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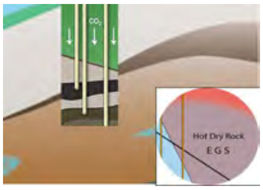

Geoscience for energy transition

We are living in the midst of a great technological revolution in history—the energy transition from today's fossil fuel-dominated civilization to low-carbon economies and industries. Geoscientists will significantly contribute to energy science, policy and technologies by advancing our knowledge base of the complex interacting processes and substances in Earth's lithosphere, oceans and atmosphere. Mapping the flow of energy in various forms and intensities in Earth systems, exploration of energy resources and minerals and evaluating the environmental impacts of energy technologies from upstream to downstream will be increasingly embedded in geoscience education, research and workforce development. This article outlines major pathways of how geoscience will contribute to various components of the energy transition.

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Energy transition to a low-carbon world with secure energy supplies is one of the most urgent and challenging issues of our time. Two trends are converging and propelling this energy transition. First, increased carbon dioxide in the atmosphere from the burning of fossil fuels (coal, oil and natural gas) particularly over the past century has been associated with global warming with grave environmental threats. Second, political conflicts and supply chain disruptions are motivating many industrial countries to diversify their energy supplies and reduce their energy dependency on volatile sources. Although the pace and priorities of the energy transition differ from one region to another, the global shift to low-carbon societies requires enormous know-how, research and development (R&D) and skillsets from various disciplines of science and engineering. Geoscience, as briefly described below, will play a pivotal role in this technological revolution.

The natural gas bridge

Since the Industrial Revolution in the nineteenth century and the invention of internal combustion engines and electricity, coal, oil and natural gas have sequentially dominated the world's energy landscape (Fig. 1). Today fossil fuels account for 80 percent of world's energy consumption, and oil consumption is nearly 100 million barrels per day (50 billion metric tons a year) and natural gas consumption stands at 4 trillion cubic metres a year. The future is an uncharted territory. Various scenarios for the future development of energy supplies by 2050 by governmental agencies (e.g. International Energy Agency and US Energy Information Administration) and energy companies (such as BP, Eni, Equinor, ExxonMobil and Shell) are based on whether the energy trend will be 'business-as-usual' or to what extent 'decarbonization' policies (reduction in CO_2 emissions from the current level of 422 ppm or limiting temperature rise by 1.5°C or 2°C) will be materialized (Fig. 2). Given today's 'stated policies scenarios', fossil fuels will still make up 60–70 percent of total energy consumption in 2050, while the aggressive 'net-zero carbon scenarios' predict a 20 percent share for fossil fuels. The massive reduction in the share of fossil fuels in world energy will largely depend on whether alternatives to oil-fueled vehicles are developed, and renewable energy technologies for electrification become widespread in the near future.

Among fossil fuels, natural gas is becoming a dominant shareholder (Fig. 3). Natural gas is an abundant resource and is already a major source of electric power. Moreover, it emits 50 and 25 percent less CO_2 than coal and crude oil, respectively. For these reasons, natural gas is viewed as an essential bridge from today's fossil fuel-dominated civilization to a low-

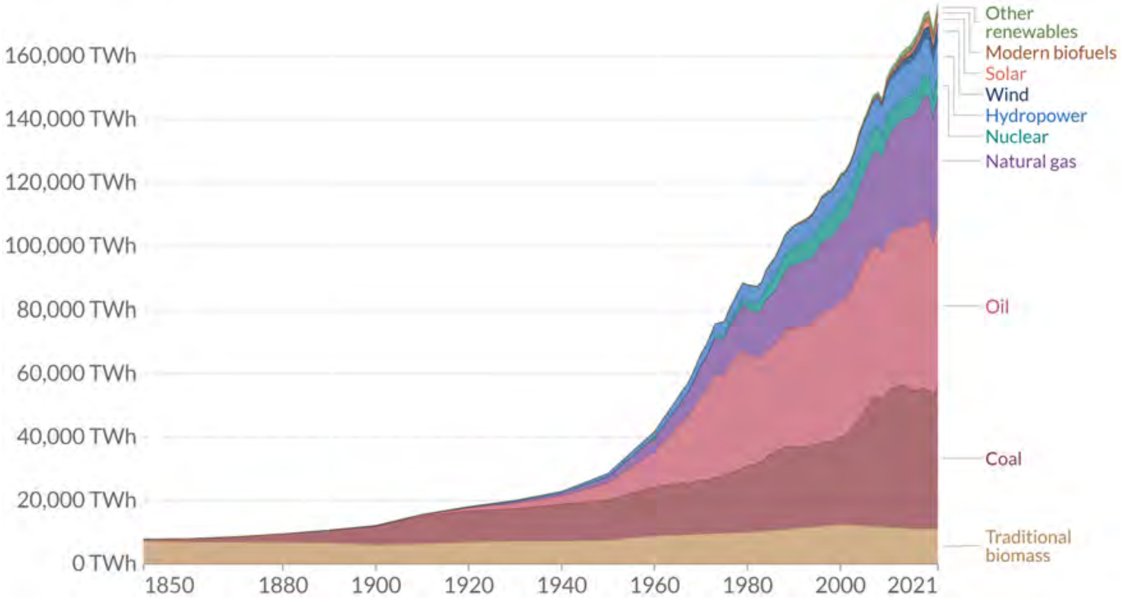


Fig. 1. Evolution of energy resources since the industrial revolution in the mid-nineteenth century to the present day. (Source: OurWorldInData.)

carbon world in the near future. For the foreseeable future, geoscientists will need to explore, discover and develop natural gas reservoirs in various sedimentary basins and regions of the world. Natural gas has a versatile occurrence: Non-associated (free) gas fields, dissolved gas and gas caps associated with crude oil, shale gas, coal-bed methane, methane hydrates, synthetic gas and even mantle volcanic gas. They all require different exploration approaches and technologies. Liquefied natural gas (LNG) plants to transport this hydrocarbon fuel across the oceans as well as natural gas power plants will increasingly grow in the coming years.

Hydrogen economy

Hydrogen as the main constituent of water (renewable) and hydrocarbons (non-renewable) is an abundant resource. In his 1874 science fiction *The Mysterious Island*, Jules Verne envisioned that the splitting of water would provide an inexhaustible source of heat and light. Of course, hydrogen, like

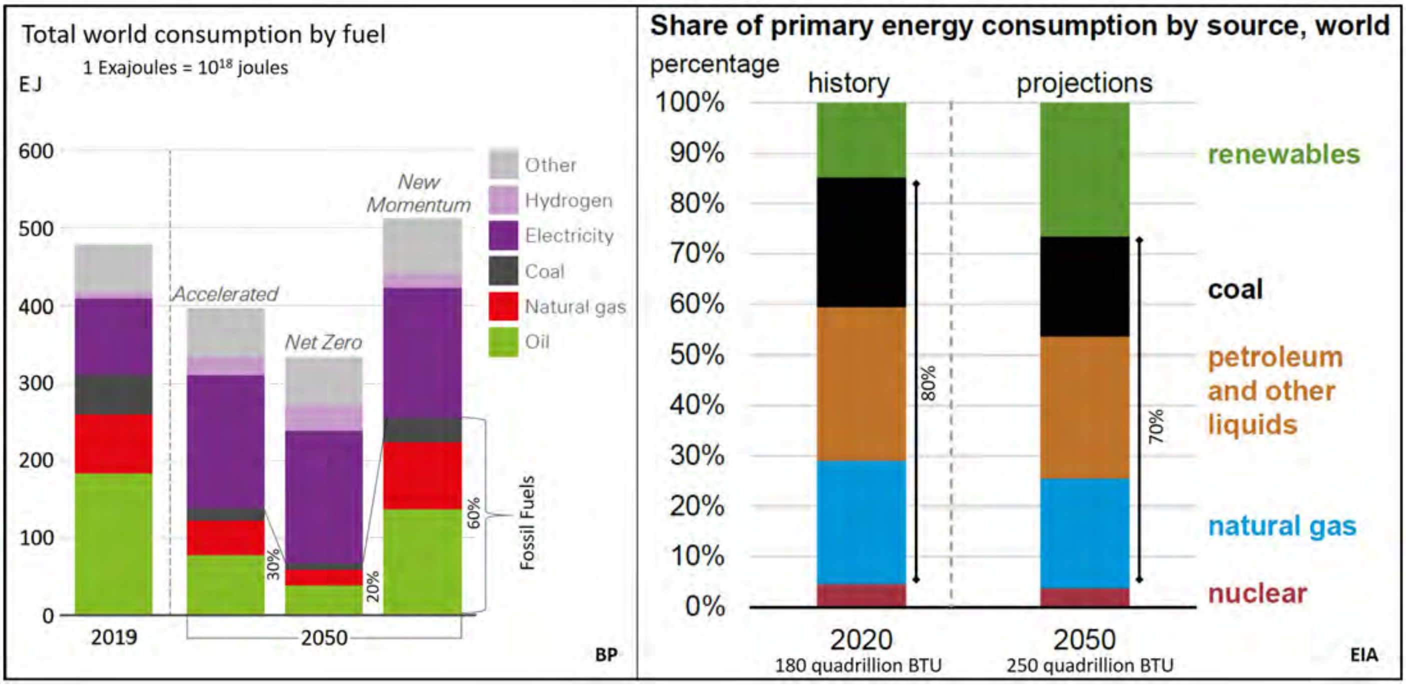


Fig. 2. Energy consumption by source in 2020 and projected to 2050 according to British Petroleum (BP, 2022) and US Environmental Information Administration (EIA, 2021). The IEA projection, much like BP's 'new momentum' scenario is mainly based on 'business-as-usual' or 'present trends', while 'accelerated' and 'net zero' scenarios in BP's report respectively assume 75 and 95 percent reduction in CO_2 emissions with more pledges and efforts by government and corporations.

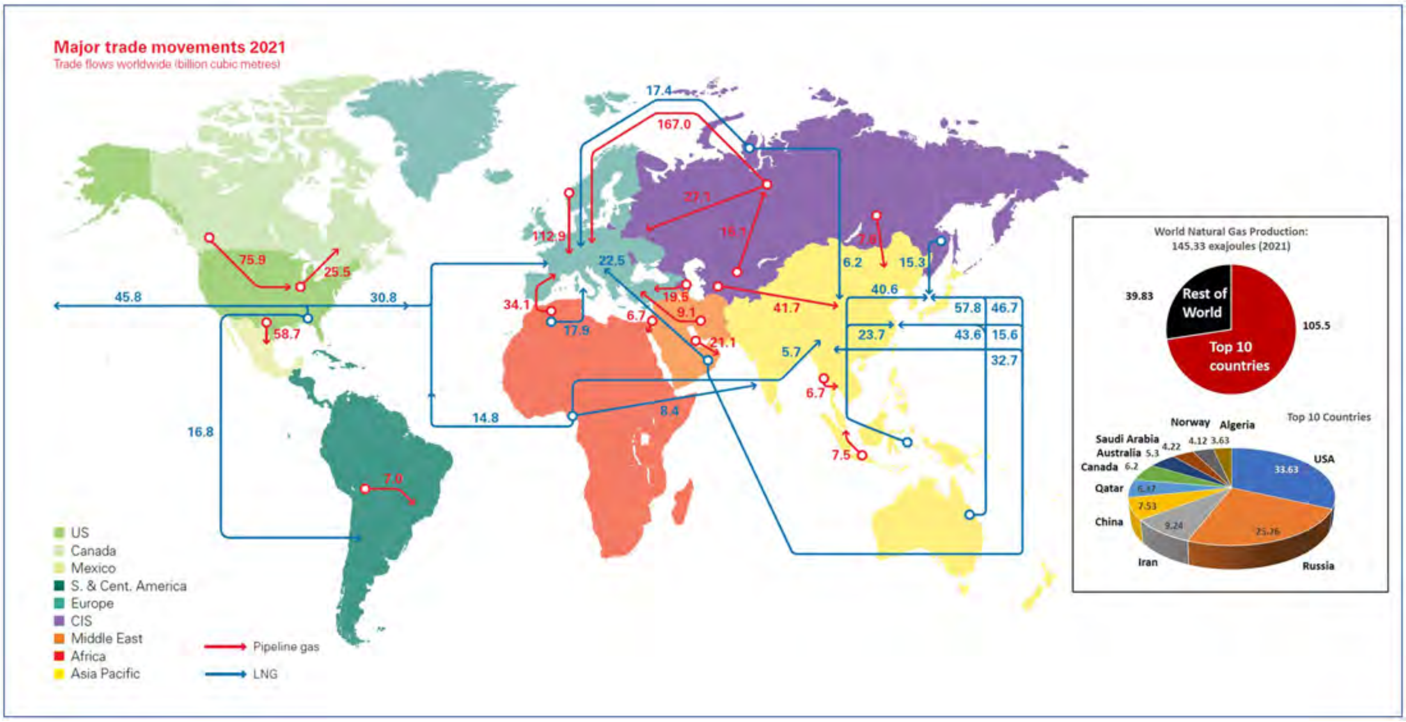


Fig. 3. Share of world's natural gas production and its trade movements in 2021. (Source: BP)

electricity, is an energy carrier, not a source; it has to be derived from primary energy sources. Nevertheless, hydrogen burned with oxygen is a zero-carbon fuel. Used in fuel cells or internal combustion engines, hydrogen is a viable alternative to petrol-powered vehicles and ships. Hydrogen can also be used in electric power plants. The term 'hydrogen economy' was coined in 1970 by John Bockris of General Motor as an alternative to 'hydrocarbon economy'.

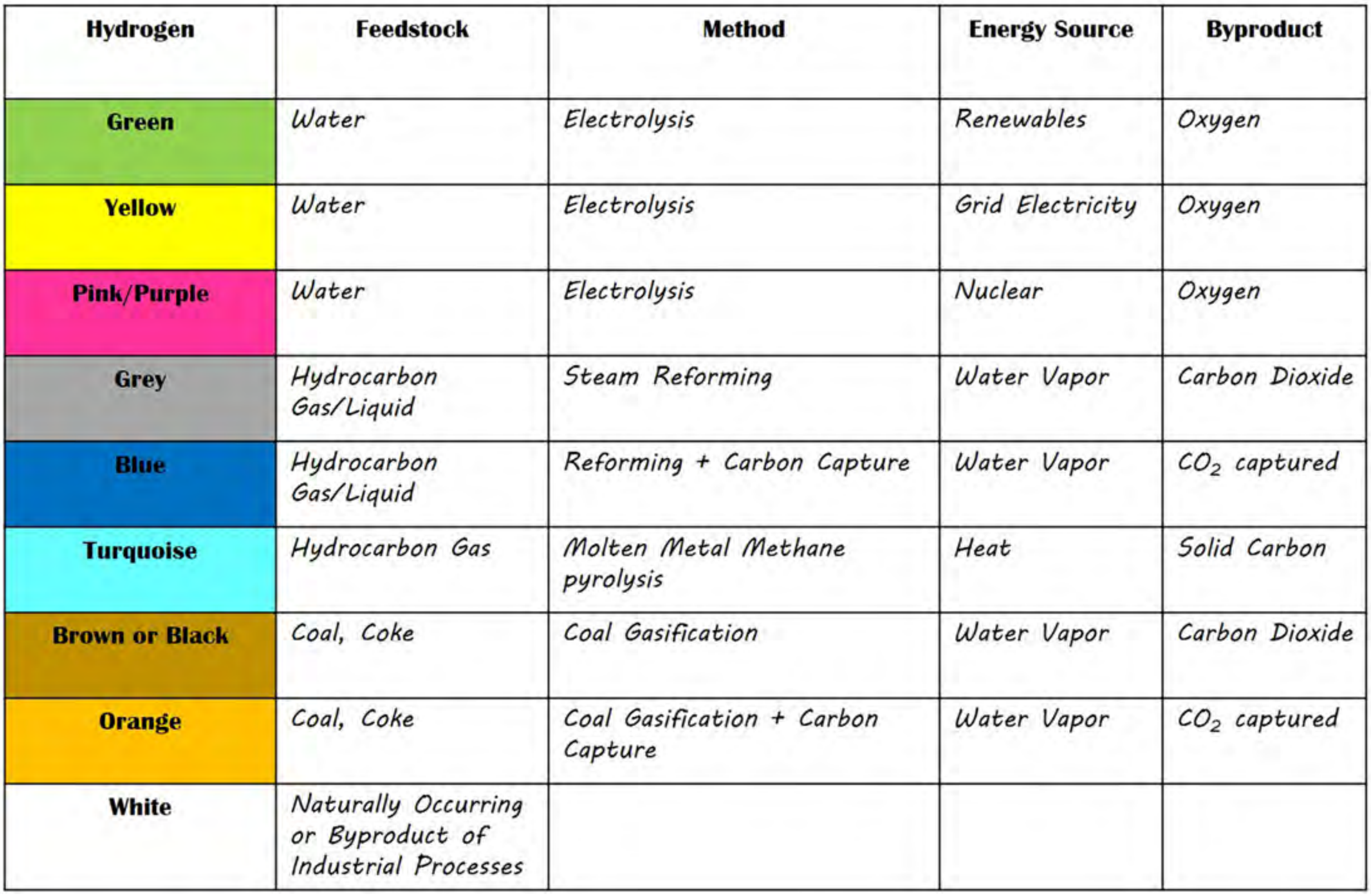
Hydrogen is currently 'mined' from water by electrolysis, from hydrocarbons (by steam reforming) or coal and coke (by gasification). Depending on side products of the technology used, hydrogen has been colour-coded as green (no CO_2 emission), grey (CO_2 emission) and blue (CO_2 captured). However, these technologies are so diversified that various grades of hydrogen are identified (Fig. 4). Currently 95 percent of hydrogen is produced from fossil fuels by steam reforming. All hydrogen technologies need to be improved for better efficiency and minimal environmental impact.

Hydrogen is the lightest element (Earth actually loses hydrogen via atmospheric escape); it is also a very reactive gas. For these reasons, storage or transportation of hydrogen is a daunting challenge. High-pressure steel tanks have been used to store hydrogen gas; cryogenic temperatures (below −252.8°C, hydrogen's boiling point) have also been used to store liquid hydrogen. However, large-scale storage of hydrogen needs subsurface reservoirs such as salt caverns or salt beds, depleted saline aquifers and depleted natural gas reservoirs. Geoscientists can locate and evaluate such sites for their physical integrity (sealing capacity) and chemical durability (risk of hydrogen sulphide or other reaction products).

Geoscientists can also explore occurrences of natural hydrogen and characterize 'natural hydrogen systems'. The discovery of a shallow natural hydrogen field in Mali, West Africa has drawn much attention to natural hydrogen because it is cheaper than industrially produced hydrogen. Natural hydrogen is indeed a hot area of research, and various processes and sites have been identified including natural gas fields, sites of serpentinization (reaction of water with ultramafic rocks), decomposition of organic matter, rock weathering, decomposition of hydroxides in minerals, hydrogen seeps from sedimentary basins and degassing of hydrogen from the mantle.

Geothermal power

Generation of electricity from renewable resources offers huge potential in the coming decades as solar, wind, hydro- and geothermal resources are both abundant and clean (they do not directly emit CO_2, although they also have land footprints and a low amount of CO_2 is associated with the manufacturing of equipment for these energy technologies). Except for geothermal reservoirs, renewable energy resources are located above the ground and their development requires the active involvement of scientists from meteorology, hydrology



Hydrogen	Feedstock	Method	Energy Source	Byproduct
Green	Water	Electrolysis	Renewables	Oxygen
Yellow	Water	Electrolysis	Grid Electricity	Oxygen
Pink/Purple	Water	Electrolysis	Nuclear	Oxygen
Grey	Hydrocarbon Gas/Liquid	Steam Reforming	Water Vapor	Carbon Dioxide
Blue	Hydrocarbon Gas/Liquid	Reforming + Carbon Capture	Water Vapor	CO_2 captured
Turquoise	Hydrocarbon Gas	Molten Metal Methane pyrolysis	Heat	Solid Carbon
Brown or Black	Coal, Coke	Coal Gasification	Water Vapor	Carbon Dioxide
Orange	Coal, Coke	Coal Gasification + Carbon Capture	Water Vapor	CO_2 captured
White	Naturally Occurring or Byproduct of Industrial Processes			

Fig. 4. Various types (colours) of hydrogen based on its feedstock, production method, energy source and byproduct (I have used mostly the colour designation by the North American Council for Freight Efficiency, NACFE).

and geography. Geothermal energy, on the other hand, is closely related to the work of geologists and geophysicists.

Earth's interior is a gigantic engine from which heat flows toward the surface; however, the heat flow in the Earth's crust is not uniform due to varying crustal thickness, rock type and tectonic processes. Consequently, the geothermal gradient varies from 20 to 40°C/km in normal crustal rocks to higher temperatures at volcanic sites. Geothermal energy comes either as dry steam (vapor-dominated) or wet steam (liquid-dominated). Given the right location and technology, geothermal energy may be extracted from a wide spectrum of temperatures (Fig. 5) as briefly described below.

1. Magmatic systems (between 700°C and 1200°C) at several-kilometre crustal depths, for which the exploitation technology has not been developed yet.
2. Hot dry rock with temperatures of 180°C–240°C in tight granitic rocks above active magma chambers. Due to their impermeability, these rocks require fracture stimulation (with pressurized water or supercritical CO_2) to create conduits for fluid circulation; therefore, they are also known as enhanced or engineered geothermal systems (EGS). Fracture stimulation of hot dry rocks is a good example of technology transfer from the oil and gas industry to geothermal fields. A pilot plant of the EGS type is the frontier observatory for research in geothermal energy in central Utah funded by the US Department of Energy.
3. Geopressured systems are formations with high-temperature brines (170°C–180°C) in deep sedimentary basins. These brines can also be mined for their metal content—a good example of 'coproduction'.
4. Hydrothermal systems include both hot water and vapour trapped in porous or fractured rock formations. Those with higher temperatures (>130°C) are used for electric power generation, while lower water temperatures (<85°C) are directly used to heat buildings and greenhouses or provide hot spring resorts.
5. Ground source heat pumps are the cheapest and easiest of geothermal systems as they utilize the ambient ground temperatures of 10°C–20°C (corresponding to depths of 15–120 m) for winter-time warming and summer-time cooling (of space or water) through water circulation in high-density polyethylene tubes placed inside boreholes.

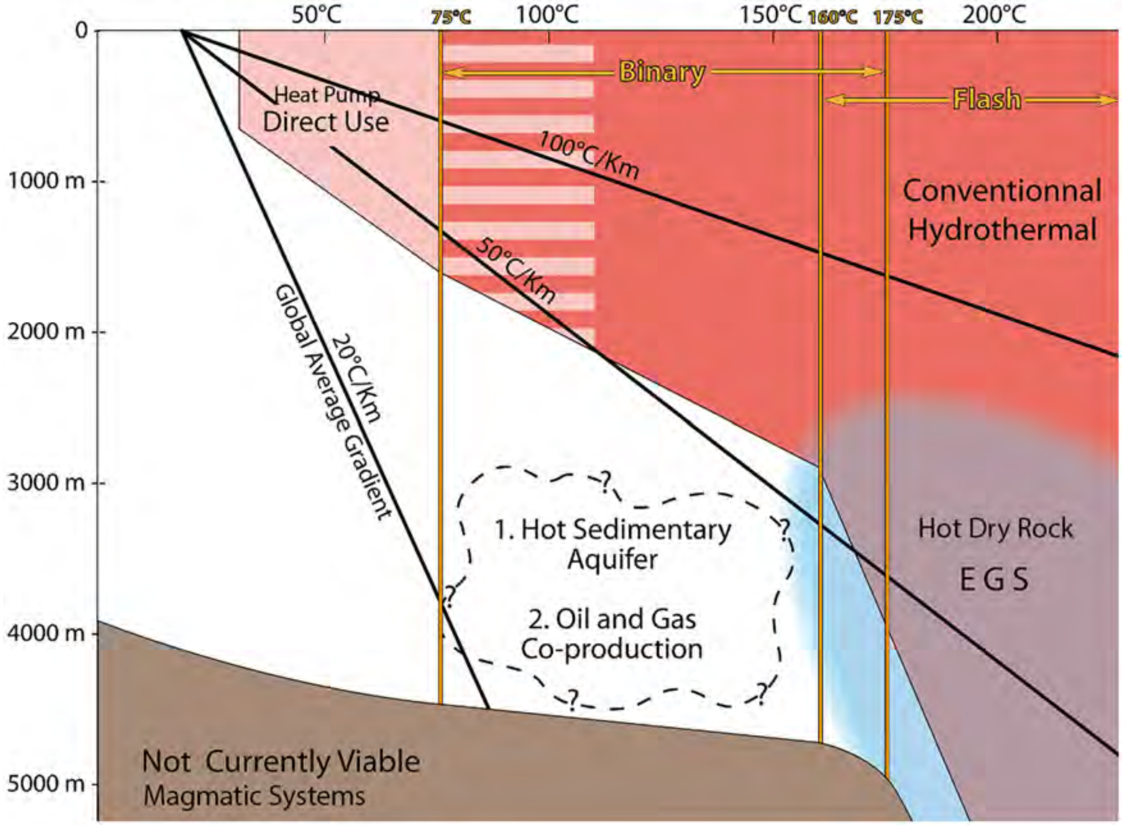


Fig. 5. Temperature and depth ranges for various geothermal power systems. (Source: EGS Inc.)

Geologists working on geothermal fields construct three-dimensional (3D) geologic models incorporating lithology, stratigraphy, structure, crustal depth and geothermal profile. Geothermal systems require heat and permeability; these rock properties should be mapped and quantified for field development.

Recently, attention has been given to abandoned oil and gas wells with high bottom-hole temperatures that can be retrofitted to geothermal power plants either as closed-loop (single well) or open-loop (injection and production well) systems. In the UK, abandoned coal mines, which are located in many towns and are unaffected by seasonal temperature variations, are considered a natural heat source.

Critical minerals

Minerals make up rocks, and geology has historically been associated with mining. Modern geology has identified about 6000 mineral species; however, not all minerals have the same economic value. They are usually divided into ‘rock-forming’ (most abundant) and ‘ore-forming’ (mainly industrial metals) and ‘precious’ (‘gemstone’) minerals. During the world wars, the terms ‘war minerals’ and ‘strategic minerals’ were used for metals and fossil fuels with inadequate resources in industrial countries. What is today categorized as ‘critical minerals’ are mostly elements (Fig. 6) that are present in certain rocks and minerals but not easily or sufficiently accessible. Their ‘criticality’ depends on various factors including high demand, industrial importance, dependency on foreign imports, rarity in occurrence, concentration or extractability (hard to find, extract or process for production) or risk of supply chain disruption. Therefore, the designation of ‘critical’ minerals may change from country to country and from time to time. In recent decades, given similar industrial needs and life standards across the developed nations, the USA, European Union, Australia and Japan and a few other countries have published very similar lists for their critical minerals (Fig. 6). For instance, the 17 rare-earth elements (REEs) are common to all these lists. Moreover, massive electrification of the world in the coming decades—electric vehicles, power plants and electric grids—will require enormous amounts of minerals and metals. These ‘energy minerals’ are used in batteries (lithium, nickel, cobalt, manganese and synthetic graphite), electricity networks (copper and aluminium), permanent magnets (REEs in wind turbines), semiconductors or superconductors, catalytic agents or converters and so forth.

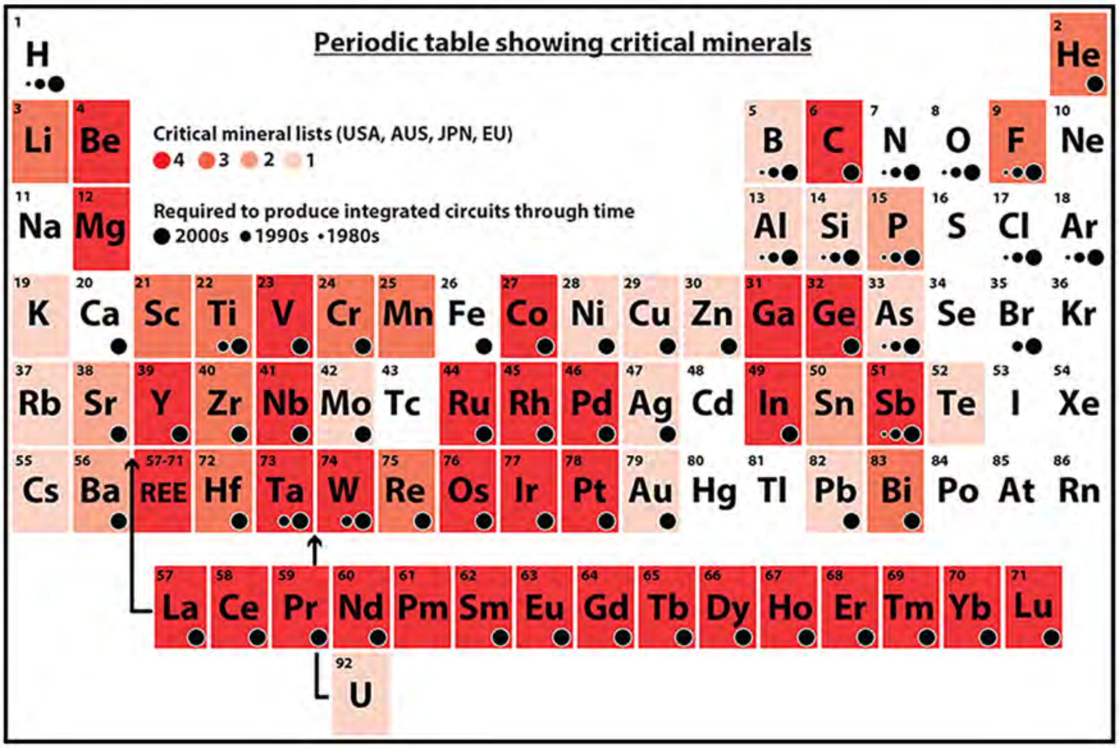


Fig. 6. Lists of 'critical minerals' by USA, European Union, Australia and Japan displayed on the periodic table of elements. (Source: Emsbo *et al.*, 2021.) Numbers 4, 3, 2 and 1 indicate how many times a particular element is listed as critical by the above-mentioned countries.

Interestingly, 50 or so designated critical elements account for almost half of the periodic table of elements. This highlights the importance of minerals for modern society and the crucial need for geoscientists in exploration, mapping, reserve estimation and mining of rare metals and critical minerals. All these areas offer research and funding opportunities for geoscientists.

Critical minerals and elements can be mined from either primary conventional (rocks and ores) or unconventional secondary sources including existing mines and their wastes such as coal fines and fly ashes, mine tailings, waste streams, smelter slag, brines, seawater deposits and end-of-life productions. The secondary sources are currently receiving immense attention because mining these wastes accumulated for decades would also help environmental clean-up. In addition, deep-sea mining of manganese nodules, cobalt-rich crusts on seamounts and sulfides from hydrothermal vents are considered as new frontiers.

Electrification and energy storage

One crucial component for the energy transition will be our capability to efficiently store energy for electricity not only in the short term (a few hours in the case of batteries) but also long duration (10–100 h) and long-term (weekly to seasonally) storage in places where energy production and consumption from renewables (solar, wind and geothermal) are localized and unconnected to a wide electrical grid.

Various types of energy storage systems are based on mechanical, thermal, electrical, chemical or electrochemical principles (Fig. 7). All of these systems are undergoing significant R&D innovation and experimental improvements in terms of size and capacity, efficiency ('round-trip' energy loss effect), discharge duration (how long), response time (how fast), capital expenditure and so forth. Geoscientists can help identify and characterize underground formations or optimize Earth materials for energy storage.

Geoengineering

American Geoscience Institute's *Glossary of Geology* published in 1997 does not have an entry under 'geoengineering'. Nevertheless, geoengineering has entered our discourse with various meanings. What is commonly implied by geoengineering is 'climate engineering'—applications of large-scale technologies to the Earth's atmosphere, oceans or rocks that cause some fundamental changes to combat the recent global warming.

Climate engineering ideas are categorized into two groups: (1) solar radiation control; and (2) carbon dioxide removal. The first group includes various methods to reduce the incoming solar radiation (heat) to Earth. For instance, installing mirrors in outer space reflects or deflects some part of solar light; aerosol injection into the stratosphere by high-altitude balloons and aircrafts would block sunlight; marine cloud brightening or seeding by sea salt would increase the cloud albedo. These

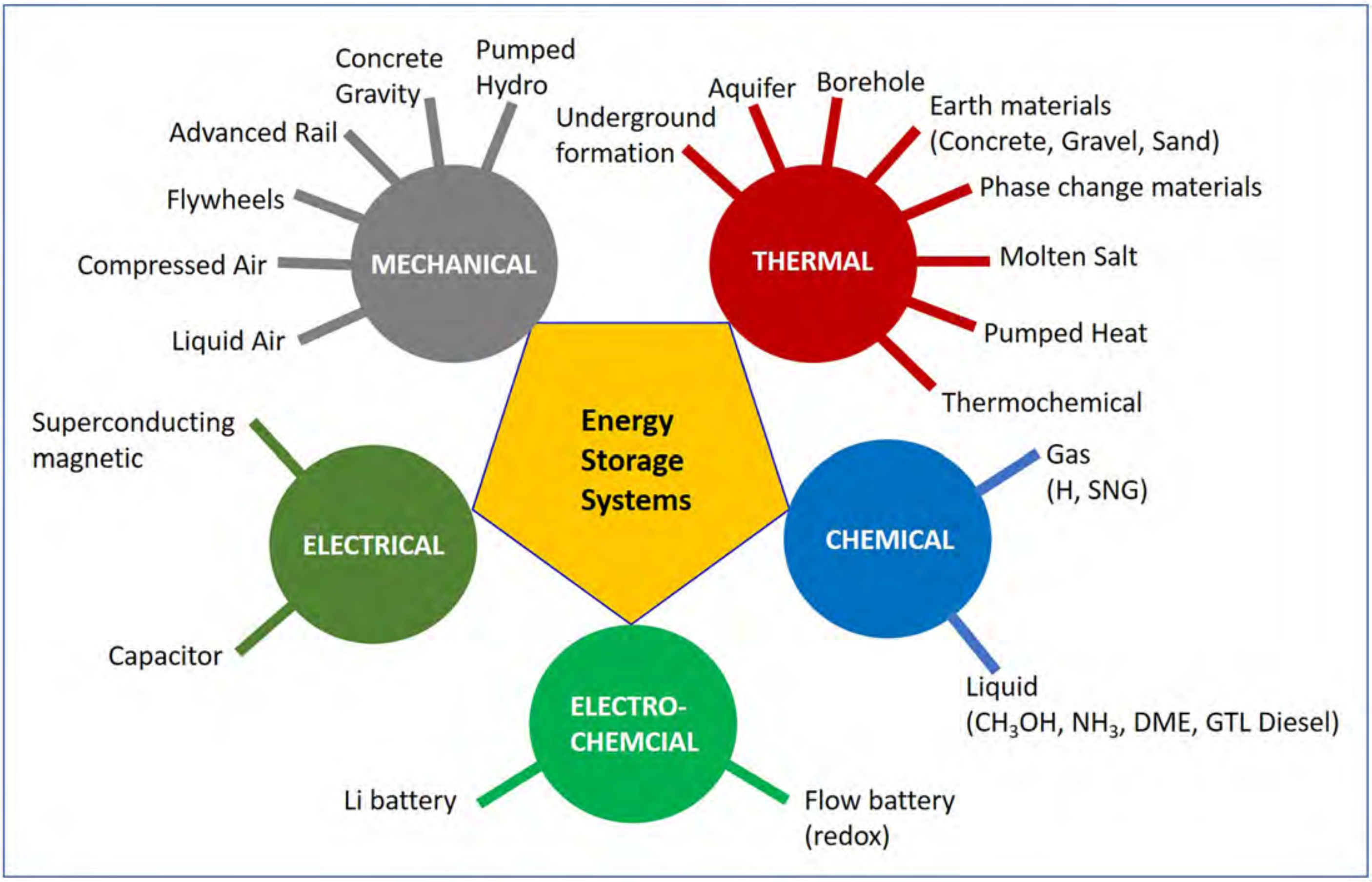


Fig. 7. Various types of energy storage systems are currently investigated based on physical, chemical and electrical methods. (Source: Palash Panja, University of Utah.)

solar radiation control schemes are good for daytime and are temporary solutions as they do not address the buildup of CO_2 in the atmosphere.

Carbon dioxide removal methods aim to absorb the atmospheric CO_2 directly or indirectly and using natural or artificial means. Tree plantation and forest expansion (thus enhancing photosynthesis) are probably the cheapest direct and natural methods to absorb CO_2. Ocean fertilization with iron to stimulate phytoplankton production and farming giant kelp (large brown algae) off the coastal areas work on the same principle. Enhancement of chemical weathering by spreading silicate rock powder onto the land surface may also help remove atmospheric CO_2.

Industrial methods of carbon capture may be applied before (e.g. coal gasification), during (the Oxy-fuel combustion with pure oxygen instead of air) or after the combustion processes. Post-combustion carbon capture includes: (1) direct air capture (DAC), which is less efficient because it requires considerable energy input to remove the dilute atmospheric CO_2 (417 ppm); and (2) point source capture (PSC) from flue gasses at power stations and other industrial plants.

All climate geoengineering concepts and methods need to be evaluated for both cost and environmental impacts. For instance, stratospheric sulphur aerosol injection may cause depletion of ozone in the stratosphere.

Subsurface carbon sequestration

After CO_2 is captured as a concentrated compressed stream, it needs to be transported and stored safely in underground rock formations, or utilized, for example, in producing chemicals such as methanol or injecting into oil fields for enhanced oil recovery (EOR) (Fig. 8). There are four mechanisms for geological trapping of CO_2: (1) Structural trapping in a porous reservoir capped by an impermeable seal rock; (2) capillary trapping in the pore space of reservoir rocks; (3) solubility trapping by the dissolution of CO_2 into formation waters and (4) mineral trapping by reacting dissolved CO_2 with fine-grained metal oxides (notably ultramafic mine tailings) to produce carbonates.

Carbon capture, utilization and sequestration (CCUS) technologies are in their infancy and have thus huge potential for development. According to the International Energy Agency, there are currently 35 commercial carbon capture facilities in operation globally, with a total annual carbon capture of about 45 million tons of CO_2, which is insignificant compared

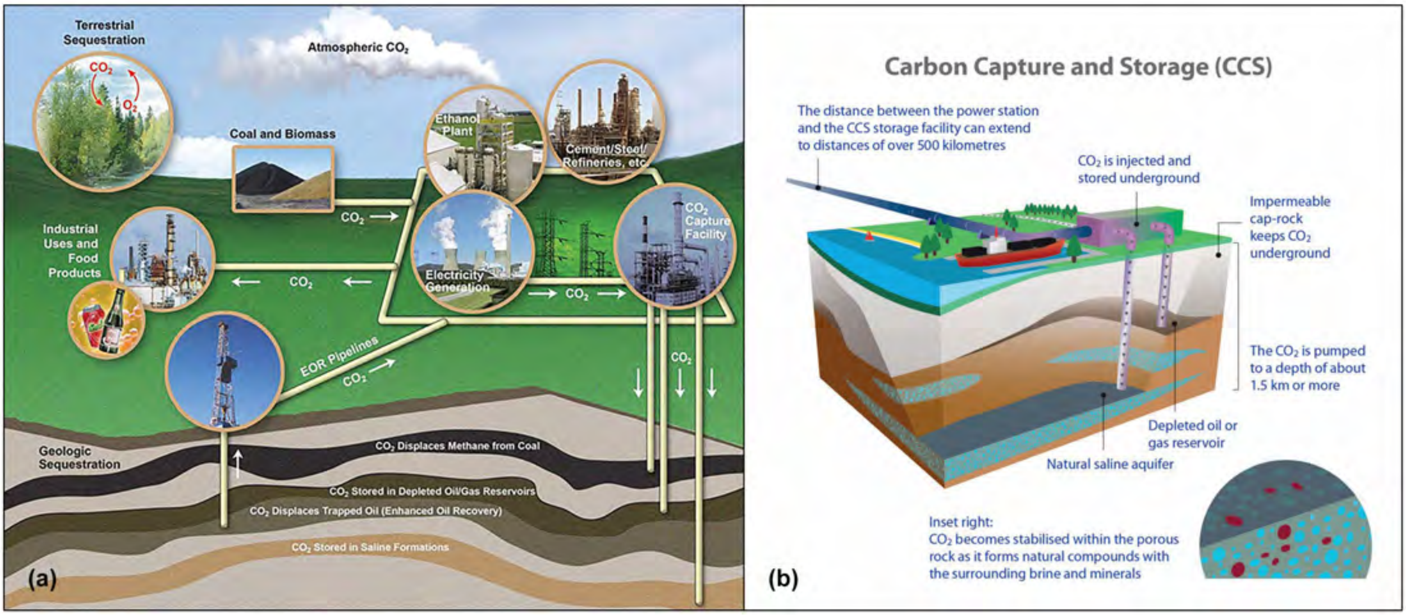


Fig. 8. Subsurface carbon sequestration: **a.** (According to the US Department of Energy) in which CO_2 can be utilized for enhanced oil recovery in oil fields or enhanced gas production in coal-bed methane fields; **b.** (According to the European Union) in which CO_2 is stored in depleted oil and gas reservoirs or deep saline aquifers.

to the annual CO_2 emission of 38 billion metric tons. However, about 300 CCUS projects are in various stages of development, and project developers aim to capture 220 million tons of CO_2 per year by 2030.

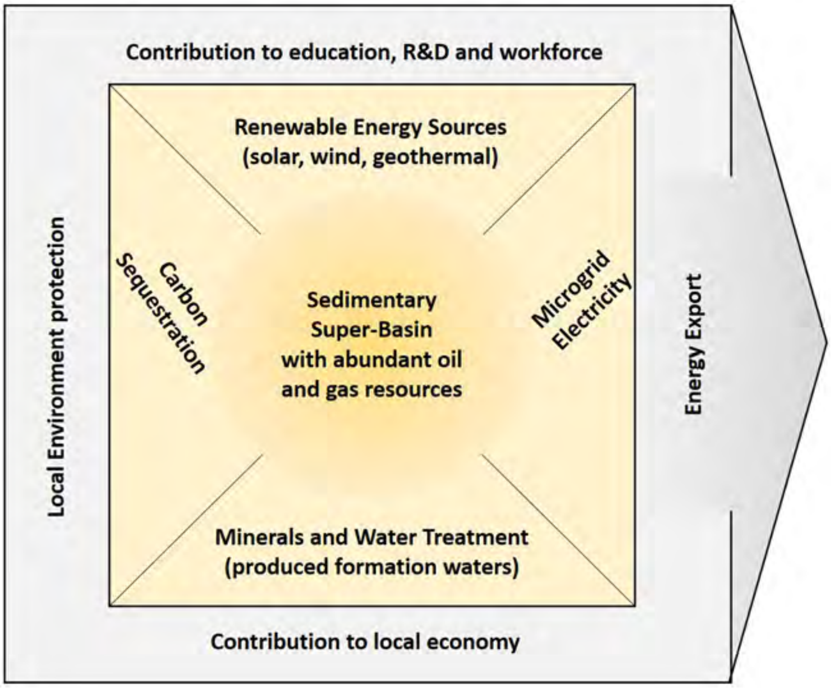
Some aspects of the CCSU projects crucially require geoscientist skills. These include identifying and mapping the extent and size of underground storage sites, characterizing the petrophysical properties of potential reservoir rocks, seal and trap integrity, forecasting fluid–rock interactions and geophysical monitoring of the CO_2 storages. Underground carbon storage sites must be properly tested and selected; poor choices that result in CO_2 leakage will undermine public confidence in this promising solution.

The petroleum industry has long injected CO_2 into subsurface reservoirs for EOR; the Permian Basin in Texas is the best example. The petroleum geoscientists' skillsets would thus be highly desirable in managing the storage sites not only in active oil and gas fields for EOR, but also in abandoned fields where residual hydrocarbons would mitigate the carbonic acid formed from the reaction of CO_2 with water.

Energy hubs and geoscientists

The pace and nature of energy transition in the coming decades will depend on a worldwide technological revolution. This revolution, however, is occurring by gradual evolution in all energy resources and technologies as they are advancing and adapting to meet the needs of peoples, policies and economies. No single energy resource appears to offer a practical, affordable solution on a global scale. All energy resources and technologies have their pros and cons and are thus undergoing evolution and improvement. The world's energy future will likely consist of mixed energy markets operated regionally. Energy resources are diverse and distributed unevenly. Some areas will emerge as 'energy hubs' as they integrate and optimize their

Fig. 9. A schematic diagram showing how present petroleum basins can be transformed into 'energy superbasins' with 'coproduction' of various energy resources and energy minerals, and net-zero carbon operations.



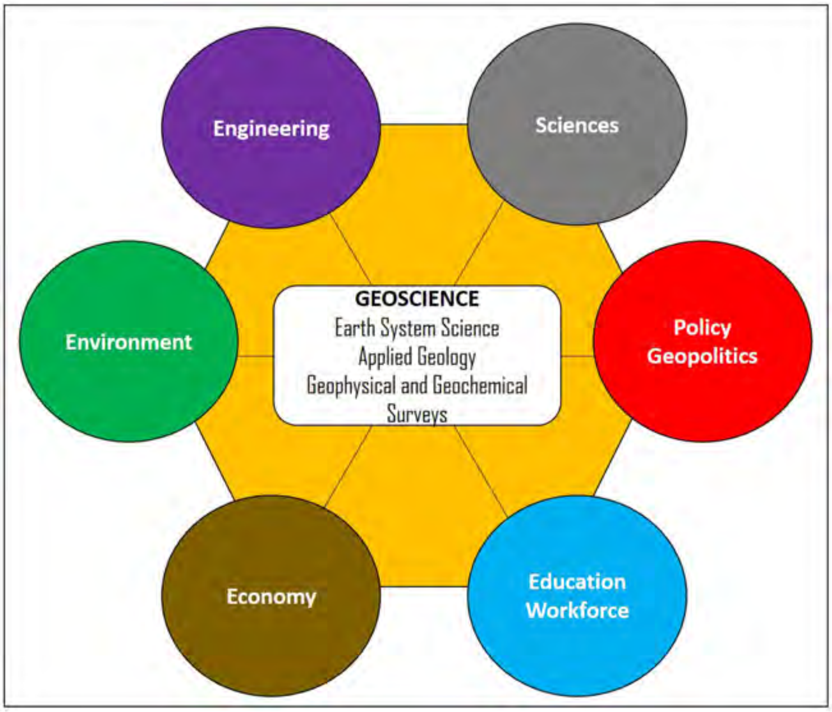


Fig. 10. Interfaces and integration of geoscience with other disciplines for energy transition.

natural, human and financial resources and advance technological and management strengths.

One facet of the energy hubs will probably occur in what Wood Mackenzie has called 'energy super basins' (Fig. 9), where oil and gas companies operating in giant fields will transform into energy companies by tapping into various resources (oil and gas, renewable energies, critical metals produced from formation waters and treated subsurface waters for irrigation); these companies will also design net-zero carbon electric microgrids for their operations, and will better contribute to sustainability, education, forestation, CCUS and environmental protection.

Just as geologists were trained and employed in large numbers to explore coal and petroleum resources in various parts of the world over the past century, the energy transition will require geoscientists in large numbers; however, they will have to advance novel ideas (out-of-box and out-of-comfort-zone thinking), relevant curriculums and adaptable skillsets. The new geoscience will also need to open lines of communication and collaboration with several other disciplines related to the energy transition (Fig. 10).

Acknowledgements

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