivocal" that anthropogenic climate change is occurring, and that the magnitude of changes measured over the timescales of observation are "unprecedented" (IPCC, 2021), and its global impact much discussed (IPCC, 2018). The 2015 Paris Agreement[4] aims to hold the increase in global average temperature to "well below 2°C" and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels (IPCC, 2018), a target that will be significantly exceeded this century unless deep reductions in greenhouse gas emissions are enacted. Thus, a substantial decarbonisation of the global economy is required to mitigate the worst excesses of anthropogenic global warming and to meet Paris Agreement targets.

The concept of "net zero emissions" as outlined in the Paris Agreement, refers to balancing greenhouse gases released to atmosphere with carbon dioxide capture and removal[5] into carbon sinks to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century (IPCC, 2018). Such removals can be accomplished by short-term measures, e.g., tree planting, or via longer term measures such as CO_2 geological storage.

Signatories to the Paris Agreement are required to make commitments for lower carbon emissions every 5 years, so-called "nationally determined contributions" (NDCs) as well as long-term low greenhouse gas emission development strategies (LT-LEDS), and will need to develop their own domestic strategy, informed by their own energy use, applicability of renewable energy technologies and decarbonisation strategies, and industrial needs (IPCC, 2018). So far, all 194 signatories to the Paris Agreement have submitted NDCs whilst 54 (as of November 2022) have submitted their LT-LEDS. For example, the UK Government has outlined a strategy for achieving net zero carbon emissions by 2050 (UK Government, 2021) and submitted this to the UNFCCC (UN Framework Convention on Climate Change) as their LT-LEDS. Although not signatories, a growing number of businesses, industry associations, and investors have pledged to meet Paris Agreement-aligned targets[6], in part driven by shareholder and/or consumer pressures.

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[3] https://www.nstauthority.co.uk/the-move-to-net-zero/net-zero-benchmarking-and-analysis/natural-gas-carbon-footprint-analysis/

[4] https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[5] We distinguish between Carbon Capture and Storage (CCS), which refers to the process by which CO_2 is captured from point sources and stored to prevent its release into the atmosphere, and Carbon Dioxide Removal (CDR), which removes CO_2 that is already in Earth's atmosphere.

[6] https://unfccc.int/news/commitments-to-net-zero-double-in-less-than-a-year

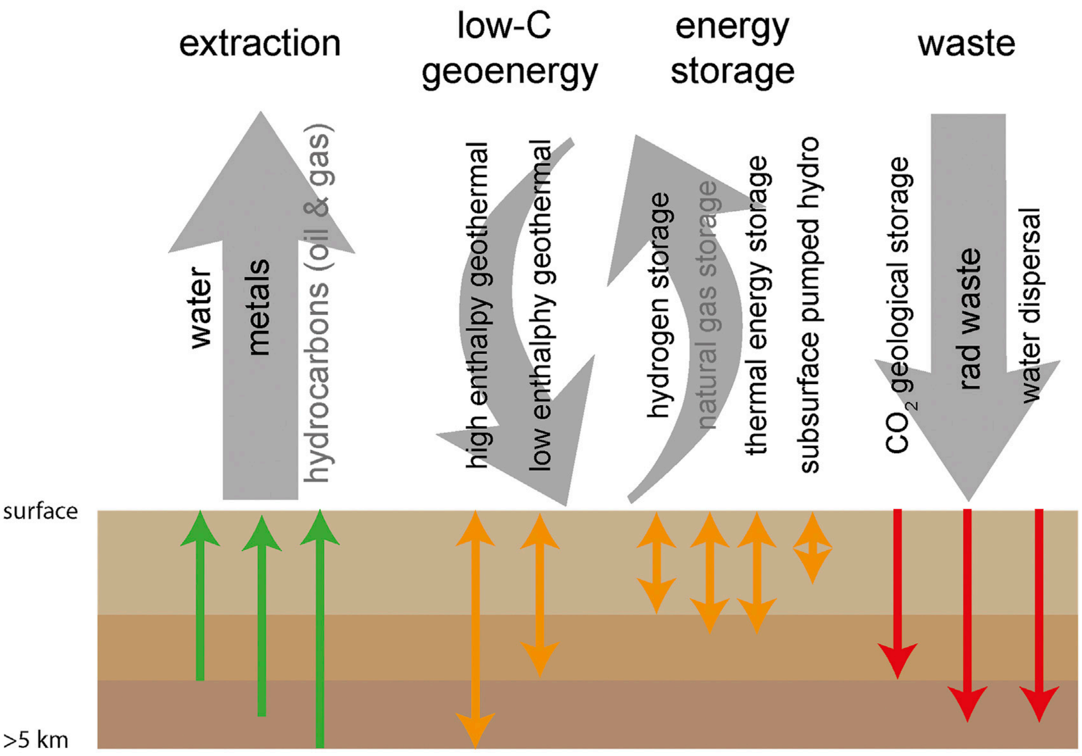

FIGURE 2 | The use of the subsurface for technologies associated with the energy transition. Adapted from Cook (2017).

Sustainable Development Goals and a Just Transition

In 2015, the United Nations published the Sustainable Development Goals (SDGs) to define ambitions for improving human lives and the environment (United Nations, 2015) with a target of 2030. The SDGs provide goals and indicators to measure the sustainability of both government and business. Whilst some critics argue that SDGs favour development over sustainability (*sensu* Brundtland Commission[7]), they have established a broad suite of criteria by which the environmental, social, and governance (ESG) performance of government, and other institutions and organisations, can be measured. The energy transition directly links to many SDGs, including (but not limited to): SDG13 Climate Action (rooted in the Paris Agreement), SDG7: Affordable and Clean Energy; SDG12: Responsible Production and Consumption; SDG9: Industry, Innovation and Infrastructure; and SDG5: Reduced Inequalities.

Viewed through the prism of the SDGs, the energy transition should involve the central principles of improved environmental performance, social justice, and human rights. A just energy transition is therefore one in which the benefits and burden are fairly distributed. This includes everything from those communities who live above geological resources being fairly compensated for any disruption during extraction, noting that this may include them owning the companies that carry out the extraction; through to those who may need to move to new industries and therefore update their skills being supported to do so. The SDGs place significant focus and reliance on businesses, investors, and governments to value people and planet in equal measure to profit.

The energy transition should be a *just* transition, which allows for threats to be minimised and opportunities to be fairly explored and actioned. It is widely acknowledged that urgent action is needed immediately to minimise the potential impacts of climate change[8], as well as acknowledgement that there are significant injustices in that those who historically and presently are responsible for the greatest emissions are perhaps those least impacted by current climate change.

Geoscience and the Energy Transition

Historically, geoscience has played a key role in resource extraction and use that has contributed to the current climate emergency. However, as nearly all forms of energy production require Earth resources, and technologies underpinned by geoscience, the geosciences are set to play a key role in delivering the sustainable net zero carbon energy system of tomorrow.

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[7] Brundtland Commission Report, 1987.

[8] https://ukcop26.org/the-glasgow-climate-pact/

In the next sections, we consider specific examples of technologies and activities that are key for the energy transition and in which geoscience plays an important part (e.g., **Figure 2**), placing emphasis on geoscience skills contributions. First, we discuss the use of the subsurface for both energy production and storage and for waste. We then outline the requirement for sufficient critical raw materials, principally metals, to enable the transition, and the challenges of mining this sustainably. Finally, we discuss the cross-cutting issues that will underpin sustainable geoscience practices.

SUBSURFACE TECHNOLOGIES FOR THE ENERGY TRANSITION

Decarbonising requires new methods of harnessing energy, new technologies to store energy, and new ways to manage waste. This section outlines how geoscience applications play a key role in each of these aspects.

Low Carbon Geoenergy

Here, we focus on two low carbon geoenergy technologies: geothermal and nuclear. “Low carbon geoenergy” refers to that energy produced with lower CO_2 emissions than from hydrocarbon extraction and combustion that is significantly reliant on a geological resource. It has been estimated that in the UK geothermal systems (deep sedimentary basins, ancient warm granites and shallower flooded mines) could provide approximately 200 EJ or 100 years supply of heat (Gluyas et al., 2018), significantly contributing to the decarbonisation of heating and meeting net zero carbon goals.

Geoscience also plays a role in enabling other forms of low-carbon energy, for example, geotechnical engineering is important for energy infrastructure design, including for ground stability, hazard assessment, and the routing of high energy cables. However, we do not consider these applications to be “geoenergy” as they do not rely on extraction or production of a geological resource; instead, these applications are classified as energy adjacent Geoscience applications.

Low Enthalpy Geothermal Energy

Geothermal energy is the heat energy contained in the subsurface of the Earth (Barbier, 2002; Arbad et al., 2022). This energy can be used directly as heat (or cooling) or to drive turbines to produce electricity, and thus can contribute to the decarbonisation of both heating and electricity production. The average geothermal gradient globally is ~25–30˚C/km but this can vary significantly—e.g., in volcanic regions it can exceed 100˚C/km (Lowell et al., 2014). The minimum temperature of geothermal fluids required to drive a turbine to produce electricity is approximately 80˚C—though more commonly above 90–100˚C (Fazal and Kamran, 2021), implying that for electricity generation heat is sourced from more than a kilometre in depth. Whilst not universally defined, low enthalpy (typically “shallow”) geothermal systems are used principally for heating and cooling purposes, and given average geothermal gradients most are limited to less than a kilometre deep. Thus, the addition of heat pumps to such systems is common (Eugster and Sanner, 2007).

Low enthalpy geothermal systems makes use of heat and coolth resident in aquifer systems or in abandoned and flooded mine workings (Adams et al., 2015; Walls et al., 2021). Minewater geothermal projects have been established in several countries including Norway, Spain, the Netherlands, Poland, Czech Republic, Russia, Canada, the United States and the United Kingdom (Walls et al., 2021). There has been a recent surge in interest in minewater geothermal for domestic heating in the UK due to slow progress in decarbonise heating [heating currently contributes 23% of UK greenhouse gas emissions; BEIS (2021)] and the co-location of many population centres with abandoned coal mines. A major advantage of low enthalpy geothermal systems is that it can be exploited globally, i.e., the temperatures required are available almost everywhere a demand exists, with the caveat that favourable geological conditions are required for economic and environmental extraction. They also provide a stable year-round heat source (when greater than ~10 m depth) compared to air or water-sourced heat pump systems where temperature fluctuates seasonally and thus impacts efficiency.

High Enthalpy Geothermal Energy

High enthalpy (typically deep) geothermal systems may be used directly for heat and/or electricity production where temperatures are high enough to drive a turbine. Global installed geothermal electrical power capacity (as of 2019) is around 15 GW concentrated in a small number of countries, with approximately 90% of that total in just eight countries: United States, Philippines, Indonesia, Mexico, Italy, New Zealand, Iceland and Japan (Tomasini-Montenegro et al., 2017). However, it is estimated that global production could be as much as 1-2 TW (Fridleifsson et al., 2008).

High enthalpy geothermal electricity production provides low carbon baseload power and as such is a good candidate to replace fossil-fuel baseload in a system likely to be dominated by variable renewable energy supply in the next decades. Bruckner and Al (2014) assume emissions intensity of high enthalpy geothermal electricity range from 6 to 79 kg(CO_2e)/MWhe, comparable to other renewable sources and significantly less than fossil fuels (**Table 1**). However, significant variation from this exists with some geothermal plants estimated to be as high as 1800 kg(CO_2e)/MWhe due to the natural variation in co-produced gases (McCay et al., 2019 and references therein). Projects such as the Carbfix project at the Hellisheidi geothermal power plant in Iceland, seek to combine geothermal power production with CCS to further reduce such emissions (Snæbjörnsdóttir et al., 2020).

Nuclear Energy

Nuclear provides an energy resource that has a post second world war legacy of energy production in the United Kingdom, and to greater and lesser extents globally. Some countries produce no nuclear power, whereas France generates about 70% of its electricity from nuclear (World Nuclear Association[9]). The raw materials for fuel rods (uranium and plutonium) are available in the Earth's crust and the equivalent volume of raw material needed to produce the same amount of electricity through fossil fuels is orders of magnitude greater: one nuclear pellet of uranium (about the size of a sugar cube) will generate the same amount of electricity as a tonne of coal; or 27 tonnes of uranium versus 2.5 million tonnes of coal (World Nuclear Association[10]). Simply, Earth is not uranium resource poor; although supply chains of uranium may be subject to energy security concerns.

There are both carbon and economic costs associated with nuclear energy. Life cycle analyses of the greenhouse gas emissions associated with production of nuclear power estimate that emissions are lower than fossil fuel technologies, similar to solar power, and higher than wind turbine or hydroelectricity (Fthenakis and Kim, 2007; Lenzen, 2008) (see **Table 1**). However, such life cycle analyses do not include "whole lifecycle carbon" and in particular emissions from materials mining, long-term geological disposal, and power station decommissioning (Pomponi and Hart, 2021). Circular economy approaches could reduce the carbon intensity of nuclear energy and handling of produced wastes (Paulillo et al., 2022).

Given energy security and climate change concerns many countries are considering new nuclear technologies in their energy portfolio including Nuclear Micro Reactors and Small and Medium Reactors (Zohuri, 2020; Nuttall, 2022). Independent of the power-generating nuclear technology used, the role for the geosciences is not so much in ensuring a supply of fuel, uranium (MacFarlane and Miller, 2007), but in the siting, geological characterisation (including ground stability, hazard assessment, and so on), and societal acceptability of secure geological disposal facilities for radioactive waste material (Ojovan and Steinmetz, 2022) material (see later section on Geological Disposal of Radioactive Waste).

Subsurface Energy Storage

Energy storage at a range of scales, and varied energy storage options, are anticipated to ensure flexible, responsive and reliable energy supply in a renewables-dependent net zero carbon energy system. Energy storage is required to provide a buffer against variable renewable energy generation and the geographical and seasonal constraints on energy demand (Kabuth et al., 2016); in short, it ensures that minimal energy is wasted, and that energy supply can flexibly match demand. For that reason, energy storage is cyclic, with the energy temporarily stored to be later extracted to meet demand. There are several options for energy storage at different scales that are dependent on geoscientific knowledge, including established technologies such as subsurface pumped hydro, hydrogen and natural gas geological storage, and emerging technologies such as compressed air energy storage and gravity storage. We outline these below.

Geological Hydrogen Storage

Hydrogen is expected to play a key role in the decarbonisation of energy intensive sectors, including heavy industry, transport and power (DNV, 2020). Hydrogen options which might be considered to be "low carbon" include hydrogen generated from methane with associated CO_2 emissions captured via CCS, and hydrogen generated from electrolysis of water using renewable energy.

Geological storage of hydrogen is anticipated to support a future "hydrogen economy" (Miocic et al., 2022). Two primary types of geological hydrogen stores are anticipated: salt caverns, whereby gas is injected into natural or engineered cavities in thick salt formations, and reservoir-caprock systems. Salt caverns have been used for decades to store hydrogen in the United Kingdom and United States (Tarkowski et al., 2021; Zivar et al., 2021). However, they have limited capacity, and there are geographic restrictions on the availability of sufficiently thick salt deposits. For this reason, hydrogen storage in porous rocks is being explored as a cost-effective solution (Tarkowski et al., 2021). Here, hydrogen is injected into a porous and permeable reservoir formation, such as a saline aquifer or a depleted hydrocarbon field, which is capped by an impermeable seal. The concept is at an early stage, with many scientific challenges that must be tackled for commercial deployment (Hashemi et al., 2021; Heinemann et al., 2021).

As well as resolving outstanding research and development challenges, geoscience plays a key role in the prospecting and site selection of suitable sites for hydrogen storage, and their operation and monitoring. There is a role for geoscience in minimising losses of stored hydrogen, including containment and microbial conversion, and remediation in the event of leakage. Finally, there is potential of prospecting for naturally-occurring hydrogen from underground reservoirs (Frery et al., 2021; McMahon et al., 2022). Hydrogen is a greenhouse gas, thus, much like natural gas production and storage, fugitive emissions of hydrogen from production, transport, storage and use must be minimised using best available technologies and practices (Ocko and Hamburg, 2022).

Natural Gas Storage

Natural gas production is anticipated to decrease significantly over the next 30 years. The IEA's "Net Zero Emissions by 2050" scenario projects a 75% reduction from 2022 levels (IEA, 2022c). Other assessments project smaller, but still significant reductions in natural gas production, for example, Speirs et al. (2021) anticipate reduction by a third. Reasons for reduction in the use of natural gas are two-fold: firstly, natural gas combustion emits CO_2 and other compounds with global

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[9] https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/what-is-uranium-how-does-it-work.aspx; last accessed 23/10/2022.

[10] https://world-nuclear.org/nuclear-essentials/how-does-a-nuclear-reactor-work.aspx; last accessed 23/10/2022.

warming potential and negative environmental impacts. Secondly, there is increasing focus on the scale of fugitive emissions of methane—a powerful greenhouse gas—associated with natural gas production, transport and storage. This focus is in response to increasing understanding on the scale of global methane emissions from the energy sector (IEA, 2022b), and action such as the 2021 Global Methane Pledge[11] launched at COP26. Methane is responsible for around 30% of the rise in global temperatures, and it is estimated that fugitive methane emissions from natural gas activities are responsible for approximately 11.5% of global methane emissions in 2022 (IEA, 2022a). There is therefore an immediate need for implementation of technologies and practices to reduce fugitive emissions from current natural gas supply, including from natural gas geological storage (IEA, 2021a). For these reasons, natural gas storage is not considered a "low carbon" technology, but, rather a transition technology, though we note that natural gas for power or for hydrogen with carbon capture and storage might be considered low carbon, as outlined in the section on "CO_2 geological storage."

Geological storage of natural gas has proven an economical method for managing gas delivery for over 90 years. In total, 630 underground natural gas storage facilities were in operation in 2009 (Evans and Chadwick, 2009). Natural gas is typically stored in engineered salt or rock caverns, depleted hydrocarbon reservoirs or abandoned mines, or in saline aquifers, with depleted hydrocarbon fields typically providing largest storage capacities (Fang et al., 2016). While geological natural gas storage is deemed to have excellent health and safety record (Evans and Chadwick, 2009), in recent years there have been some high-profile incidences of gas leakage in the US, including the well-failure at Aliso Canyon in Los Angeles in 2015 (Pan et al., 2018).

Much like hydrogen geological storage, geoscience plays a key role in the prospecting and selection of suitable sites for underground gas storage, site operation and monitoring, and remediation in the case of leakage or environmental degradation.

Thermal Energy Storage

Of the many thermal energy storage technologies available, those of most interest to the geoscience world include large pit storage and underground thermal energy storage (UTES) (Heinemann et al., 2019). Large pit storage encompasses shallow lined pits filled with water and gravel as the storage medium. Examples include the Vojens project in Denmark where 200,000 m^3 of water is warmed by 70,000 m^2 of solar panels for use as seasonal storage (summer-winter) in a district heating system (Lund et al., 2016).

UTES comprises a number of potential configurations using aquifers (ATES), boreholes (BTES) or caverns/mines (C/MTES) as the storage reservoir using water as the storage medium. These are typically used as pit storage for seasonal storage of heat, injecting hot water in the summer and producing it back during the winter. Examples include the Danish Broadcasting Corporation (DR) building in Copenhagen (ATES), Drakes Landing, a housing development in Alberta Canada (BTES) and the Heerlen project in the Netherlands (MTES). Of note with the latter is that mine abandonment planning could consider future use of mines for thermal storage and/or geothermal heat extraction.

Geoscientific knowledge is needed to inform structurally safe pits and subsurface systems required for TES, as well as understand the dissipation and ultimate recovery of heat, i.e., the efficiency of the system.

Subsurface Pumped Hydro

Pumped hydroelectric storage (PHES) is well established. PHES harnesses the gravitational potential energy of water by pumping water to a higher elevation at times of energy excess, to be released in time of demand. It is currently the largest source of installed storage capacity globally, and is set to increase by over 25% between 2021 and 2026, accounting for nearly all global electricity storage capabilities globally (IEA, 2021d). According to IEA analyses, adding PHES capabilities to existing reservoirs would add more energy storage capability than developing new PHES projects (IEA, 2021b). PHES projects can range from gigawatt storage capacity and megawatt generation capacity to small-scale systems from distributed energy storage (Blackers et al., 2021).

Geoscience plays a critical role in the geotechnical engineering and hazard assessment of new and operational reservoir PHES projects, including adding PHES capabilities to existing reservoirs, and the assessment of catchment scale impacts of such sites. Poor quality geotechnical investigations, which overlook basic bedrock geology have resulted in expensive failures, such as GlenDoe, Scotland (Hencher, 2019).

In addition to conventional surface reservoir PHES, subsurface schemes have been developed (SPHES) which deliver low carbon energy without the surface footprint. SPHES might use old mines, such as the Bendigo project (Australia) which pumps water to different levels within an old gold mine (Provis, 2019), Dinorwig Power Station in Wales (UK) which modified an old slate mine (Baines et al., 1983) or Pyhäjärvi (Northern Ostrobothnia–Finland), a deep base metal mine. Alternatively, underground reservoir systems can be engineered, through excavation of rock mass, such as the Mingtan project in Taiwan (Cheng and Liu, 1993). Geoscience knowledge and expertise informs the resource estimate, siting, stability, maintenance and containment of SPHES as well as its safe and efficient operation.

Other Geological Energy Storage Technologies

Emerging geological energy storage technologies include compressed air energy storage (CAES) and underground gravity energy storage (UGES).

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[11] https://www.globalmethanepledge.org/#pledges

Similar to hydrogen geological storage, CAES offers the potential for local small-scale energy storage in addition to large-scale storage. It operates in a similar way to PHES in that periods of excess power are used to store energy, which in the case of CAES, uses air or another gas which is compressed and stored under pressure either above ground (air tanks) or below ground—typically in salt cavern storage, reservoir-caprock or aquifer systems (King et al., 2021). In times of energy demand the gas is depressurised (and heated) to drive a generator for power production (Mouli-Castillo et al., 2019). Subsurface CAES is suitable for seasonal energy storage and has low operating costs per unit of energy (He et al., 2021b), and heat recovery processes reduce the carbon intensity of CAES (Zakeri and Syri, 2015). There are two commercial sites in operation, in Germany (Huntorf power plant) and the United States (McIntosh CAES plant, Alabama), both of which store compressed air in engineered salt caverns (King et al., 2021).

For UGES, there are different arrangements or designs for storing energy (Hunt et al., 2023). UGES works on the concept of lifting rock mass or material (e.g., sand) via hydraulic pumping or electric motors in times of excess energy. At times of energy demand, the potential energy in the elevated rock mass is released by, for example, lowering the mass, turning generators, or discharging the water through a turbine.

For both CAES and UGES, geoscience plays important roles in feasibility studies, site selection, development, operation and monitoring, including cost and risk reduction.

Disposal of Energy Wastes

CO_2 Geological Storage

A suite of technologies and approaches involve geological CO_2 storage, either to manage and mitigate CO_2 emissions, or to remove CO_2 from the atmosphere. In its simplest form, CO_2 geological storage involves capturing CO_2, compressing and transporting it, and injecting it into subsurface geological formations (Ringrose, 2020; Martin-Roberts et al., 2021). Where the CO_2 sources are the capture of emissions from point sources such energy production and/or industrial processes—with the aim of dramatically reducing atmospheric emissions from those processes—the process is Carbon Capture and Storage (CCS). Where the process is capturing atmospheric CO_2, it is Carbon Dioxide Removal (CDR) (**Figure 3**). Regardless of the source, the CO_2 must remain stored geologically in the subsurface on a time scale of utility to the climate [thousands of years, Alcalde et al. (2018)].

There are different formulations of geological CO_2 stores, including: reservoir-caprock systems, reservoir-overburden systems, and rock mineralisation (e.g., of ultramafic composition). Often considered distinct from CCS, geoengineering to accelerate geological processes such as

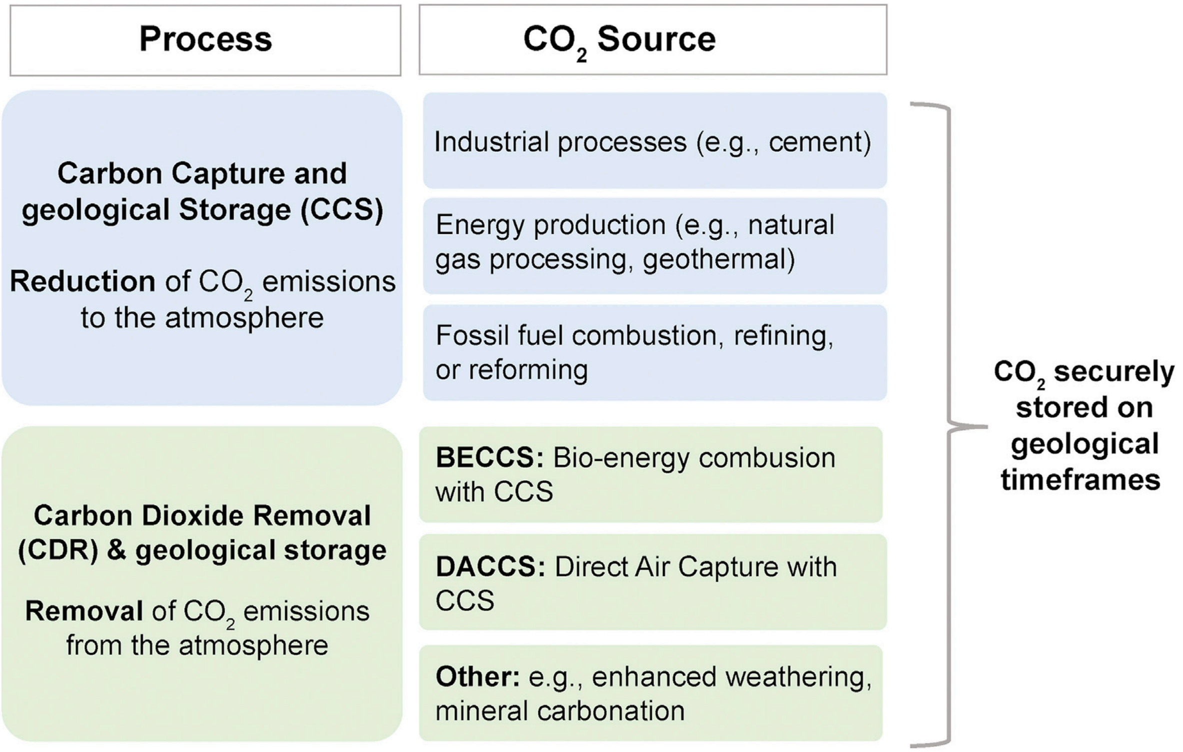

FIGURE 3 | A suite of technologies and approaches involve geological CO_2 storage, including CCS and CDR.

enhanced weathering (thereby trapping CO_2 into minerals) can also be classified as geological CO_2 storage.

As highlighted in **Figure 3**, achieving the "balance of sources and sinks" as described in the Paris Agreement will require CO_2 removal (CDR) as well as mitigation of emissions, achieved by a variety of means. Some of this will be achieved by nature-based solutions such as tree-planting and soil management, and some will require geological storage. CO_2 may be captured directly from atmosphere (DAC) or via biological processes (Bioenergy with Carbon Capture and Storage; BECCS), whereby photosynthesis captures CO_2 from atmosphere, the biomass is then used in energy production and the resultant CO_2 by-product is then stored geologically.

A hybrid approach of nature-based solutions and technological solutions is the case of enhanced weathering. Here, acceleration of natural chemical weathering by increasing surface area for reactions through grinding of silicate rocks provides a way to drawdown CO_2 from the atmosphere. Of note here is the ability to use existing mine waste material, e.g., in tailings, typically of olivine-rich ultramafic rocks (Wilson et al., 2011; Power et al., 2020; Bullock et al., 2021), potentially coupled with critical metal recovery (see section on sustainable mining) or tailings stabilisation (Power et al., 2021). New research highlights potential for significant CO_2 removal via trapping in polymineralic rocks through treatment during rock crushing to produce, for example, construction aggregate (Stillings et al., 2023).

Pathways to net zero envisage the combined deployment of CCS and geological CDR on the order of 7–10 $GtCO_2$/year by 2050, through engineered carbon capture solutions, with proportionally more for CDR than for emissions reduction (IEA, 2021c; Energy Transitions Commission, 2022). This is two orders of magnitude greater than the current ~40 Mt/year capture rates. Thus, geological CO_2 storage is anticipated to be a large industry with significant employment prospects for geoscientists. How and where CCS and geological CDR developments take place will vary depending on regional contexts (Vaughan et al., 2018) including matching of CO_2 sources and sinks (Power et al., 2020) and existing infrastructure (Alcalde et al., 2019). Expansion of global CCS programmes is slowly occurring, the Global CCS Institute Report for 2022 records a 44% increase in the CO_2 capture capacity of facilities under development over the previous 12 months (Global CCS institute, 2022).

Regardless of the geological CO_2 storage formulation, geoscience knowledge, experience and workflows underpin the selection of appropriate storage sites, the development, operation and monitoring of the storage sites (Roberts and Stalker, 2020), and their eventual closure (Krevor et al., 2022).

Geological Disposal of Radioactive Waste

All countries using nuclear power generation take responsibility for their own nuclear waste. Therefore, disposal facilities are of national concern in nuclear power generating countries. Nuclear waste derived from power generation is often combined with industrial, medical and military nuclear wastes.

Plans for radioactive waste disposal (often termed "rad waste") vary between countries and are dependent on the types and levels of waste generated. Different wastes have different radioactivity and heat generation properties. Lower levels of waste can be disposed of in several different ways, including below ground in near-surface facilities. For higher level waste, most countries have opted for deep geological disposal facilities (GDFs) (Kim et al., 2011; Ojovan and Steinmetz, 2022) (see the World Nuclear Association[12] for a description of waste levels). GDFs for nuclear waste are at various stages of development globally. The design of a GDF is dependent on the available geologies; the NRC identified three main lithologies suitable for deep geological disposal (NRC, 1957): clay-rich rocks, evaporites, and crystalline rocks. These are still considered the most appropriate due to a combination of properties including: permeability, reactivity, and strength. For example, the Onkalo GDF in Finland is in crystalline basement; the Waste Isolation Plant Pilot (WIPP) in the US disposed of wastes in subsurface salt deposits; and the Cigeo facility in France plans to dispose of wastes in clays. Deep borehole disposal has also been proposed for higher activity waste (Beswick et al., 2014; Mallants et al., 2020; Ojovan and Steinmetz, 2022). However, deep borehole disposal is at a lower technological readiness level than GDFs, and if developed, is likely to be more appropriate for small volumes of lower activity wastes.

There are both carbon and economic costs associated with radioactive waste disposal. Carbon emissions associated with GDFs are significant, but mostly source from the construction of the deep geological storage facility (Paulillo et al., 2020). The amount of high level waste is a key factor in determining the carbon intensity of the construction and decommissioning phases. Regarding economic costs, the development of a GDF in the UK is estimated to cost of £20–53 billion (undiscounted) (Nuclear Waste Services, GDF Annual Report 2020–2021[13], last accessed 10th November 2022), and the cost of nuclear power station decommissioning and GDF construction in France was estimated at €54 billion (Dorfman, 2017).

A wealth of geoscience skills are required for development and operation of radioactive waste disposal, and GDFs in particular: from site characterisation techniques (including seismic interpretation through to detailed borehole analysis); geomechanics, hydrogeology, and scenario modelling for risks and uncertainties. Geoscience skills and knowledge will be important in ensuring long-term security and cost-optimisation of siting and construction, for which allied skills in geotechnical engineering for design and construction will also be key. Sourcing of materials in the form of aggregates in addition to other raw

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[12] https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx

[13] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1057186/GDF_Annual_Report_2020_21.pdf

materials is crucial for engineering projects. Finally, radioactive waste disposal introduces important and sensitive geo-ethical considerations regarding intergenerational decision-making (Tondel and Lindahl, 2019).

Water Injection or Disposal Associated With Energy Production

Many geoenergy applications, including the processes leading for CO_2 geological disposal, energy storage, and geothermal cycling, require water injection for water disposal and/or pressure management and/or site sustainability. Examples include water production from geothermal energy extraction, where the water is reinjected into the subsurface (Kaya et al., 2011). The Gorgon CCS project (Western Australia) produces CO_2 and brine from with natural gas production, both of which are then injected into the subsurface, in different rock units (Trupp et al., 2021). Another example from CCS is brine production or injection for pressure management and to support storage capacity (Buscheck et al., 2016).

Water and wastewater injection particularly requires geological knowledge of managing subsurface risks relating to injectivity and pressure management, to minimise issues such as induced seismicity (Yeo et al., 2020), or brine migration (Maliva et al., 2007).

RAW MATERIALS FOR THE ENERGY TRANSITION

Metals

The energy transition involves a shift to an energy infrastructure (generation, transmission, and storage) based on renewable technology. This requires the sustainable sourcing of sufficient quantities of non-renewable raw materials—principally specialty, strategic and/or 'battery' metals. Whilst recycling may in time allow the creation of a genuine circular economy, at present we require ongoing and enhanced sourcing of many metals from both new and existing mines, ideally with a smaller environmental footprint than in the past (Smith and Wentworth, 2022). Further, a renewed interest in onshoring supply chains means there is increased attention to the issue of responsible local sourcing, and to resource stewardship.

Transitioning towards a renewable energy infrastructure means the large-scale manufacturing of solar panels, wind turbines, and Li-ion batteries amongst many other technologies; the widespread deployment of electric vehicles and other future transportation technologies; as well as enhanced infrastructure for electricity transmission and storage. This all will require a significant increase in the sourcing of key raw materials, principally metals (e.g., Herrington, 2021; Jowitt, 2022). A number of so-called "critical metals" (see below) have been highlighted as being especially vital to this effort (World Bank, 2020; Lusty et al., 2021), with significant estimates in the increase of production volumes of these metals required by 2050 over current production. For example, as the principal transmitter of electricity, copper is a key energy transition metal; although the increased copper demand from new technologies may be only a modest increase (Hund et al., 2020), a growing world population which is also undergoing societal and technological development, means that in the next 25 years the global copper demand will be significant—perhaps more than three times greater than at present (Schipper et al., 2018; Jowitt and McNulty, 2021).

Although many metals are in principle infinitely recyclable, in practice recycling rates are highly variable, with those especially for critical metals being low to negligible (Reck and Graedel, 2012). Recycling also assumes that metals in circulation are at their end-of-life stage, but the fact is many green technology metals such as lithium and cobalt were not previously in high demand, and are therefore not available in significant quantities within existing end-of-life products. Metals become available for recycling after a product's lifetime, which may be decades after first manufacture—hence metal stocks in scrap and end-of-life products represent production from decades ago (Ruhrberg, 2006). Given growing demand for most metals, over time, recycling stocks are insufficient to meet contemporary demand (Graedel et al., 2011). In essence, to reach a true circular economy, we need more metals actually in use in the global economy, in various lifecycle stages, than at present. Mining is therefore forecast to continue to grow despite improving recycling efforts. Thus, for the foreseeable future there will be a continued requirement for the exploration and extraction of a large range and volume of metals. This has significant implications for industry, for national economies, and for geopolitics.

The type of metals which will be required are both those traditionally mined—such as iron, aluminium, nickel, and copper—but also a range of specialty metals including the rare earth elements, lithium, and cobalt for battery and power technologies (**Table 2**), many of which are traditionally by-products of mining for other primary metals. The build-out of new renewable energy infrastructure requires both iron (for steel), copper for wiring, and tin for electronics (Nassar et al., 2015). However, as new technologies come on board and/or as metal substitution innovation occurs, then other metals may in turn become essential. Nuclear power requires mining of uranium, which may have its own demands and geological constraints (see section on Nuclear Energy).

Some metals have well-defined geological and metallogenic models and significant effort is expended on the exploration of new deposits by major multinational mining companies. For metals such as copper, there is broad agreement between industry and academia that future resources will largely come from the porphyry-style mineral deposits, and supply will be dominated by producers in South America (Singer, 2017; Hammarstrom, 2022). However, for other metals, a lack of significant historic demand has resulted in comparatively poor geological understanding and less well-developed models, and hence there is new research interest in the metallogenesis of metals such as lithium and cobalt.

TABLE 2 | Energy transition metals, and their "criticality"—as defined by current and projected future demand, and recycling rates.

Element		Production (metric tonnes pa)[a]	2050 projected demand[b]	Recycling Rate[c]	Criticality[d]	Comments	Uses
Lithium	Li	85,800	1,630,000	<1%	44	Lithium metal	Batteries, alloys
Magnesium	Mg	945,795		25%–50%	78	Primary Mg metal	
Aluminium	Al	65,400,000		>50%	22	Primary aluminium	Alloys, electronics
Titanium	Ti	6,500,000		>50%	26	TiO_2 content, including rutile and ilmenite concentrates	
Vanadium	V	95,000		<1%	46		Alloys, catalysts, batteries
Chromium	Cr	31,000,000	22,490,000	>50%	43	Ores and concentrates	
Manganese	Mn	49,600,000		>50%	45	Manganese ore	
Iron	Fe	3,016,000,000		>50%	20	Iron ore	Steelmaking
Cobalt	Co	126,000	1,260,000	>50%	78		Battery electrodes, catalysts, superalloys
Nickel	Ni	2,510,000	10,000,000	>50%	19		Batteries
Copper	Cu	20,600,000	120,000,000	>50%	14		Wiring, energy storage
Zinc	Zn	11,500,000	14,580,000	>50%	21		
Gallium	Ga	372	5,250	<1%	71		Semiconductors
Germanium	Ge	93	2,800	<1%	88		
Arsenic	As	50,684		<1%	63		
Selenium	Se	3,684	28,000	<1%	39		
Niobium	Nb	64,800		>50%	71		Alloys, superconductors
Molybdenum	Mo	297,000	280,000	25%–50%	32		
Silver	Ag	24,563	127,000	>50%	40		
Cadmium	Cd	24,500	93,000	10%–25%	33		
Indium	In	818	9,000	<1%	84	Refinery production	Touchscreens, solar panels
Tin	Sn	278,000	340,000	>50%	50		Solder, magnets
Antimony	Sb	123,000		1%–10%	95		Solder, lead-acid batteries
Tellurium	Te	633	17,000	<1%	47		Semiconductors
Lanthanum	La	264,439		<1%	93	Rare earth oxides	
Tantalum	Ta	1,200	6,600	<1%	77		Capacitors, reactors, batteries
Tungsten	W	92,500		10%–25%	88		Alloys, electronics
Platinum	Pt	430,000		>50%	93	Platinum group	Catalysts, fuel cells, turbines
Gold	Au	3,190		>50%	38		
Mercury	Hg	2,500,000		1%–10%	70		
Lead	Pb	4,500,000	7,650,000	>50%	13		
Bismuth	Bi	3,800		<1%	79		Solder
Uranium	U	46,300			29		Nuclear reactors
Legend			>20x production 2020	<1%	<80%		
			15–20x	1%–10%	60%–80%		
			10–15x	10%–25%	40%–60%		
			5–10x	25%–50%	20%–40%		
			<5x	>50%	<20%		

[a] *Data from Iodine et al. (2022), for 2020 data.*
[b] *Data from Watari et al. (2020), uses "maximum" demand.*
[c] *Data from Reck and Graedel (2012); end-of-life recycling rates.*
[d] *Data from Hayes and McCullough (2018); shows percentage of studies that consider elements to be critical.*

Through the exploration process, mineral deposits are discovered and scrutinised to convert them to mineral "reserves"—the legally, technically and economically mineable portion of the ore deposit. Mineral reserves are therefore only a fraction of the Earth's true inventory of metals, and in general reserves have kept pace with demand (Jowitt and McNulty, 2021). There is little to suggest that the world's supply of metals will be exhausted during the energy transition, but the time taken to explore for, and commence production of, an ore deposit leads to the pertinent issue of "mining latency," whereby the timescales of both greenfield and brownfield exploration and subsequent mine development are of the order of 10–25 years or greater (**Figure 4**). This means that in the event of a surge in demand there will be an inevitable supply lag, with implications for the price of those commodities and their availability for the energy transition. Such supply challenges need to be acknowledged and acted upon since they in turn may impact the projected transition timeline—unless there is a transformation in innovation such as reliable substitutions.

Critical Metals

Many of the required specialty metals such as lithium and cobalt are only mined in small quantities—in terms of both tonnage and/or mine supply diversity—with the increase in

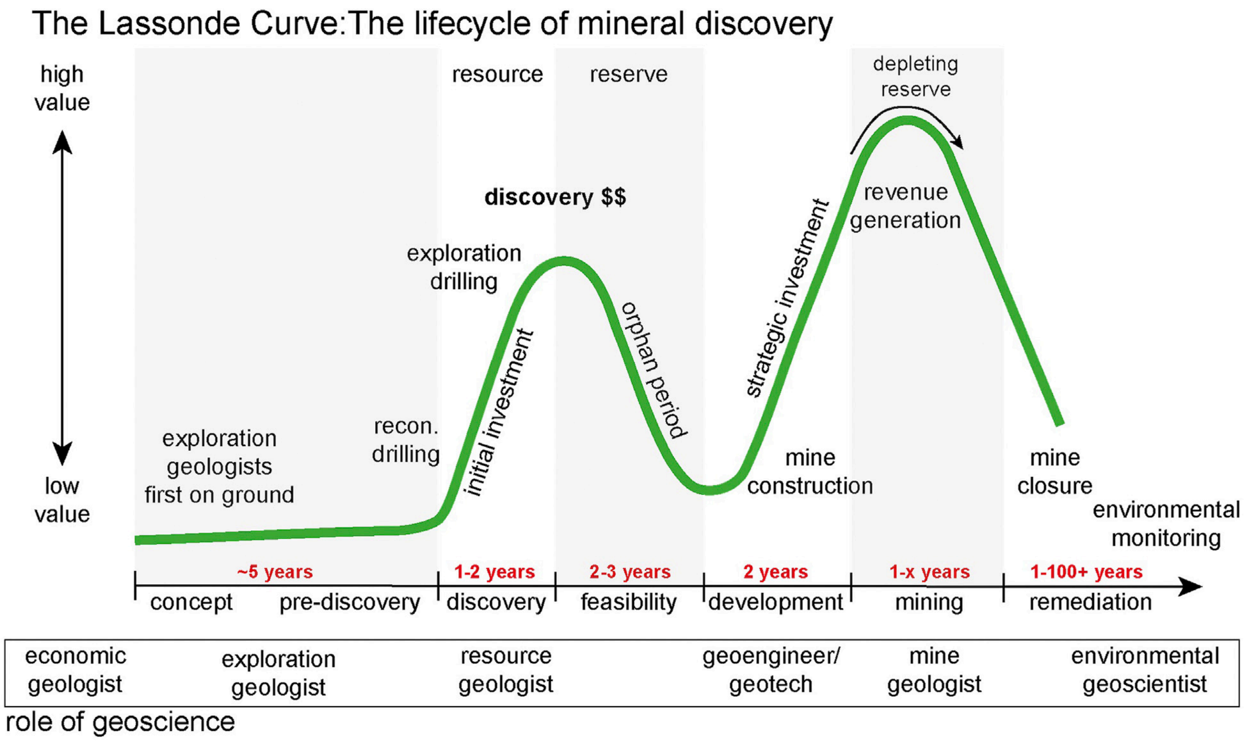

FIGURE 4 | The Lassonde curve—the lifecycle of a mineral discovery and as a function of asset value. After: https://www.visualcapitalist.com/visualizing-the-life-cycle-of-a-mineral-discovery/.

demand therefore constituting a significant real-term increase in their production. For example, it is projected that by 2025, some three- quarters of all lithium demand will be for use in Li-ion batteries (Azevedo et al., 2018; Bibienne et al., 2020)—a major increase from only 14% in 2019, assuming that Li-ion batteries are projected to dominate lithium demand into the middle of the century.

Minor and specialty metals typically have exploration and production dominated by small mining companies (juniors and prospectors), in limited mining jurisdictions, which in turn may mean less secure supply and an increased social impact. The geoscientific models for these metals, found in diverse and often idiosyncratic deposits, often originally exploited for other metals, are less well-defined, and there is limited ability to predict the geology of future supply (Sykes et al., 2016). Existing supply for some metals has relatively few providers, due to geological scarcity, challenging process methods, historic low demand, or relatively low value to producers. Many specialty metals are not mined for in their own right but are instead recovered as by-products of industrial and precious metals, or from wastes generated during their processing (e.g., cobalt, selenium, indium). These factors all combine to produce insecure supply chains for some metals—with strong dependencies on a small number of countries and companies as dominant producers, weak relationships between demand and price, and hence low economic stimuli for new exploration (e.g., Frenzel et al., 2017). This has led to some strategic metals being classified as *critical*—having both economic/industrial importance and a threatened supply (**Table 2**)—although it is worth noting that criticality is subjective and may only be a temporary designation (e.g., Jowitt and McNulty, 2021).

Major industrial metals may be vital to industry and society, but a geographically and commercially diverse supply makes for a robust supply chain. It is typically only minor metals and industrial minerals that are considered critical. The determination of a raw material's criticality will change depending on the country or company carrying out the analysis; the US and EU have different critical lists, and for the first time the UK Government drafted its own strategy in 2022[14], a practise now seen with other national governments, e.g., Canada, Japan. The availability of critical metals may influence the choice of decarbonisation technologies, the cost of the energy transition, the timeframes for change, and the ability for all the world's nations to meet their Paris Agreement obligations, and may drive technological change and/or substitution technologies.

Implications for Mining and Sustainability

The concept of "sustainable mining" in the extraction of a non-renewable resource, we take to mean minimising the environmental, economic, and societal impacts of: resource

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[14] https://www.gov.uk/government/publications/uk-critical-mineral-strategy

discovery; extraction, processing and usage; waste and tailings management; and closure and remediation/reclamation. Present mining activities have variably significant footprints in terms of energy used during mining, processing, and transportation of concentrate (with associated CO_2 emissions), and water impact. Routes to reduce these impacts include: discovery of large, high grade deposits in brownfield regions and/or their discovery closer to smelting and manufacturing; decarbonisation of mining activities including via renewables-powered operations and/or CO_2 drawdown activities; and enhanced processing technologies. If responsibly carried out, mining activities can assist UNSDGs, especially in developing nations.[15]

Even though we now mine more metals than at any point in human history (US Geological Survey, 2021), increased metal production for the energy transition will see the further expansion of the mining industry. This might mean the extraction of poorer quality ores and working of smaller deposits, with consequent negative impacts on energy use, CO_2 emissions, water consumption and waste. Explorers may have to work in new frontiers; this might mean deeper (and more expensive) mines in established areas, or the development of mines in new areas, including deep sea environments and biodiversity hotspots. The pursuit of new resources to satisfy the demands of the energy transition needs to be balanced against the potential impacts across the Sustainable Development Goals (United Nations, 2015; UNECE, 2021b).

For major industrial metals such as copper and iron ore, the significant reserve and production volumes and larger more diversified mine base of these metals mean their supply is relatively insulated from external shocks. However, the sourcing of small-scale metals—which tend to fall to smaller producers, from a restricted number of key mines, perhaps in less well developed mining jurisdictions—means their supply is at much greater risk from geoeconomics and geopolitics: e.g., lithium is sourced mainly from a limited number of Australian hard rock mines and from Chilean Salars—meaning supply is at a much greater risk of disruption. Critical, minor and by-product metals generally suffer from more volatile pricing (Redlinger and Eggert, 2016), and hence more challenging business conditions for explorers, miners and investors (e.g., Gardiner et al., 2015). These issues are in some instances causing a rewiring of supply chains, where major consumers of metals which suffer from price instabilities, are now making direct offtake agreements with, and in some cases direct investments into, producers to ensure supply (e.g., GM sourcing lithium from Thacker Pass, Nevada[16]).

In terms of the geoscience response, there is a need to find more deposits of most major and minor metals, in particular with a focus on identifying and exploiting giant orebodies to minimize mining impact. The drive towards more sustainable mining practice, which seeks to minimise environmental footprint, requires that we explore and produce from larger, higher grade deposits (against a backdrop of declining size and grade), with more efficient processing technologies, and work deposits sited closer to eventual consumption of the metals (European Commission, 2020). New discoveries may require building new exploration tools to enable new exploration approaches. The mineral systems paradigm (McCuaig and Hronsky, 2014) provides a framework for breaking down the essential parts of ore formation, with the ability to then target and interrogate with novel exploration tools.

The "quality" of mineral deposits, in terms of ore grade, accessibility and mineralogy (e.g., presence of deleterious components) has declined in the 21st century, through the depletion of the most optimal ores (e.g., Mudd, 2010). In some cases we now mine what was once considered uneconomic "background" mineralisation (e.g., Figure 3 of Goldfarb and Groves, 2015). As mining environmental performance (energy consumption, water consumption, waste) is strongly dependent on grade, future exploration may be dominated by the search for higher grade deposits in new frontiers. This might mean mining activities further encroach into wilderness areas and biodiversity hotspots (Sonter et al., 2018; Sonter et al., 2020), the pursuing of resources in novel environments including the sea floor (Miller et al., 2018), or searching deeper under cover in conventional mining landscapes (Schodde, 2014). Exploration and mining in these new frontiers requires innovation in geophysical techniques, improved geological and geometallurgical models for deposit types, and significant research into the potential environmental impacts and their mitigation. Whole life-cycle planning of the exploration to post-mining programme and expanding the potential to involve circular economics as much as possible is essential for future responsible resourcing (e.g., Wall and Pell, 2020).

The implications for geosciences is multi-fold. Research leading to better metallogenic models at a range of scales can help with discovery of metallic resources not previously explored for at scales; development of novel exploration tools can help to "vector" to mineralisation; a better understanding of deposit and grade morphology can assist with mining strategies; mineralogical constraints can inform new processing approaches. Improved geometallurgical technologies are required to both improve processing efficiencies, as well as process new mineralogical associations. Environmental geoscientists are needed to both help with responsible mining operations, as well as post-mining remediation and monitoring efforts.

Water

Often referred to as the "energy-water nexus" (IEA, 2016), water and energy resources are intertwined, and geoscience is relevant for both. Further, it is anticipated that the interdependency of water and energy will intensify due to climate impacts and changing energy provision, with

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[15] https://www.unep.org/news-and-stories/story/how-minerals-and-metals-companies-can-help-achieve-2030-agenda-sustainable

[16] https://www.mining.com/gm-lithium-americas-to-jointly-develop-thacker-pass-mine-in-nevada/

TABLE 3 | A summary of cross-cutting issues that cut across the geoscience sector that are important for a just transition to net zero carbon.

Cross-cutting issue		The challenge
Technical geoscience	Data availability and access	Open and transparent sharing of geoscience data is not currently standard practice. Moving to open data sharing in useable formats will accelerate energy transition applications by removing the need to invest in duplicate data acquisition—and the associated social and environmental impacts Gill and Smith (2021)
	Multiple uses of the subsurface	Into the future, there may be multiple, competing and/or complimentary uses of the subsurface. Siting and management decisions and surface monitoring techniques must account for and manage these multifold uses, adapting the decades of learnings on, e.g., subsurface pressure management from the hydrocarbon sector, and care-and-maintenance from the mining sector
	Monitoring approaches	Real time, transparent, and low-cost monitoring approaches must be developed to optimise net zero geoscience applications, reduce costs, support transparent and open reporting, and to build trust amongst stakeholders
	Geotechnical knowledge	Geoenvironmental and geotechnical engineering knowledge, skills, and techniques directly underpin all of the activities we have outlined in this paper. These skills are also required for, say, tunnelling for high voltage cables and pipelines, ground stability for renewable energy developments including wind turbines and transmission infrastructure
Skills and workforce	Skills for sustainable transition	While many geoscience skills are transferable to new energy transition geoscience applications, some risks and workflows are specific. Geoscience education at both apprenticeship and degree-level must pivot to ensure sufficient training and skills development for energy transition geoscience applications, including cross-cutting skills for sustainable development Rieckmann (2018)
	Workforce transition	The workforce currently employed in sectors anticipated to decline must be supported to transition into growing or emerging geoscience sectors. Further, since the global energy sector has low diversity[a], efforts to improve equality and inclusivity must be embedded across the sector. Doing so will both widen the pool of talent within geoscience and reduce inequalities
	Diversifying geoscience higher education	In countries the number of geoscience graduates is in rapid decline and geoscience programmes currently have poor representation Dowey et al. (2021). This presents an opportunity for geoscience Higher Education sectors to transform their programmes to encourage a wider range of students from different backgrounds to study geosciences, and to remove systemic barriers to inclusion and retention
Environmental impact	Life cycle emissions and impact	Geoscience developments and activities must reduce or design out life cycle emissions including “upstream” emissions related to extraction. Approaches can include reducing fugitive emissions, switching to clean fuels, and changing practices. CCS can be applied to mitigate emissions from processes that co-produce CO_2, such as deep geothermal [c.f. carbfix; Snæbjörnsdóttir et al. (2020)]. New metallurgical technologies can help reduce the environmental footprint of minerals processing
	Data and infrastructure	Countries with modern day extractive industries have the subsurface data, infrastructure and sectors that can facilitate new low-carbon geoscience applications. It may therefore be more challenging for countries without such sectors to decarbonise by developing geoscience technologies such as CCS[b]
Spatial considerations	National vs. global approaches	As Smil (2016) notes, energy transitions assessed at a global level are slow. Coal, for example, took 35 years to rise from 5% to 25% of global primary energy supply and another 60 years to reach 50%. However, when assessed at a national level, transitions can be quick. Netherlands grew their natural gas supply from 5% to 46% in 10 years. Thus global pathways to achieve net zero, whilst informative, will vary significantly in rate from national pathways. This will depend on who moves when and how far with some nations opting for first mover advantage and others waiting for technologies to be established. This has implications, for example, in the timing and need for geotechnical expertise in establishing foundations for offshore wind farms and for the amount of geological storage of CO_2 required in a particular basin. Geoscientists as a profession must then remain flexible and adaptable to where demand is in space and time
	Developing local supply	The environmental footprint of critical raw materials supply can be reduced by developing local supply chains, either through new ventures, rehabilitating old mining workings (e.g., SW England), or recycling or reprocessing of wastes. Streamlining and simplifying the permitting landscape for exploration and production of minerals would boost activities
	Matching sources and sinks	To minimise environmental and economic cost through energy losses, energy demand will ideally be co-located with energy sources, however this is not always the case—particularly for geothermal applications (heat/coolth/thermal storage). The concept applies also to emissions, leading to the development of the ‘hubs and clusters’ approach to industrial decarbonisation
	Responsible resource stewardship	Operating sustainable mineral exploration, mining, and mine remediation efforts in line with Environmental and Social Governance (ESG) good practice. Ensuring issues such as water, biodiversity, greenspace are accounted for
Geoscience sector	Speed of transition	Rapid and deep decarbonisation is necessary to meet climate objectives. The scale and speed of transition poses challenges in terms of enabling political and societal support, as well as ensuring the skills and supply chain are in place
	Enabling *transition*	There’s risk that geoscience developments and applications can support “carbon lock-in,” hindering sustainable transition

(Continued on following page)

TABLE 3 | (*Continued*) A summary of cross-cutting issues that cut across the geoscience sector that are important for a just transition to net zero carbon.

Cross-cutting issue		The challenge
	Stakeholder engagement and awareness	Societal awareness of geoscience solutions to net zero varies depending on a range of factors such as technology, country/region, and socio-economic considerations, but for some technologies such as CCS and geoenergy storage, awareness is systematically low Leiss and Larkin (2019); Roberts and Lacchia (2019). This includes amongst policymakers. Thus, there is a need for increased engagement in geoscience aligned activities, framed in such a way that responds to stakeholder interests and concerns
Societal acceptability	Social context and framing	The social context, including political, cultural, and governance shapes how publics engage with and respond to different policies, technologies, activities or developments, and geoscience is no different. These factors influence which frames and approaches might be more effective in supporting effective and sustainable deployment [e.g., Gough and Mander (2019)]. Geoscientists must connect more deeply with and respond to societal interests and concerns regarding the discipline and geoscience developments
	Community participation	Many net zero geoscience applications follow the long-outdated "Decide-Announce-Defend" model of public engagement, giving little routes for community say in the development of projects. For community acceptability, approaches to geoscience developments must broaden to follow best practice community engagement and resource community participation Demski (2021)
	Incentives	Geoscience solutions for net zero require supportive policy frameworks to incentivise developments such as CCS and geothermal, and also to ensure ESG is embedded in the development approach. This requires geoscientists to work closely with policymakers at difference scales, as well as legal and economic experts
Policy and reporting	Trusted and transparent reporting	Transparent reporting on ESG and life cycle carbon is necessary to ensure sustainable transition and to support societal acceptability

[a] *https://www.iea.org/topics/energy-and-gender*

[b] *https://www.globalccsinstitute.com/resources/publications-reports-research/the-carbon-capture-and-storage-readiness-index-2018-is-the-world-ready-for-carbon-capture-and-storage/*

significant implications for both energy and water security (IEA, 2017).

Not only does water treatment and supply require energy, but many geoscience and energy applications use water. Example applications which rely on water include: cooling of power plants and carbon capture processes (Rosa et al., 2021); hydrogen production via hydrolysis (Beswick et al., 2021); production of geothermal energy (Lohrmann et al., 2021); drilling wells; subsurface pressure management (for hydrocarbon production, and hydrogen and CO_2 geological storage); mining and processing of key metal resources (Meißner, 2021); and for growing and producing crops for biofuels and bioenergy for BECCS (Gerbens-Leenes et al., 2009).

Climate change and urbanisation is causing water resource stress (He et al., 2021a) in addition to water extraction and use. For example, the UN estimates that ~70% of the mining operations of the world's six biggest companies are in countries facing water stress, and that resource extraction and processing is responsible for more than 90% of global water and biodiversity stress (Hellweg et al., 2020). In particular, mine supply of base metals such as copper, nickel and zinc are exposed to water stress (Northey et al., 2017). Thus, for a sustainable energy transition, planning and policies must consider the interconnection between water and energy to ensure that water resource scarcity and social impacts is not exacerbated, and that energy and material supply is sustainable, reliable and secure (Milman and MacDonald, 2020).

Geoscience skills are important for understanding the interdependencies and interactions between demands and/or pressure on water resources for sustainable water management in different environments and contexts. Critical, also, will be improved methods to evaluate and reduce water use, as well as integrated risk management to ensure that potable water supplies are not depleted or contaminated.

CROSS-CUTTING CHALLENGES AND OPPORTUNITIES FOR GEOSCIENCES

A number of cross-cutting issues will impact the pace, scale, and style of transition across different geoscience sectors, and therefore geoscience contribution to energy transition. As summarised in **Table 3**, such cross-cutting issues include: technical challenges, geoscience industry policy and practice, as well as political, economic and societal themes.

One key topic is the issue of skills and workforce transition—encompassing university and professional training for geoscientists, appropriate graduate-level jobs, and reskilling existing professionals. There is a steady decline in geoscience graduate degree recruitment, at both honours and higher level, in many countries worldwide (Anonymous, 2021). Might a geoscience skills shortage present a risk to a sustainable energy transition? We are in a pivotal time, and the geoscience sector and Higher/Further Education institutions must urgently respond to this. Geoscience must be reframed to showcase the exciting, important and holistic role that geoscientists will play in enabling a fair and sustainable future. This will require

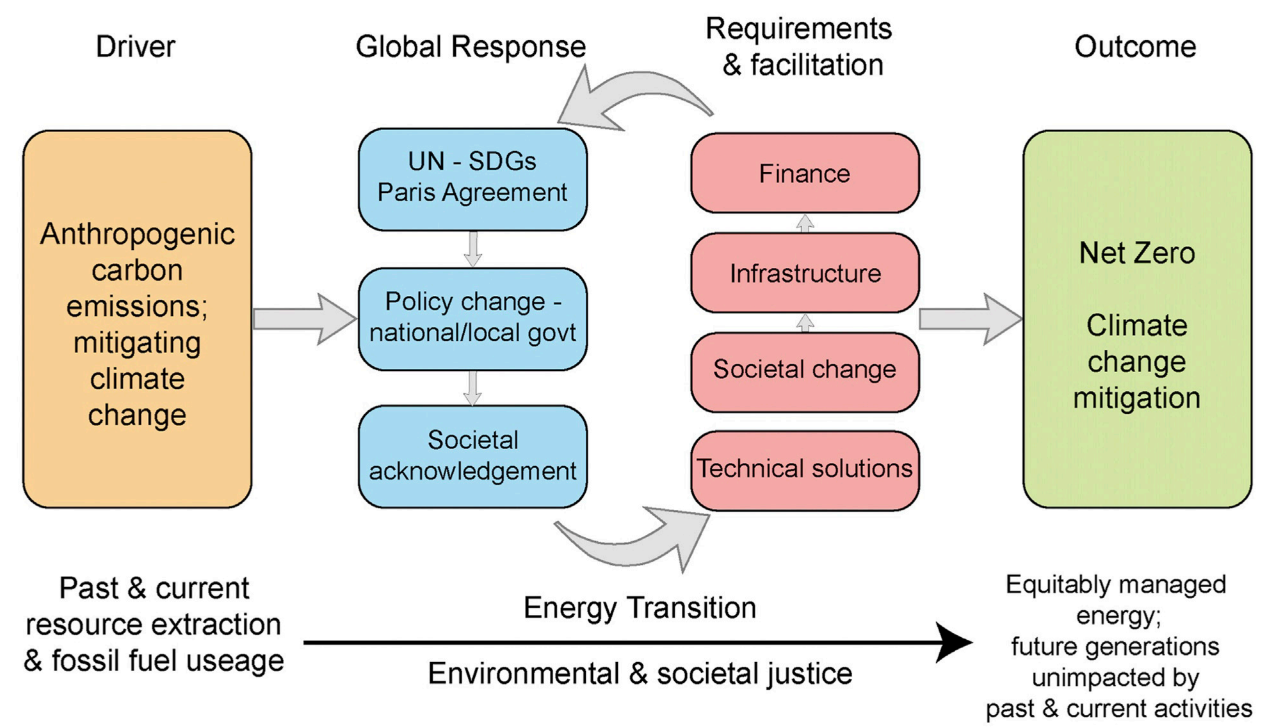

FIGURE 5 | Schematic of various stakeholders in the energy transition.

changes in curricula and in changes student recruitment to encourage a wider range of students from different backgrounds to study geosciences (Dowey et al., 2021). Further, systemic barriers to inclusion and retention in geoscience higher education and workplaces must be identified and mitigated or removed. Geoscientists must connect more deeply with and respond to societal interests and concerns regarding the discipline and geoscience developments.

Related disciplines including geoenvironmental and geotechnical engineering are important for energy infrastructure siting, design and operation—including for ground stability, hazard assessment, and geothermal considerations. Developments for which this input is crucial include: hydro and tailing dams, tunnelling for high voltage cables and pipelines, and infrastructure such as CCS and underground hydrogen storage industry, mining and quarrying, and renewable energy developments including wind turbines and subsurface pumped hydro.

A related issue concerns societal acceptability and interaction with the suite of potential geoscience solutions at different scales that we have outlined in this paper. Many of the technologies outlined in this paper are unfamiliar to wider society, and awareness of the role of geoscience solutions for net zero is low (Leiss and Larkin, 2019; Roberts and Lacchia, 2019). Further, prospective developments might be met with caution, due to lack of trust or associations with past harms. For the energy transition to be fair and sustainable, these technologies and the energy system that they form part of must be designed and developed and implemented in partnership with local communities and in such a way that delivers multiple sustainable development objectives (Roberts et al., 2023). This requires an integrated “whole systems” approach, with strong emphasis on partnership building and societal considerations regarding net zero infrastructure and energy systems of the future. There are valuable roles for geoscientists in developing effective engagement programmes to widen societal awareness of geoscience aligned activities, framed in such a way that responds to stakeholder interests and concerns. Partnerships across disciplines to support societal and political awareness of geoscience for climate action is key. Therefore there is are valuable opportunities for geoscientists with excellent communication skills, reflective thinking, and listening skills to nurture creative approaches for communication and societal engagement to support sustainable geoscience development (see **Table 3**).

Transitioning From Fossil Fuels

As we transition from a fossil hydrocarbon dominated society, the role of continued fossil hydrocarbon production and use is contentious. Continuing fossil hydrocarbon production does not support climate goals (IEA, 2021c; IPCC, 2023). CO_2e emissions from hydrocarbon production, refining, transport and storage are significant, in addition to combustion for energy, thus as well as tackling fugitive emissions from hydrocarbon supply chains, reducing fossil fuel reliance is key.

Different transition pathways for the phase out or the phase down of fossil hydrocarbons have been proposed. Some have proposed a phased transition in production involving preferentially targeting "advantaged" hydrocarbons, i.e., those with minimal impact in discovery and production (Davies and Simmons, 2021), or prioritising hydrocarbon production from lower income countries. Phased transition in hydrocarbon use is also proposed, with some applications being prioritised over others and/or an initial focus on the continued use of oil, gas over coal. The enactment of Geological Net Zero also provides a potential route to achieve net zero emissions within the timescales of the Paris Agreement. Regardless, the transition from fossil fuels will shape the geoscience workforce of the future, and inclusive strategies must be designed and implemented to ensure equality of opportunity.

SUMMARY

Progress and action for the energy transition to net zero carbon is critical, and both geoscience sectors and geoscientists will play multiple key roles - direct and indirect—in achieving this. Geoscience knowledge and skills are necessary for the development of many energy transition technologies and supply chains, from the sourcing of raw materials, to new modes of low carbon heat and power generation and subsurface energy and thermal storage technologies, to the sustainable management of energy wastes and balancing of carbon budgets.

Mitigating climate change is one facet of the energy transition, and geoscience applications will need to meet the technical demands of decarbonisation alongside broader sustainable development and just transition objectives. The multidisciplinary and integrated nature of the energy transition means that it will involve working across and beyond geoscience disciplines to deliver innovative solutions and develop new lines of research and applications. Geoscientists are therefore well-placed to support policymakers, stakeholders, industry and business, and communities in the wider society (**Figure 5**), in the responsible management of Earth resources fundamental to the energy transition, and the use and stewardship of the subsurface, to build a sustainable future.

This paper has shown a rich future for geoscience, underpinned by the importance of a broad range of geoscience knowledge and skills for a sustainable energy transition. The geoscience community must recognise its responsibility in facilitating a fair and sustainable energy transition, ensure inclusive geoscience skills and supply chains are in place, support sector decarbonisation, and support knowledge exchange and cross-disciplinary and cross-sectoral partnerships for net zero.

A systems approach is essential to the success of integrating geosciences into the complex and multi-layered challenges of achieving net zero. As a result, geoscientists must work across and beyond geoscience disciplines and sectors to ensure environmentally and socially equitable energy transition.

POSTSCRIPT

An Energy Transition Discussion Meeting, held at the Geological Society of London in April 2022, provided a forum to discuss "*What does Geoscience need to do now for a sustainable transition to Net Zero?*" (Knipe et al., 2022). The impetus for the meeting was that there was a clear and immediate need for climate solutions, but that gaining public and political trust is essential for progress; that geoscientists in academia and industry play a key role both in progressing the science and technology, but also in providing deliverable solutions that bring environmental and social benefit. The meeting followed on from a series of related webinars and events, and all brought into sharp focus the scale of the challenge of the energy transition, as well as the critical role of Geoscience in achieving it. The key issues raised by the attendees of the meeting included:

- A lack of recognition and discussion of the urgent need for rapid deployment of CCS to achieve net-zero, that the tools and knowledge exist, but need applying, which could be achieved via a "Carbon takeback policy" (Jenkins et al., 2021). Understanding of timescales and the contributions from geological versus "nature-based" solutions.
- Engagement with a wide range of stakeholders, including the public, is urgently required to communicate the value of the sub-surface, engage with and listen to residents, public, policy, management, etc., and thus skills needed by geoscientists include an ability to communicate and develop trust.
- An understanding of critical mineral supply chains and latencies is essential to secure future sufficient supplies for the decades ahead. However, there is a need to speed up the implementation of exploration/production programmes to meet demands of the energy transition, but also a requirement to shift to more sustainable mining practices, to change the reputation of the mining sector, and to highlight progress in e.g., environmental, social and governance (ESG).

In summary, geoscience knowledge and skills are essential to meet net zero, but enabling and harnessing these technologies requires integration and cooperation with other disciplines to build an integrated approach to ensure a sustainable and equitable energy transition. It is the responsibility of the geoscience community to help drive these essential collaborations, to address the skills gaps for existing workers, and to help identify opportunities and careers paths for those entering the workplace.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

CONFLICT OF INTEREST

Author SG was employed by the company Satarla.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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