Affordable and Clean Energy

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Energy Geoscience and Human Capacity

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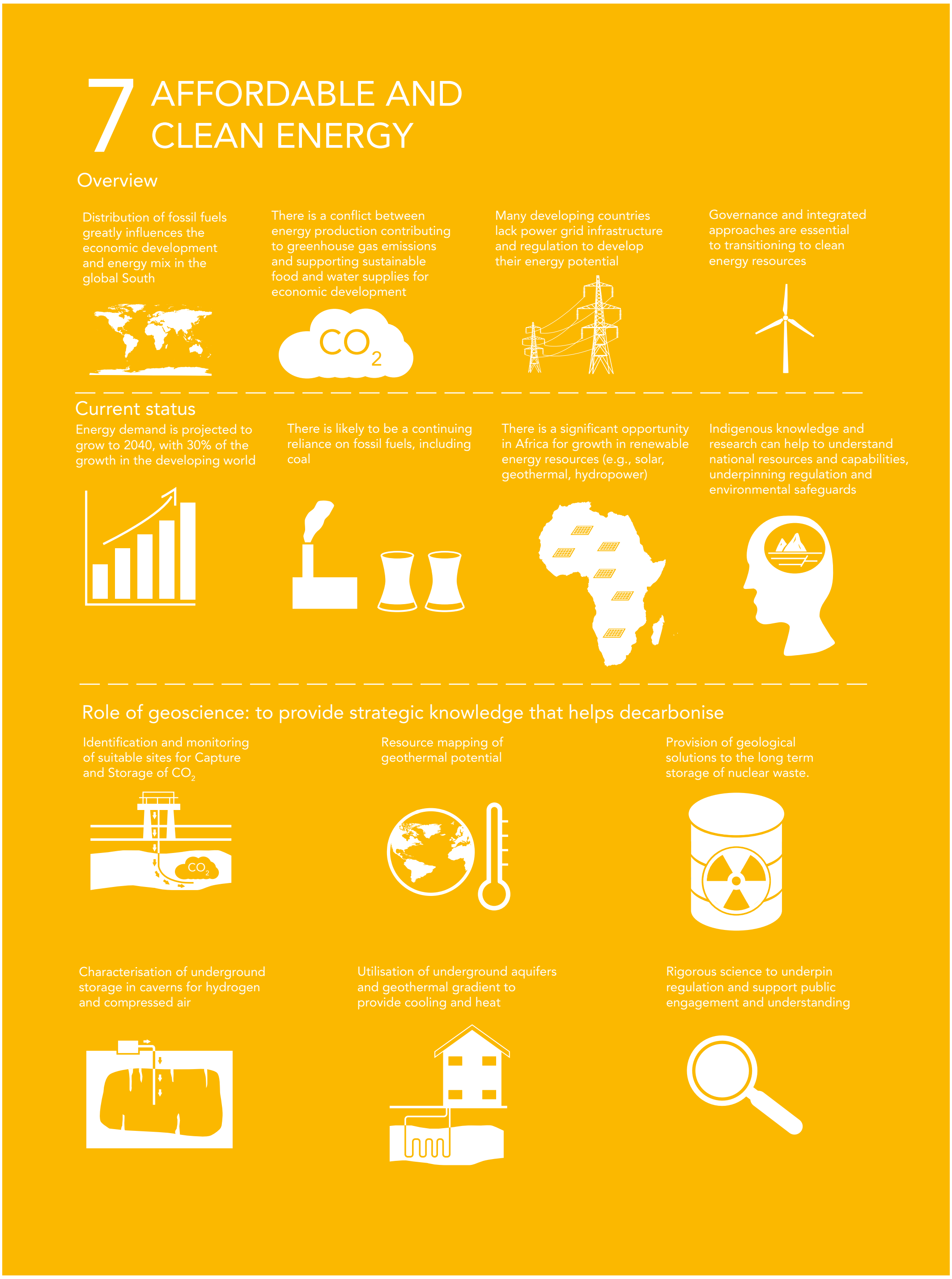
Abstract



7 AFFORDABLE AND CLEAN ENERGY

Overview

Distribution of fossil fuels greatly influences the economic development and energy mix in the global South

There is a conflict between energy production contributing to greenhouse gas emissions and supporting sustainable food and water supplies for economic development

Many developing countries lack power grid infrastructure and regulation to develop their energy potential

Governance and integrated approaches are essential to transitioning to clean energy resources

Current status

Energy demand is projected to grow to 2040, with 30% of the growth in the developing world

There is likely to be a continuing reliance on fossil fuels, including coal

There is a significant opportunity in Africa for growth in renewable energy resources (e.g., solar, geothermal, hydropower)

Indigenous knowledge and research can help to understand national resources and capabilities, underpinning regulation and environmental safeguards

Role of geoscience: to provide strategic knowledge that helps decarbonise

Identification and monitoring of suitable sites for Capture and Storage of CO$_2$

Resource mapping of geothermal potential

Provision of geological solutions to the long term storage of nuclear waste.

Characterisation of underground storage in caverns for hydrogen and compressed air

Utilisation of underground aquifers and geothermal gradient to provide cooling and heat

Rigorous science to underpin regulation and support public engagement and understanding

7.1 Introduction

Before the industrial revolution, global energy demand was limited and supplied essentially by traditional renewable sources. The evolution of simple steam engines accelerated in the seventeenth and eighteenth centuries and improvements by Thomas Newcomen and James Watt in the mid-1700s produced the modern steam engine powered by coal, providing energy for locomotives, factories, and farm implements. Coal was also used for heating buildings and smelting iron into steel. In 1880, coal powered a steam engine attached to the world's first electric generator leading to the development of thermal power stations which still provide most of the world's electricity and in the late 1800s, petroleum began to be processed into gasoline (petrol) for firing internal combustion engines.

With the advent of cheap cars in the early 1900s, and the spread of electricity, energy demand increased and by the 1950s, nuclear power joined coal and petroleum to help satisfy that demand. However, geopolitical concerns over petroleum affected the pattern of energy supply in the latter part of the 1900s, as well as concerns over the safety of nuclear electricity generation (Fig. 7.1). In addition, increased evidence of anthropogenic climate change (IPCC Fifth Assessment Report 2014), recognised that the largest human influence has been the emission of greenhouse gases such as carbon dioxide, mostly related to the burning of energy fuels in transport and electricity production. For a detailed discussion of climate change, see **SDG 13**.

Despite the huge rise in demand and supply of energy for electricity and transport, its global distribution remains very uneven. In 2016, sub-

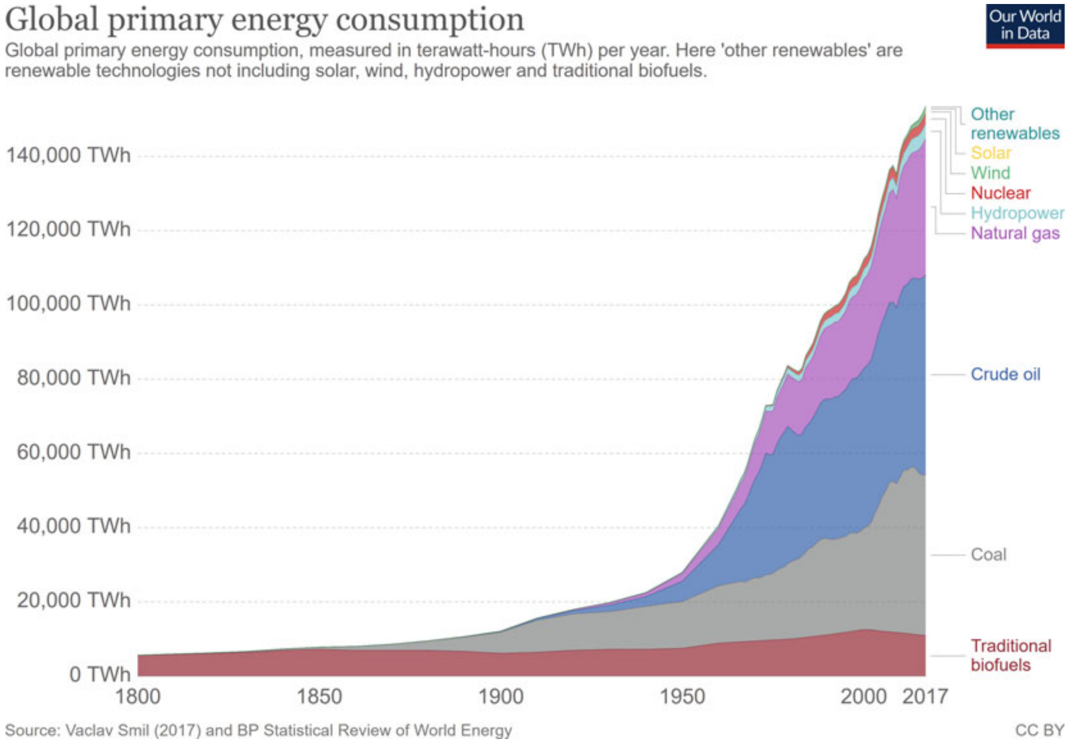


Fig. 7.1 Global Primary energy Consumption (measured in terawatt-hours, TWh). *Credit* Ritchie and Roser (2019a). Reproduced under a CC BY License (https://creativecommons.org/licenses/by/4.0/)

Saharan Africa and South Asia had approximately 600 million and 200 million people, respectively, with no access to electricity (Ritchie and Roser 2019a), while in the Global North this figure was negligible. Approximately 800 million Indians and 600 million sub-Saharan Africans, use traditional biomass as their primary cooking fuel (Kaygusuz 2012). Thus, a central industrial and social challenge of the twenty-first Century is to satisfy growing energy demand while reducing emissions related to energy production, but also to ensure that energy is available to all (Fig. 7.2).

The Sustainable Development Goals (SDGs) are a collection of 17 global goals set by the United Nations General Assembly in 2015, for the year 2030. **SDG 7: 'Ensure access to affordable, reliable, sustainable, and modern energy'** aims at improving energy access, increasing renewables in the energy mix, energy efficiency and integration, and international cooperation, and has targets to 2030, and indicators of progress. Many of the targets are closely associated with geoscience, for example, in exploration and feasibility studies for subsurface renewables such as geothermal, as well as sustainable use of fossil fuels within strict carbon budgets (Table 7.1).

Energy in its broadest sense enables business, industry, agriculture, transport, communications, and modern services such as health care; but it also enables improvements in living standards. **SDG 7** is, therefore,intimately connected with most of the other 17 SDGs (Fig. 7.3), mainly through providing improved living standards, economic growth and activity, and improved environmental protection. The services that energy provides improve human, social, economic, and environmental conditions; and final energy use and the Human Development Index (HDI) are correlated (Steckel et al. 2013), the correlation implying early rapid gains in HDI

Fig. 7.2 Wind turbines in rural India. India is one of the largest producers of renewable energy, currently accounting for approximately 35% of energy production *Credit* Vestas (CC BY 2.0, https://creativecommons.org/licenses/by/2.0/)

Table 7.1 SDG 7 Targets by 2030

Target	Description of Target *(7.1 to 7.3)* or Means of Implementation *(7.A to 7.B)*
7.1	By 2030, ensure universal access to affordable, reliable, and modern energy services
7.2	By 2030, increase substantially the share of renewable energy in the global energy mix
7.3	By 2030, double the global rate of improvement in energy efficiency
7.A	By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency, and advanced and cleaner fossil fuel technology, and promote investment in energy infrastructure and clean energy technology planning
7.B	By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular, least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programmes of support

Fig. 7.3 Relationship of SDG 7 to other SDGs

with relatively small gains in energy usage, with HDI levelling off at levels of energy usage around 75 GJ/yr per capita.

On the negative side, energy (for example, fossil fuel power and hydropower), can be produced and deployed in ways that pollute the environment, affect land use, and increase greenhouse gas emissions. Similarly, energy is an element of the food-energy-water nexus and thus its sustainability is tensioned against water (**SDG 6**) and food (**SDG 2**). Finally, the financial value that energy can release, can also be syphoned into the ruling elites of kleptocracies and autocracies, rather than be cascaded down to benefit society at large. Thus, the benefits of energy for sustainable development are strongly dependent on ethical governance and strong institutions (**SDG 16**).

In general, the effectiveness of energy systems to supply sustainable development depends on a number of factors (illustrated in Fig. 7.4). These include

- Availability, affordability, security, reliability, and safety of energy supplies
- Environmental sustainability of the energy supply
- Planning, design, construction, operation, financing and pricing of energy-using buildings, industrial processes, and transport systems in end-use sectors
- Social and cultural norms of the use of energy
- Access to alternative technologies and energy sources
- Investment assistance to develop and deploy energy service
- Government policies that ensure energy systems develop in a way that best supports and accords with sustainable development.

Geoscience has a direct role in several of these areas including in establishing the geographical distribution, geological habitat, geotechnical feasibility of construction and infrastructure, and environmental sustainability, of energy supply (Table 7.2). Though it discusses affordable and clean energy, which is a requirement across the world to a greater and lesser extent, this chapter

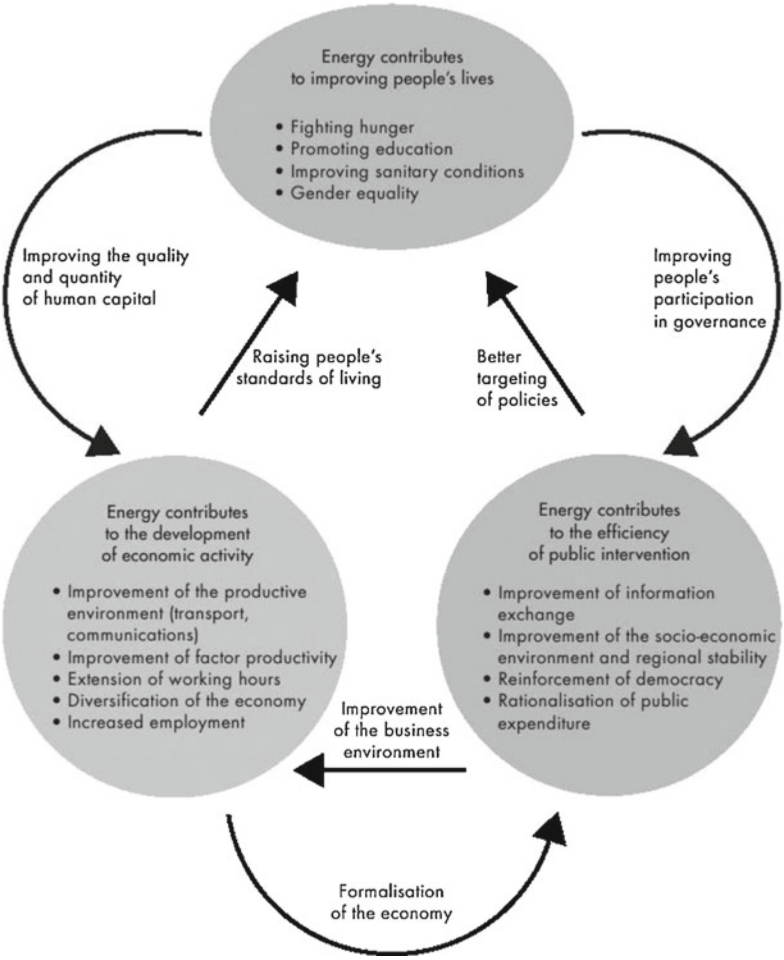


Fig. 7.4 Energy for sustainable development. Reprinted from Renewable and Sustainable Energy Reviews, 16 (2), Kaygusuz, K., Energy for sustainable development: A case of developing countries, 1116–1126, Copyright (2012), with permission from Elsevier

Table 7.2 SDG 7 Indicators and geoscience relevance

Indicators	Geoscience link
7.1.1 Proportion of population with access to electricity	Geoscience for exploration and sustainability of renewable and appropriately used fossil energy sources
7.1.2 Proportion of population with primary reliance on clean fuels and technology	
7.2.1 Renewable energy share in the total final energy consumption	Geoscience to support the expansion of renewables, e.g., geothermal, wind turbine ground conditions
7.3.1 Energy intensity measured in terms of primary energy and GDP	Holistic planning involving the subsurface
7.A.1 Mobilised amount of United States dollars per year starting in 2020, accountable towards the $100 billion commitment	Improved links between geoscientists/geoscience institutions and other energy specialists
7.B.1 Investments in energy efficiency as a percentage of GDP and the amount of foreign direct investment in financial transfer for infrastructure and technology to sustainable development services	Improved links between geoscientists/geoscience institutions and energy system specialists including energy distribution specialists and finance sector

concentrates on affordable and clean energy in the Global South (so-called, developing countries), which has the most to develop in energy and the most to gain economically. It also has the most difficult challenges. In this chapter, Sect. 7.2 will examine the distribution of present-day energy resources and forecasts for future supply and demand, and Sect. 7.3 the geoscience implications of the main options for affordable and clean energy, including research and development needed, as well as training needs.

7.2 Energy Resource Distribution and Use

7.2.1 Fossil Fuels in the Global South

The distribution of fossil fuels has a bearing on the way that nations develop and the energy mix that they develop, as well as on the human capacity needed to develop and maintain sustainable supplies. Amongst oil (Fig. 7.5), proven reserves are concentrated in well-explored parts of the Middle East, North America, Africa, Northern Asia and South America. The occurrence of significant resources of unconventional oil (from low permeability reservoirs) is notable in North America, Eastern Europe and Eurasia, and South America. Gas has a similar pattern (Fig. 7.6). North America, Eastern Europe and Eurasia, South Asia, and Asia-Pacific all have large coal reserves (Fig. 7.7). Of relevance to this chapter is that several of the largest developing countries: India, Indonesia, and South Africa, have very large coal resources.

The International Energy Agency (IEA), forecasts using three ‘scenarios’ which contain predictions of energy infrastructure investment and energy demand and supply, based primarily on the need to reduce CO_2 emissions and on common assumptions of economic conditions and population growth. The most relevant is the New Policies Scenario which takes account of broad policy commitments and plans that have been announced by countries and their governments, including national pledges to reduce greenhouse gas emissions and plans to phase out fossil energy subsidies, even if the measures to implement these commitments have yet to be identified or announced. This might be regarded as the most realistic and widely quoted of the IEA’s scenarios.

The IEA’s 2016 World Energy Outlook New Policies Scenario (IEA 2016), predicts an increase in energy demand between now and 2040. 30% of this increase will be from the Global South, particularly in Asia and Africa.

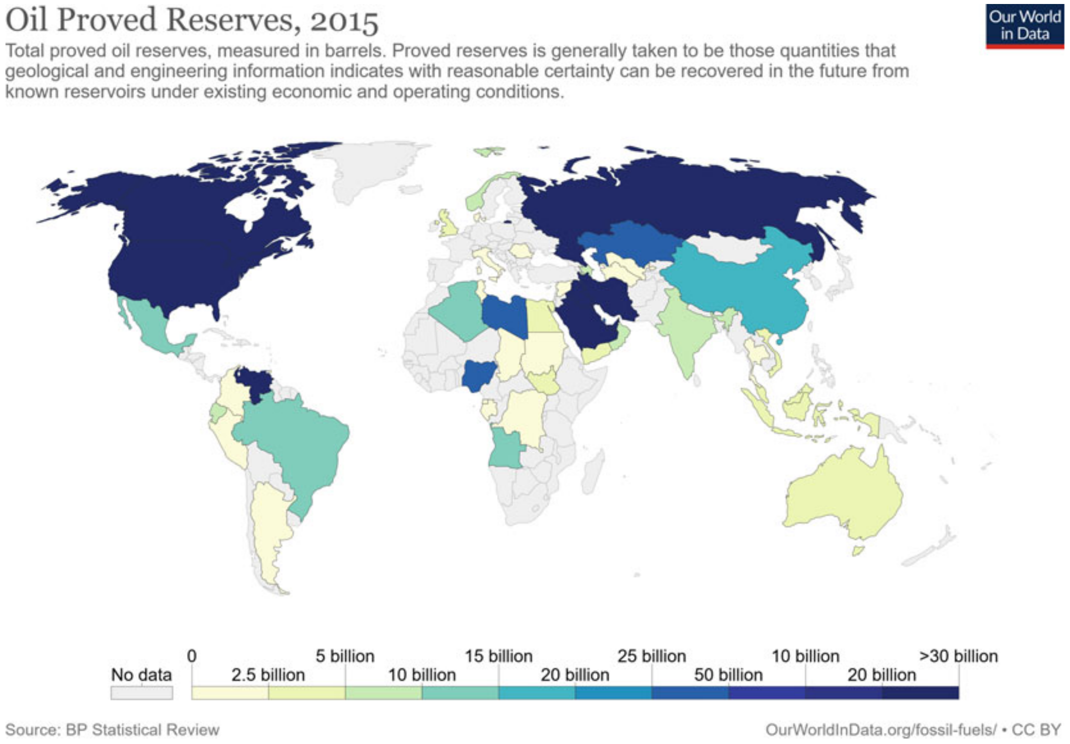


Fig. 7.5 Oil Proven Reserves (as of 2015), measured in barrels *Credit* Ritchie and Roser (2019b), using data from BP Statistical Review of World Energy 2016. Reproduced under a CC BY License (https://creativecommons.org/licenses/by/4.0/)

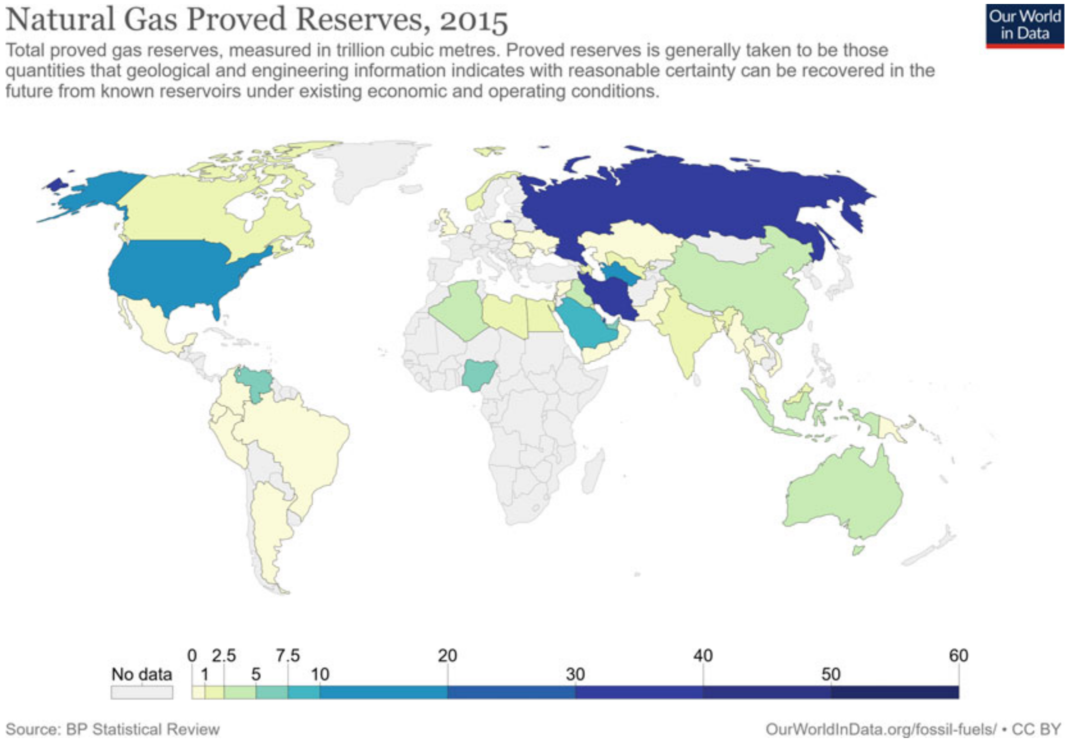


Fig. 7.6 Natural Gas Proven Reserves (as of 2015), measured in trillion cubic metres. *Credit* Ritchie and Roser (2019b), using data from BP Statistical Review of World Energy 2016. Reproduced under a CC BY License (https://creativecommons.org/licenses/by/4.0/)

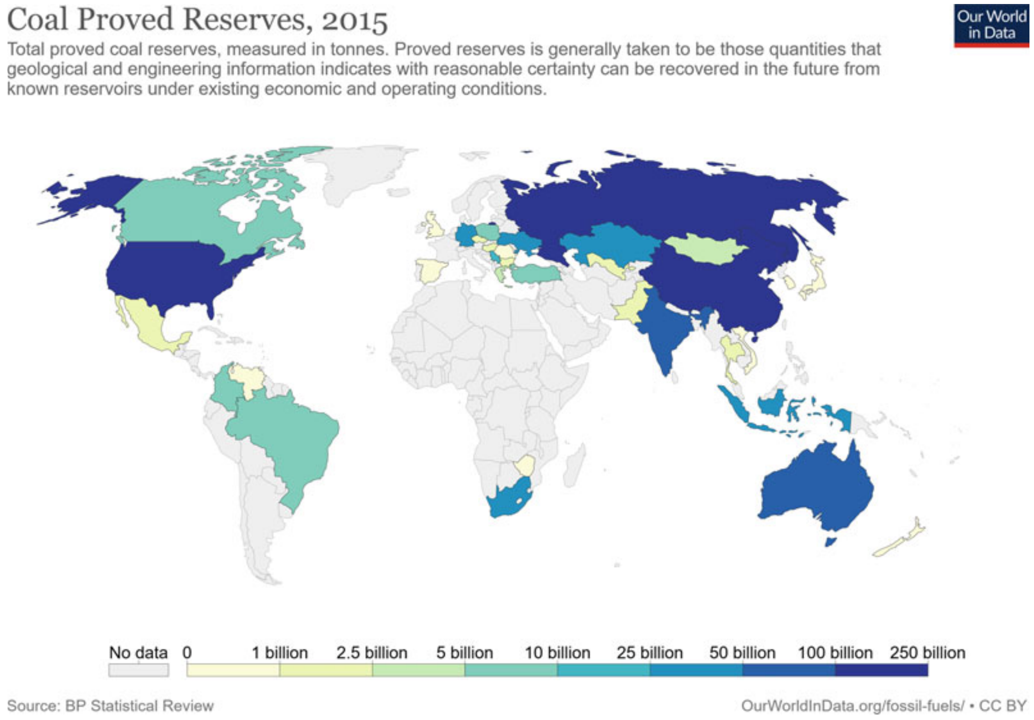


Fig. 7.7 Coal Proven Reserves (as of 2015), measured in tonnes. *Credit* Ritchie and Roser (2019b), using data from BP Statistical Review of World Energy 2016. Reproduced under a CC BY License (https://creativecommons.org/licenses/by/4.0/)

According to the IEA, breaking this down into types of energy including the three major fossil fuels shows little change between now and 2040. Important factors to note include the marked increase in renewables, but also that all three of the main fossil fuels do not decline but in fact increase. Focussing on coal alone in the IEA's New Policies Scenario suggests a shift from the developed to the developing world.

The drive for development, poverty alleviation (**SDG 1**), and improved health (**SDG 3**) are all connected with greater energy requirements. Countries in the Global South that contain significant fossil fuel resources will be able, through conventional forms of commercialisation, to realise those resources for electrical power and other energy requirements (e.g., transport, heat or air conditioning). Coal has particular appeal to countries with large reserves and problems of rural development, poverty alleviation, and health.

Box 7.1. Coal in India and South Africa

India has very large coal resources and problems of rural development, poverty alleviation, and health. Much domestic energy in India, comes from biomass (firewood, crop residue, dung) and India consumes 200 Mtoe (million tonnes of oil equivalent) of biomass each year. One hundred million Indian households still use firewood to cook food, mainly in rural areas (Kaygusuz 2012). Cooking with firewood takes its toll on the health of Indians with an estimated 50,000 deaths per year (household fires, accidents, and ill health). India's rural electrification programme aims to introduce healthier fuel in households, to improve agricultural production (for example, through better irrigation pumps), and to develop business and trade in agriculture. Significant inroads into rural electrification have been made with small scale solar, particularly to provide domestic lighting in rural areas (e.g., Kamalapur and Udaykumar 2011).

However, the forecasts of the IEA (2016), suggest that at least some of India's future electricity supply will come from coal (Fig. 7.8). At present coal provides about 70% of India's electricity but about 243 GW of coal-fired power is planned in India, with 65 GW actually being constructed and an extra 178 GW proposed. Shearer et al. (2017) surveyed this proposed 'fleet' of coal power stations to forecast the amounts of power that could be provided should these power stations be completed. Their survey shows average annual capacity additions beginning in 1960, as well as future additions based on proposed new plants. For the future, Shearer's survey shows that coal plants under development could be producing 435 GW of coal power by 2025, and assuming an average lifetime of 40 years, the coal plants could be operating as far ahead as 2065. South Africa, like India, has a large number of rural people without access to electricity (roughly 60% of South African households), but also a strong demand for electricity, particularly for the mining industry. South Africa's coal reserves are large—28 billion tonnes—which would allow 100 more years of mining at current rates. According to the IEA New Policies Scenario (IEA 2016), South African coal production will be driven mainly by domestic demand for coal for power supply. At present, more than 90% of electricity is generated by coal in South Africa, and this will remain the case well into the next decades. Coal production is predicted to rise to a peak of around 230 Mtce by 2020, and then fall to 210 Mtce by 2035 (IEA 2011).

Fig. 7.8 Coal mining in India. India's coal plants could be operating as far ahead as 2065. *Credit* Nitin Kirloskar (CC BY 2.0, https://creativecommons.org/licenses/by/2.0/)

Gas and oil resources in the developing world are less certain than those of coal because there have been fewer systematic surveys in these areas. Having said this, there are well-established producing areas in Africa and southeast Asia, for example, Nigeria, Angola, Gabon, and Sarawak. The IEA New Policies Scenario (IEA 2016), forecasts gas and oil demand to grow to 2040 in Africa and India, and a new gas province to emerge offshore Mozambique and Tanzania. Egypt's gas production is expected to grow. The potential for shale gas in Africa and Asia is not known in detail but South Africa, India, Indonesia, and Pakistan are believed to have significant resources (EIA 2013). The continued extraction and use of gas and oil, like coal, depends on the adherence to climate policies and more locally to increasing standards of environmental assurance.

7.2.2 Renewable Energy Resources in the Developing World

Solar energy uses concentrated solar power (CSP) systems and photovoltaic (PV) systems. Global horizontal irradiation data (Shahsavari and Akbari 2018), indicate that much of the developing world is suited to solar power (Fig. 7.9). Global wind potential modelled with wind climate data with high-resolution terrain information shows high potential in coastal areas and high latitude areas with rather lower potential in the tropics and subtropics. Wind and solar development require site-specific information to aid investment decisions though suffer the same need for site-specific information to aid investment decisions (Gies 2016).

Miketa and Saadi (2015) and the Africa Progress Panel (2015), note the challenges to realise solar and wind as bankable technologies. The locations of wind and solar resources in Africa are not known in enough detail at present to stimulate private investment by companies hoping to select sites for projects. Another problem is that Africa and the developing world lack big electricity grids and transmission lines to move large amounts of power within countries and across regions (Gies 2016).

Hydropower plants are highly site-specific, but can be broadly categorised into three. Storage hydropower uses a dam to impound river water, which is then stored for release when needed. Storage hydropower can be operated to provide base-load power, as well as peak-load through its

Fig. 7.9 Solar Power Plant Telangana II in the state of Telangana, India. *Credit* Thomas Lloyd Group (CC BY SA 2.0, https://creativecommons.org/licenses/by-sa/2.0/)

ability to be shut down and started up at short notice according to the demands of the system. It can offer enough storage capacity to operate independently of the hydrological inflow for many weeks, or even up to months or years.

Run-of-river hydropower channels flow water from a river through a canal or penstock to drive a turbine. Typically, a run-of-river project will have short term water storage and result in little or no land inundation relative to its natural state. Run-of-river hydro plants provide a continuous supply of electricity and are generally installed to provide base load power to the electrical grid. Pumped-storage hydropower provides peak load supply, harnessing water which is cycled between a lower and upper reservoir by pumps, which use surplus energy from the system at times of low demand. When electricity demand is high, water is released back to the lower reservoir through turbines to produce electricity, and thus a zero-sum electricity producer.

Africa has abundant hydropower resources. It is estimated that around 92% of technically feasible potential has not yet been developed. Central Africa has about 40% of the continent's hydro resources. At the end of 2014, there was 28 GW of hydro capacity installed in Africa (IRENA 2015). Of the resources available, the Congo River has the largest discharge of African rivers, followed by the Zambezi, the Niger, and the Nile.

India's economically exploitable and viable hydroelectric potential is estimated to be 148,701 MW (Govt. of India 2018), but south Asia hydropower is cross-border in nature due to the size of catchments and so its development involves geopolitical factors (Box 7.2).

Box 7.2. Indus hydropower cross-border issues.

The large discharges that are needed for hydropower are sustained best by very large catchments which often span several countries so that the building of hydropower dams have effects on downstream countries. The Indus River is an example, being one of the longest rivers in Asia. It originates in the Tibetan Plateau and flows through Ladakh, India, towards the Gilgit-Baltistan region of Pakistan and the Hindukush ranges, and south through Pakistan to the Arabian Sea near Karachi. The river's catchment is more than 1,165,000 km^2 and its annual flow of 243 km^3 is one of the largest in the world. The river and its catchment spans four countries and supports 215 m people. India and Pakistan, the two main countries in the basin, divided up rights to the various tributaries under the Indus Water Treaty (IWT) of 1960.

India has approved major dams on the Chenab, and Jhelum rivers, and the Indus itself. However, the Nimoo Bazgo hydro plant, situated at Alchi village (Fig. 7.10), is under dispute. Pakistan says that the 57-metre high 45 MW Nimoo Bazgo dam will substantially reduce downstream water flows in the Indus River, because the project is designed to store 120 million cubic metres of water. This Pakistan says will allow India to regulate the water of Indus, a situation which is "not acceptable to Pakistan." Because the IWT treaty does not provide a definitive solution, the two countries have been in dispute. Downstream in the Punjab, India and Pakistan share the alluvial Indo-Gangetic aquifer (recharged partly by the Indus River) which helps support the huge population of the Indus region, accounting for 48% of all water withdrawals in the basin.

Geothermal is an important renewable source of energy with a strong geoscience aspect. It can be divided into two types: heat that is sufficient to generate electricity, and heat that is sufficient only for supplementing heating systems in buildings or for industrial processes. By 2017, about 13.4 GW of geothermal electricity was being produced from power stations globally; but a much larger amount of power, about 28 GW, is provided for direct heating of houses and public buildings, spas, industrial processes, desalination, and glass

Fig. 7.10 Nimoo Bazgo Power Project, situated at Alchi village, on the Indus River in Ladakh. *Credit* Mehrajmir13 (CC BY SA 4.0, https://creativecommons.org/licenses/by-sa/2.0/)

houses (Dickson and Fanelli 2003). Conventional electric power production is commonly limited to fluid temperatures above 180 °C, but with binary fluid technology, lower temperatures can also be used to generate electricity down to about 70 °C. For direct district heating, useful temperatures range from 80 °C to just a few degrees above the ambient temperature. At least 90 countries have potential geothermal resources though only about 70 tap this potential. Electricity is produced from geothermal energy in only 24 countries (Dickson and Fanelli 2003).

In the developing world, geothermal potential is considered high in East Africa, the Philippines, and Indonesia. In the East African rift valley, geothermal potential is considered greater than 20,000 MW of electricity, though currently, only Kenya has operational geothermal power stations (Omenda 2018). Slow progress in East Africa relates to high start-up costs (including costs of drilling), inability to secure finance and lack of trained human capacity (Omenda 2018).

Tidal range resource potential varies considerably across the globe and is amplified by basin resonances and coastline bathymetry. Tidal energy has a relatively high cost but limited availability of sites with sufficiently high tidal ranges or flow velocities, but technological developments and improvements, both in design (e.g., dynamic tidal power, tidal lagoons) and turbine technology (e.g., new axial turbines, cross-flow turbines), extend the suitable locations and bring down costs. Historically, 'tide mills' have been used in Europe and on the Atlantic coast of North America. Tidal is not well developed in developing countries, though India is reported to have tidal energy potential of around 8,000 MW (Energy World 2018). **SDG 14** discusses Ocean Thermal Energy Conversion Technologies.

7.2.3 Urbanisation and Climate Change

Cities presently cover only approximately 3% of the land surface but they account for >70% of energy consumption and 75% of carbon emissions and are, therefore, major contributors to climate change (see **SDG 11**). Most future urbanisation will take place in the developing world, having strong effects on supply and generation of energy.

A recent study in China (Zhao and Zhang 2018), showed that for every 1% increase in the urban population relative to the total population, national energy consumption rose 1.4% and also that urbanisation increased energy consumption through urban spatial expansion, urban motorisation, and increase in energy-intensive lifestyles. Urban households consume 50% more energy than rural households per capita, which indicates that continued urbanisation in China, will increase national energy consumption. This is likely across the developing world. Urban policies are required, therefore, to encourage compact urban growth, green buildings, and low energy vehicles.

Smart grids will likely also improve energy response to urbanisation. These are electricity transmission networks that use digital technology to allow two-way communication between supplier and customers allowing the grid to respond digitally to quickly-changing electricity demand. This will also allow more efficient transmission of electricity, quicker restoration of electricity after power disturbances, lower power costs for consumers, less energy wastage, and better integration of large-scale renewable energy systems.

Climate change (see **SDG 13**) adds another level of complexity to urbanisation with implications for energy supply and usage including the requirement for more cooling/heating, and for power supply reliability.

7.2.4 Transport

Transport worldwide consumes about one-fifth of global primary energy and increasing transport demand is expected in the rapidly growing economies of the developing world because economic growth is strongly correlated with growth in transport volumes (Aßmann and Sieber 2005). After the energy sector, transport is the most important producer of carbon dioxide so it is likely that an increasing proportion of global emissions will come from transport. Transport is also in many cases harder to decarbonise than fixed infrastructure such as power stations or cement works.

Thus, a sustainable transport strategy has to take into account the growing transport demands in developing countries and reduce emissions at the same time. Technical solutions could include (1) more efficient conventional engines, better designed vehicles, improved inspection and maintenance, and fuel quality; (2) renewable fuels in transport, such as ethanol and biogas; (3) better transport demand management, land-use planning and fuel pricing; (4) lower carbon natural gas vehicles; and (5) electric vehicles.

Of these options, only electric vehicles has implications for geological science research or human capacity, mainly because an understanding of the primary resources used to make batteries is crucial. These include deposits of lithium, sodium, vanadium, copper, cobalt, and nickel. Estimates based on electric vehicles being 30% of the global vehicle fleet by 2030 suggest that an extra 2 million tonnes of copper, 1.2 million tonnes of nickel, and 260,000 tonnes of cobalt will have to be mined per year into the future (Financial Times 2017). These are considerable increases on present production levels and suggest that more resources will have to be found, and that recycling of materials will have to be improved.

7.3 Geoscience Research for Affordable and Clean Energy in Developing Countries

7.3.1 Fossil Fuels

IEA forecasts (IEA 2016), indicate that fossil fuels will have a role to play in future energy systems in the developing world and these are likely to be used as feedstock for chemical industry and fertilisers, but also combusted in transport, heating and in electricity generation (with or without CCS, see below). As such, geoscience research into fossil fuels will contribute to **SDG 7.1** '*Proportion of population with access to electricity*'.

Coal, oil, and gas need similar geological research and knowledge for their exploration and extraction, for example, 3D seismic, resource and basin analysis, and structural geology. Coal, oil, and gas are also related in that research and knowledge are commonly provided by commercial, often multinational, companies following earlier pre-competitive surveys done by in-country geological survey organisations. However 'home-grown' knowledge and research, in exploration techniques, for example, are needed to be able to provide data on potential new resources for inward investment, to ensure a development pipeline of resources. Regulatory bodies also need the technical capability to maintain optimal environmental and sustainability safeguards, and to ensure that commercial negotiations over the development of resources are done on an equal footing to ensure equitable distribution of value between developer and government.

7.3.2 Electrification

If electrification is seen as a solution in primary energy in transport (electric vehicles) and heating and cooling in the developing world, then it is likely that demand for electricity will be very high and that the production of electricity will have to be fundamentally decarbonised. Geoscience research that enables the decarbonisation of electrification would contribute to **SDG 7.1**. In a scenario with high renewables or nuclear electricity, this would not be an issue, but for countries in the developing world with large coal or hydrocarbon reserves, for example, South Africa, Indonesia, and India, decarbonising electricity at source would require carbon capture and storage on fossil fuel power stations (see also **SDG 13**).

Geological storage of CO_2 relies on the ability to demonstrate that the storage operator can predict the future evolution of the CO_2 plume within known limits of certainty. Doing this requires robust and reliable observations of the site behaviour before, during, and after injection of CO_2 (Holloway 2007). Geological CO_2 storage must also lead to the permanent containment of the CO_2. Fundamental to the safety of achieving this reduction in atmospheric CO_2 emissions is the need to select and characterise geological sites that are expected to enable permanent containment. The largest stores are saline aquifers, which require the displacement of the in situ pore waters during CO_2 injection. The rate of injection and ultimately the mass of CO_2 that can be injected can be limited by the pressure increases that can occur during injection. Research is still needed to better understand the limits on pressure increases, improved methods for improving injectivity and managing pressure increases in saline aquifers. In contrast, depleted oil and gas fields that are subsequently used for CO_2 storage may require careful management during injection due to a number of processes that might limit injectivity, including Joule–Thomson cooling, well integrity, and seal integrity issues. Key challenges in CCS for the developed and developing world include de-risking the economic model for CCS and de-risking the full supply chain, as well as looking into public attitudes to CCS. In many cases, the solution to these problems will involve the development of industry-scale CO_2 storage pilots (Stephenson 2013; Holloway 2007).

Renewable energy that can feed directly into electricity production includes high enthalpy geothermal, solar and wind. Geological research and knowledge input into solar is focused on the raw materials needed for their production, and for wind consists mainly of the provision of geotechnical data for construction offshore and onshore. However, to support high enthalpy geothermal, geological studies will involve accurate resource mapping, as well as a detailed understanding of the fracture systems, geochemistry, hydrogeological systems, and thermal properties of the potential source rocks.

Geological studies on geothermal would, therefore, contribute to **SDG 7.1** and **7.2**.

In the case of a greatly increased need for low carbon nuclear electricity, geological considerations are very important. Long-term, safe management of highly radioactive waste is a significant challenge for countries with developed nuclear industries and will continue to be as nuclear energy plays a role in the future energy mix. Deep geological disposal is a key solution to managing waste for the long term, but it requires understanding and validation of complex subsurface processes and their interactions and feedbacks for up to one million years into the future taking into account seismicity and volcanism, as well as climate-related processes such as permafrost and ice loading and unloading (e.g., McEvoy et al. 2016).

The isolation of waste from the geosphere over long timescales requires fundamental knowledge of flow paths from the waste canister, through natural and induced discontinuities in the engineered barriers and surrounding host rock, to the surface environment. Geomechanics also play an important role in the long-term evolution of a repository and can strongly influence flow. Key science questions include the influence of stress state, burial history, and the generation and behaviour of faults and fractures. The long-term integrity of a repository and its surrounding geological and surface environment is central to developing safety arguments. Understanding near-field (geological characteristics, hydrogeological regime) and far-field (plate tectonics, climate) processes is required to build an integrated understanding of the evolution of the subsurface. Studies of deep geological disposal would, therefore, contribute to **SDG 7.1** and **7.2**.

7.3.3 The Hydrogen Economy

The hydrogen economy encompasses fuel for transport (road vehicles and shipping), stationary power generation (for heating and power in buildings), and an energy storage medium feeding from off-peak excess electricity. A system for hydrogen generation, salt cavern storage and electricity generation can begin with wind and solar energy. At times of excessive wind or solar electricity production, electrolysers can use this electricity to produce hydrogen and oxygen from water. The hydrogen is stored below the plant in a salt cavern. A gas combustion power plant using hydrogen alone or combined with natural gas can generate electricity. Excess renewable electricity can also be used to produce hydrogen from natural gas, through steam reforming (Ozarslan 2012).

An important geological aspect of the hydrogen economy is the need for the large-scale, long-term, and intermittent storage. The technology of compressed hydrogen gas storage in salt caverns is similar to that of natural gas, however, hydrogen energy density by volume is only one-third of that of natural gas, and so gaseous hydrogen energy storage is more expensive. For an integrated hydrogen economy, geological survey of salt beds including detailed facies mapping would be required mainly because salt cavern construction and performance are strongly impacted by salt heterogeneity. Studies are also required of the response to salt of repeated pressurisation cycles over long periods (Ozarslan 2012). Studies of geological hydrogen storage would contribute to **SDG 7.1** and **7.2**.

7.3.4 Energy Storage

With both electrification and hydrogen decarbonisation strategies, grid-scale energy storage will be needed, including compressed air energy storage (CAES). In CAES a storage pressure of about 70 bar is envisaged. Salt caverns are favoured because, being impermeable, there are no pressure losses, and because there is no reaction between the oxygen in the air and salt. Again studies of the facies variation and mechanical properties of the salt will be required (Evans et al. 2009). For the siting of other grid-scale storage options, for example, pumped hydro storage schemes, detailed geotechnical and seismic risk studies are required for dam building and deeper geological site characterisation for tunnels and underground installations. Studies of subsurface energy storage would contribute to **SDG 7.1** and **7.2**. Holistic planning involving the subsurface in relation to energy storage coupled with smart grid electricity distribution could contribute to **SDG 7.3**.

7.3.5 Ground Source Heat and Cold

Global energy demand from air conditioning is expected to triple by 2050, with climate change and developing country growth, requiring large new electricity capacity (IEA 2018). Air conditioning use is expected to be the second-largest source of global electricity demand growth after the industry sector, and the strongest driver for buildings by 2050 (IEA 2018). Although electricity is likely to power many air conditioners, a geothermal heat pump or ground source heat pump that transfers heat to or from the ground can also be used to cool and provide heat to buildings. This is achieved by using the shallow subsurface as a heat source (in winter) or a heat sink in the summer (contributing to **SDGs 7.1** and **7.2**). Although the use of ground source heat pumps is growing, common scientific and technical uncertainties that impede private investment include accurate estimates of the potential of the subsurface and rates of natural replenishment of extracted heat. In addition, the frequent lack of regulation of ground source heat and cold discourages investment.

7.3.6 Regulation and Compliance

Geological monitoring of the integrity and efficiency of subsurface energy installations will be important, as will mathematical concepts of risk and uncertainty. In areas such as disposal (CCS) and extraction (geothermal), geoscience and society (including engagement and communication with the public, Government, industry, and other stakeholders) will be important to secure a social licence.

In data science and infrastructure, the monitoring for compliance of subsurface energy installations will particularly demand more capability in telemetry, data streaming techniques and visualisation, as well as a greater ability to store and manage very large amounts of data. To understand the change in data (for example, change points and anomalies in production or containment behaviour), and in order to forecast better, new statistical and artificial intelligence techniques will be needed. To manage subsurface energy installations a full suite of modelling techniques will be needed from conceptual static modelling to dynamic modelling, to forward modelling, to simulation.

It is worth noting that improved energy efficiency in buildings, industrial processes and transportation could reduce the world's energy needs in 2050 by one third (IEA 2016), however, at present geoscience and geological materials have a little direct role in energy efficiency, improvements in domestic appliances and building design being more important.

Box 7.3 Study of the effects of geothermal development on the Maasai community of the Kenyan Rift Valley

The study carried out by the Kenya Electricity Generating Company Ltd, Olkaria Geothermal Project (Mariita 2002) examined (1) the beneficial impacts of the project (e.g., employment, provision of water and infrastructure); and (2) the negative impacts of the project (e.g., displacement, noise, and pollution). On whether the geothermal project has had any impact on their lives, many respondents mentioned the positive benefits such as water, shops, and school. Most said that the noise or gas emissions did not discomfort them in any way, nor have any of their livestock been hurt by the project facilities. Negative comments included resentment due to resettlement, reduction in their land for grazing and Maasai cultural values being eroded by outsiders. Perhaps most telling, some respondents complained that they did not receive any of the energy generated at the site (Fig. 7.11).

Fig. 7.11 Olkaria Geothermal Project, Kenya © Chris Rochelle (used with permission)

7.3.7 Energy Governance

For many developing countries, rich resources have often paradoxically lead to low economic growth, environmental degradation, deepening poverty, and in some cases, violent conflict (Pegg 2006; Fischer-Kowalski et al. 2019). Primary resources such as oil and gas, apart from supplying energy for a nation's infrastructure, also constitute a source of revenue. For oil and gas revenue to contribute to a nation's wealth, particularly for its poorer citizens, depends on a number of factors including the manner in which resource income is spent, system of government, institutional quality and governance, type of resources, and stage of industrialization (Torvik 2009). Similarly, for the benefits of rural electrification or other affordable and clean energy to be made available to the wider population, good governance is needed. As an example, Van Alstine et al. (2014), indicated that within the emerging 'petro-state' of Uganda, four significant governance gaps might allow a lack of equitable development: (1) lack of coherence amongst civil society organisations; (2) limited civil society access to communities and the deliberate centralisation of oil governance; (3) industry-driven interaction at the local level; and (4) weak local government capacity.

Improvements can be made in public sector institutions like geological surveys, and government departments such as mines, energy, and water ministries through capacity building programmes. These programmes aim at understanding the business of the organisation within the context of government and regulation and can initiate training needs analysis to improve the qualifications and skills of staff (Box 7.4). Programmes can also advise on the functions of organisations and parts thereof. The ways that donor funds and projects are used can also be optimised so that development projects are not primarily organised to reflect donor agendas rather than the needs of the recipient institution (Stephenson and Penn 2005).

7.4 Geoscience Training for Affordable and Clean Energy in Developing Countries

An analysis of the training needed for modern energy geoscience is shown in Table 7.3. The table divides the geoscience energy disciplines into 5 major categories: geothermal and renewables, energy storage, radioactive waste disposal, CCS, and hydrocarbon systems. Each of these also has subtopics.

In general, the main skills needed include rock volume characterisation and process understanding in order to establish the geological feasibility of different solutions to energy, decarbonisation,

Table 7.3 Training needed for modern energy geoscience

	Highly radioactive Waste Disposal		CCS		Energy Storage		Geothermal and Renewables		Hydrocarbon Systems	
	Description	Required training and level	Description	Required training and level	Description	Required training and level	Description	Required training and level	Description	Required training and Level
Subtopic	Containment (fluid processes)	Geophysics, hydrogeology, geochemistry, computing, telemetry; BSc, MSc, PhD	Developing a plan for CO2 storage pilot	Geophysics, geomechanics hydrogeology, geochemistry, computing, economics, law; BSc, MSc, PhD	Thermal storage	Geophysics, hydrogeology, geochemistry, computing; BSc, MSc, PhD	Geothermal shallow	Geophysics, hydrogeology, geochemistry, computing; engineering geology; BSc, MSc, PhD	Conventional	Geophysics, structural geology, stratigraphy, biostratigraphy, organic geochemistry
	Siting — geological context	Geophysics, structural geology, stratigraphy; BSc, MSc, Ph.D.	Developing and maintaining technologies and methodologies	Computing; BSc, MSc, Ph.D.	Cavern storage	Geophysics, geomechanics, computing, telemetry; BSc, MSc	Geothermal deep	Geophysics, hydrogeology, geochemistry, computing; BSc, MSc, PhD	Unconventional	Geophysics, structural geology, stratigraphy, biostratigraphy, organic geochemistry
			Containment: safety, site characterisation	Geophysics, petroleum engineering; hydrogeology, geochemistry, computing, telemetry; BSc, MSc, PhD	Formation storage	Geophysics, structural geology, sedimentology, stratigraphy; BSc, MSc	Offshore siting (wind, barrage)	Geophysics, geomorphology, sedimentology, stratigraphy		
			Injectivity, pressure management, storage optimisation	Geophysics, petroleum engineering hydrogeology, geochemistry, computing, telemetry; BSc, MSc, PhD	Pumping storage	Geophysics, geomorphology, structural geology, stratigraphy; BSc, MSc				
			Planning and licensing regulation	Geology and policy; BSc, MSc						

and low carbon industry, all of which have a strong relationship to appropriate regional and site-specific geology, and the processes associated with that type of geology. For example, in radioactive waste disposal and CCS, the site-specific characterisation of rock masses is vital to understand the feasibility of containment; similarly, process understanding in relation to that rock mass is vital to understand long term change in the subsurface. In general, these areas of research and activity will need a full range of qualification level in the tertiary education sphere from BSc to Ph.D. In rock volume characterisation and process understanding the quantitative disciplines of geoscience will be most important, including geophysics, geochemistry, geomechanics, and in some cases petroleum engineering.

Beyond rock volume characterisation, existing and novel methods of monitoring will be become important, as geological energy and decarbonisation options develop—as will concepts of risk and uncertainty, thus requiring mathematical and statistical training. Training in science and society will be needed to understand the social licence and public engagement (see **SDG 4**). Again for these areas of research and study, the full range of qualification level in the geoscience tertiary education sphere from BSc to Ph.D. will be needed.

As well as developing home-grown training, skills, and knowledge can be transferred between the developed and developing world through shared geoscience courses, integration of energy industry expertise and training (e.g., visiting professorships in the developing world) and international cooperation. An example of such cooperation is included in Box 7.4.

Box 7.4. Capacity Building in Afghanistan.

Using experience in a number of developing country and post-conflict contexts, a methodology for Business Needs Analysis was developed and used at the Afghanistan Geological Survey in Kabul between 2003 and 2004 (Stephenson and Penn 2005). The main aim of the analysis was to help the AGS to function better in the post-conflict context, providing independent information on sustainable use of resources to the Afghanistan government. Extensive stakeholder analysis carried out as part of the Business Needs Analysis gauged the organization’s strengths and weaknesses and took account of the local social, political, and business context. Training was designed to be tuned to business need, including appropriate IT and communication skills, technical and scientific (Fig. 7.12).

A vital part of the training was to foster a corporate understanding of the private sector in the AGS, so that it could interact successfully with business and commerce.

Fig. 7.12 Capacity Building in Afghanistan. Left: The Afghanistan Geological Survey, a crucial public sector science institution providing independent information on sustainable use of resources to the Afghanistan government. Right: female Afghan students learning about geological maps. Photos by author (M Stephenson)

The analysis also established a system allowing regular cyclical business/training review, so that the AGS could adapt to further change.

Following feedback from stakeholders, it was considered important to help to understand how donor projects (often from very different donors with different priorities and agendas) could be better organised, coordinated and tuned to the business need of the institutions. Further information on this collaboration is included in the chapter exploring **SDG 17**.

7.5 Discussion and Conclusions

The concept of energy transition (e.g., Sovacool 2016), concerns the wholesale change of energy supply from one source to another, for example, from wood biomass to coal in the Industrial Revolution of the eighteenth Century. According to Sovacool (2016), amongst the stages that are experienced are a period of extended experimentation with small scale technology and a diversity of design, followed by scale up of technologies as designs improve and economies of scale emerge, and finally by scaling up at the industry level. As industry structure becomes standardised and core markets become saturated, further industry growth is driven by globalisation and the diffusion of a successful design from the innovation core to rim and periphery markets.

The speed of energy transition in developing countries will be governed by the rate at which new technology becomes available, knowledge of the opportunities for new energy technologies including the locations for suitable developments, as well as the opportunities for scale up beyond the small scale which involves commercialisation, addressing market failure and strategic investment. In many ways, geoscience can be expected to provide the strategic knowledge that addresses market failure and encourages investment, rather like the way, for example, that the way that strategic public sector science research investment in the 1980s and 1990s in the US paved the way for a successful shale gas industry (Stephenson 2015).

What kind of energy system will evolve in developing countries? Will it be electricity-dominated with primary decarbonised and centralised electricity sources (e.g., large fossil fuel power stations with CCS), or dominated by more distributed renewable resources, or based on hydrogen as a fuel. How much will ground source geothermal provide heat and air conditioning to buildings? As in the developed world, these questions are not easy to answer. The forecasts of the IEA suggest that fossil fuels will continue to be used for several decades in the developing world while renewables gain ground. Facilities and technologies for storing grid-scale electricity as well as transporting it are mostly inadequate in the developing world and will be needed whichever system is adopted, even if (most likely) it is a hybrid.

It is also likely that much development in subsurface energy will take place along development or trade corridors in the developing world, for example, the Nacala and Northern corridors in East Africa (Stephenson 2018), and so targeted regional geological studies will be needed to support integrated decarbonisation and resource management technologies (including integrated hydrogen and CCS). Also, geotechnical studies will be needed to support new railways, roads, pipelines and tunnels.

The present underinvestment in ‘home-grown’ education and research will tend to concentrate expertise in the commercial sector, which often being multinational, will not necessarily encourage local expertise, and will take away some of the ability of the government institutions to deal with multinational companies on an equal footing. So it seems clear that increased investment in energy geoscience training and research that has a clear application in developing country energy challenges and opportunities is needed.

In the compiling of this chapter, it became clear early on that data on energy resources and energy geoscience for developing countries is nowhere conveniently stored or collated, being concentrated more often on particular areas of interest, for example, Africa and India, as geographical categories. This means that the similarities and differences between developing countries cannot easily be ascertained, so that useful generalisations are difficult. This hampers planning and better understanding. For example, IEA and BP energy statistics do not routinely contain sections on the developing world as a category. It is also true to say that sectoral differences in energy—for example, between the oil and gas industry and the geothermal industry, or other renewables—makes a generalised view difficult. Thus, it might be wise to institute better developing country energy geoscience data collation and storage.

7.6 Key Learning Points

- Energy in its broadest sense enables business, industry, agriculture, transport, communications, and modern services such as health care; but it also enables improvements in living standards.
- Geoscience has a direct role in several of these areas including in establishing the geographical distribution, geological habitat, geotechnical feasibility of construction and infrastructure, and environmental sustainability, of energy supply.
- The geographical distribution of energy resources in the developing world indicates large potential in fossil fuels, including oil and gas but particularly coal, in several large key developing nations. Whether these fuels will be developed will depend on local needs and emissions policies. Many renewable energy resources are abundant in the developing world but their development depends on market conditions, often in tension with fossil fuels.
- Underpinning geological activities for affordable, reliable, sustainable, and modern energy will need to gain an understanding of the resource, but also how it can be used within limits that do not damage the environment, locally or through emissions, but still also be affordable. Electricity will clearly be key and decarbonisation of electricity could involve carbon capture and storage on fossil fuel power stations, which will involve in-depth geological studies in resource and containment.
- Geological studies will be needed for other low carbon electricity, for example, wind turbines, geothermal, and nuclear power. For the hydrogen economy, similar in-depth geological studies will be required.
- Geological studies will also have to feed into appropriate regulation that manifestly protects people and property, and regulations will need to be enforced by strong, independent local institutions. Facilities and technologies for storing grid-scale energy (electricity), as well as transporting it will be required, as will be an understanding of the development corridors where the most activity will take place.
- It is clear that increased investment in energy geoscience training and research is needed; and better data on energy geoscience research and training needs for the developing world would allow for better analysis and planning.

7.7 Educational Resources

In this section, we provide examples of educational activities that connect geoscience, the material discussed in this chapter, and scenarios that may arise when applying geoscience (e.g., in policy, government, private sector international organisations, NGOs). Consider using these as the basis for presentations, group discussions, essays, or to encourage further reading.

- Think about some of the rocks you've recently described as part of a petrology practical class. What contribution could they make to delivering SDG 7? What types of geological environments (think of both rock types and geodynamics) could be suitable for (i) carbon capture and storage, (ii) containment of radioactive waste, and (iii) hosting minerals used in solar panels?
- Prepare a review of information on energy access, energy consumption, and energy generation in (i) Zambia, (ii) Fiji, and

(iii) Canada. How easy is to access information for the three countries, and what may the reasons be for any differences in the availability of statistics? With the information you have collated, consider what steps each country could take to tackle climate change?

- How may implementation of the 16 other SDGs increase/decrease demand for energy? Are these changes likely to be the same everywhere, or affect particular regions? What are the implications of your findings on geoscience training?
- Explore the energy use per capita for different locations around the world (e.g., Tanzania, India, Vanuatu, and Australia)? Debate the statement '*it is unreasonable to prevent countries with very low energy use per capita from increasing their use of fossil fuels*'.

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