Global energy and the role of geosciences: A North American perspective

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ABSTRACT

The world contains abundant energy resources. The challenge is extracting and utilizing these resources affordably, in an environmentally responsible way, and in a dense enough form to be useful to humans. The link between energy, the environment, and the economy is unavoidable and involves the geosciences at its core.

Carbon-based fuels such as wood, hay, and coal powered human society for millennia. Then, in the early twentieth century, petroleum in various refined forms came into use for lighting, heating, and early combustion engines. Today, fossil fuels—coal, petroleum products, and natural gas—represent an important 85% of the global energy mix, but they are not without challenges. Coal’s greatest challenges are environmental: the impact of surface mining; water contamination; discharge of airborne pollutants including sulfur, nitrogen, and mercury; and the emission of CO$_2$. The emerging technologies of carbon capture and sequestration may offer the prospect of solving one of coal’s problems; large, stationary sources of CO$_2$ (such as coal-fired power plants) are the most efficient targets for carbon capture. However, capturing CO$_2$ is expensive. Oil and, to a much lesser degree, natural gas also produce CO$_2$ and other emissions when combusted. Oil and natural gas require drilling, entailing the associated environmental impacts of oil-field operations; yet there remain considerable global oil and natural gas resources. The current frontiers for conventional oil and natural gas production include ultra-deep water, the Arctic, sediments deposited beneath major salt formations, and other extreme operational environments. As existing and new conventional oil and natural gas reserves decline, unconventional reservoirs—shale gas, coal bed natural gas, tight gas, shale oil, oil shale, oil sands, and perhaps eventually natural gas hydrates—will represent a growing part of the fossil-fuel mix.
Nuclear energy—today fission, and tomorrow, perhaps, fusion—is very dense, has no emissions, is highly efficient, and is very affordable on a kilowatt-hour basis. Adoption of nuclear energy is limited by the high initial cost of building a power plant, public perception, issues of waste handling, the fear of proliferation, and the very real need to make reactors safe from natural and human-caused disasters.

“Renewable” forms of energy—those that are generated by “renewable” motion such as wind and moving water; or “renewable” sources of heat such as geothermal and solar; or those that are grown such as biofuels—will increase as a proportion of the energy mix. These sources are currently limited in growth rate by their lower energy density and, for some, their intermittency. Intermittency—the wind does not always blow and the sun does not always shine—must be addressed by significant improvements in energy storage technologies: in chemical batteries; as pumped water or compressed air; as heat stored in molten salt, buildings, and other forms; as kinetic energy in flywheels; as electrons in advanced capacitors; or by various other technologies. But these energy storage technologies need to be made efficient, affordable, and scalable before they will be deployed broadly.

Because the transition from a fossil-energy present to an alternate-energy future involves the interplay between energy, environment, economy, and policy, almost without exception all forms of energy involve the geosciences. Coal mining requires geologic understanding. Large-scale geologic carbon sequestration, which might someday make coal more environmentally friendly, will rely on a whole new discipline involving advanced subsurface characterization and monitoring. The subsurface understanding and technology required for conventional and unconventional oil and gas exploration and extraction are substantial. From the scale of nanopores to tectonic plates, the use of advanced seismic imaging, ever more-quantified field and laboratory experimentation, airborne remote sensing, and much more is required to unlock the fossil-fuel resources that remain trapped in the Earth.

Nuclear energy relies on sources of uranium, plutonium, thorium, and many other mined products. And eventually, geologic repositories will be required to store the waste products of nuclear power generation.

In terms of renewable energy, production of biofuels involves soil science, hydrogeology, fertilizers, weather, and climate. Harnessing geothermal energy involves the ability to characterize the subsurface geothermal resource. Generating power from tides and waves involves oceanography and analysis of coastal change. Utilizing wind depends on weather pattern studies and geomorphology for the siting of turbines, as well as the mining of copper, carbon, and other materials. Producing solar energy involves the geosciences, with the need for silicon, gallium, cadmium, copper, and other materials. As large-scale energy-storage solutions become necessary, input from the geosciences will range from characterizing the subsurface for compressed-air storage to mining rare-earth elements for chemical batteries.

The involvement of geosciences in energy does not stop with subsurface understanding or the construction of a power plant. “Above-ground” environmental and policy challenges covering the full lifecycle of any form of energy are as great as the “below-ground” technical challenges. Environmental geologists, biologists, energy economists, and policymakers must come together to develop sensible policies and regulatory rules that make it possible for industry, government, academe, and non-governmental organizations (NGOs) to work together to deliver balanced solutions.
ENERGY: THE MOST IMPORTANT ISSUE OF OUR TIME

It took well over four billion years, until just after the turn of the nineteenth century, for the human population of the planet to reach one billion. Today the global population exceeds seven billion, growing by one billion people approximately every 15 years, heading toward a projected plateau of around 10 billion people near the middle of the twenty-first century (BP Statistical Review of World Energy, 2012). Providing energy for 10 billion people is a daunting prospect. But the world contains abundant energy resources. The challenge is extracting and utilizing these resources in an affordable, environmentally tenable, and dense enough form to be useful to humans.

In developed and even developing nations, people are too caught up in modern life to realize that energy makes everything possible. Some things, such as cars, are powered by fuel in an obvious and recognizable way, but everything else runs on energy, too: the internet, phone systems, appliances, air conditioning and heating, and every device in offices and homes. This is true even for things people might not expect, such as food, which is planted, fertilized, irrigated, harvested, processed, packaged, transported, and sold using energy all along the way. Every home; every business; every government; every major issue such as poverty, hunger, health, medicine; and education are underpinned by energy, which means energy is the most important human issue of our time.

The Waltz of the Three E’s: Energy, Economy, and the Environment

In the aggregate, global energy consumption has risen with population (Fig. 1). As China and India industrialize, the impact on total global energy consumption will be substantial; of the 2.5 billion people in these two countries, some 1 billion currently do not have access to electricity. The primary way to slow the growth in energy consumption, other than economic recession or a decrease in population, is through more efficient use of energy, made possible initially by energy awareness. Efficiency does not require a major change in lifestyle of people in developed nations, and in fact has positive benefits ranging from emissions reductions to lower net cost of energy. Importantly, affordable efficiency measures could be adopted by developed nations.

Historically, per capita energy consumption has been positively correlated to per capita gross domestic product (GDP) (Fig. 2). The United States consumes more energy per capita than any other major economy on Earth, and has a higher GDP per capita than any other nation except Norway. However, as stated clearly in the recent Global Energy Assessment by the International Institute for Applied Systems Analysis, “As economies develop, countries’ energy needs and priorities change. The evolution of demand at different stages of economic development changes. As economies develop, as happened with industrialized countries, the tendency is to adopt more efficient technologies..."
for the provision of energy services, and the composition of economic activities change \[\text{sic}\] with energy intensity tending to decline over time” (Yeager et al., 2012).

In order for the developing nations such as China, India, and Brazil (representing nearly 3 billion people) to industrialize, they will need energy. If they consume energy in the way that Organization for Economic Cooperation and Development (OECD) nations, a group of 34 industrialized countries, did when they industrialized, then the world could be hard-pressed to meet aggregate energy demand. On the other hand, if energy efficiencies and conservation continue to progress, bringing down per capita consumption, then the world could meet its energy demands and still experience economic growth and prosperity.

U.S. data show an interesting correlation between inflation-adjusted oil price, as a proxy for energy price, and GDP (Fig. 3). When the inflation-adjusted price of oil rises sharply, the U.S. economy tends to turn down, often into recession. In fact, six of the last seven global recessions have been preceded by a sharp rise in the price of oil. Correlation is not causation; economies are complicated and respond to many factors, not only the price of energy. However, the relationship between energy price and the economy is hard to deny.

Energy production has well-known environmental impacts, including airborne and waterborne pollution, solid wastes, land use, greenhouse gas emissions, and others. Less obvious, but equally important, is the relationship between the economy and the environment. In a nutshell, when economies are unhealthy, investment in environmental protection suffers. As an example, consider CO\(_2\) emissions. All fossil fuels, when burned, produce CO\(_2\). Nearly half of all CO\(_2\) emissions come from coal and more than a third come from oil. Many nations are trying to reduce CO\(_2\) emissions, and toward this end a meeting was held in Copenhagen in December 2009. By many accounts, Copenhagen failed. One underpinning reality was that the world was in a recession, and nations simply could not afford to implement CO\(_2\) protocols. There are countless other emission, land use, and water use examples of the economy-environment relationship.

In general, developed nations have been reducing the environmental impacts of energy over time, but producing energy more cleanly usually makes energy more expensive, at least initially, and that cost gets passed along to consumers. Different countries will accept different levels of environmental cost. Developed nations that can afford the expense of cleaner energies will pay for them, while developing countries will often endure more pollution in exchange for affordable energy—energy that is used to help lift people out of poverty. Passionate, and at times distorted, advocacy by some academics, film makers and environmental groups to boycott the use of certain forms of energy, or government policies that pick energy winners before they are ready to meet the required scale of demand, although perhaps well intended, often have unintended negative consequences. Forced market distortions often hurt the economy, and by extension reduce investment in the environment. The goal of thoughtful energy policy, and advocacy, must be to minimize environmental impacts while keeping energy affordable and economies healthy. In other words, utilize the prosperity that affordable

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Figure 2. Global gross domestic product (GDP) per capita versus total primary energy requirement (TPER) per capita (the energy needed to facilitate total final consumption, which does not include conversion and transmission losses); data shown are from 1992 to 2009 for several major economies. Source: Medlock (2012).
energy provides to invest in the environment: the Waltz of the Three E’s (Tinker, 2009).

Energy Security

Much is made over the concept of energy independence; sensu stricto the term means no net import of energy. Some countries, such as Saudi Arabia, are independent in that they do not import energy, but their energy mix, both in production and consumption, is almost exclusively limited to oil and natural gas today. In other words they are not diverse, and a non-diversified energy portfolio is not necessarily a secure portfolio. Others, such as Brazil and Norway, have vast hydro and/or biofuel resources in addition to oil and natural gas. Such countries are both energy independent and cushioned by the diversity of their energy portfolio, making it easier for them to use the revenues from nonrenewable fossil fuels to build a strong financial foundation for the future. But such nations are uncommon, and although independence sounds good in concept, it is not realistic for most nations. Instead, energy security is a more viable, and perhaps more healthy, goal.

Energy security extends the concept of the 3E waltz into more actionable space. Secure energy is available, reliable, affordable, and environmentally apposite. The energies that best meet these four criteria will be the energies used in the future, and the pace of change will be driven by how well these criteria can be met.

- **Available** energy means resources that are accessible in substantial quantities. Countries tend to use what they have, where they have it; such as hydro in Norway, geothermal in Iceland, and solar in Spain. One may wish for a solar resource in Seattle, Washington, or Berlin, Germany, but solar intensity is not high in those places. The pattern holds true for fossil fuels, hydro, geothermal, and wind. Availability also includes access. The eastern Gulf of Mexico and Great Lakes region may contain abundant sources of oil and natural gas, but if drilling is not permitted in those areas, then the resource will not be utilized. If the required energy source is not locally available, it needs to be easy to transport. Most countries use more oil than they have. This is possible because oil has a highly developed transportation network, which has made oil into a global commodity.

- **Reliable** energy is energy that is there when it is needed. Interruption of supply can be caused by natural disasters such as a hurricane, human-made events such as a war or terrorism, or such natural conditions as the day/night cycle or variation in wind speed. Intermittent sources of energy
such as wind and solar require “backstopping” with other reliable, or baseload, sources, such as natural gas.

- **Affordable** energy takes into consideration the cost of a unit of energy, such as a kilowatt-hour of electricity or a gallon of gasoline. Affordability also includes the cost of infrastructure, such as the construction of a nuclear power plant or major transmission lines. Finally, affordability considers volatility. Does the price remain stable or does it fluctuate in ways that are unpredictable and uncontrollable? It is hard for an expensive resource, such as solar, to compete in the open market with a cheap one, such as coal. For better or worse, individuals, companies, and governments make energy choices based first on price. Affordability is partly a function of what users don’t pay. For instance, pollution from some forms of energy is released at no cost. Paying for these so-called externalities would increase their price, potentially bringing competing sources closer together. But if some countries follow such a policy and others don’t, a market disadvantage arises. This is not an easy issue: at the moment, subsidies bring down the cost of certain expensive new technologies. But it is unlikely that governments will choose to subsidize them forever. Energy that is expensive is ultimately not sustainable.

- **Environmental** energy must have acceptable consequences in terms of land use; water consumption; and solid, liquid, and gaseous waste. For example, highly dense energy sources, such as nuclear, use much less land than does industrial solar, whereas wind uses very little water compared to the cooling water required by nuclear, coal, and natural gas power plants. And solar and wind have very low atmospheric waste output compared to that produced by the combustion of fossil fuels. Nothing is perfect. Some wastes are secondary and harder to recognize. For example, electricity from batteries may seem to be pollution free, but most electricity still comes from coal, natural gas, or nuclear. And there are harmful chemicals in batteries and battery housings that will require disposal. CO₂ emissions are a component of the environmental equation but must be balanced against land and water use. Nothing is without some challenges.

Importantly, countries can and will meet these energy security guidelines with a varied mix of energy sources, because nations tend to use the resources available to them. Thus, forcing certain kinds of energy into the energy mix by “picking winners” via policy and regulation is not advisable and can ultimately hurt the economy. Instead, it is better to create security guidelines, support via incentives, and then let markets compete.

**ENERGY RESOURCES**

**The Resource Challenge**

Modern economies were built on the back of energy; coal for heat, trains, and ships, and later to generate electricity; oil for heating and lighting, and later for transportation. A century later, OECD nations, in the aggregate, still depend on petroleum (oil), in the form of gasoline, diesel, and jet fuel, to provide more than 90% of the fuel for transportation. And coal still produces more electricity than does any other fuel. Non-OECD nations are now developing their economies. These industrializing countries are building a substantial number of coal-fired plants for power generation (Fig. 4). In China, for example, a new coal power plant on the order of one gigawatt is being commissioned every 7–10 days (Ansolabehere et al., 2007).

It should also come as no surprise that most of the cars being sold in developing nations run on gasoline. What may come as more of a surprise is the stunning growth in car sales in China. The number of cars sold in China in 2006 was ~5 million, compared to ~16 million in the United States (Fig. 5). By 2011, that relationship had inverted, with nearly 20 million sold in China and around 13 million in the United States. To reiterate, in six years, China went from one-third of U.S. car sales to 1.5x! India is following a similar growth pattern to that of China in both coal-fired power plants and gasoline-powered cars.

This is not to imply that China is pursuing only coal. They are also building 26 new nuclear power plants (IAEA, 2012), in addition to liquefied natural gas (LNG) import terminals, massive hydropower plants, huge wind farms, and solar facilities. The challenges of powering and fueling economic growth for a combined 2.5 billion people in China and India are monumental.

In the sections that follow, we will first examine oil as the foundational transportation fuel, followed by alternatives to oil for transportation. Then we examine coal as the foundational power generation fuel, followed by alternatives to coal for power generation. For each form of energy we will discuss what it is and how it is used; the known resource; some of the current and emerging technologies, including the role of the geosciences where applicable; and finally the benefits and challenges for each resource.

**Transportation: Oil**

**What is it and how is it used?** For over a hundred years, oil has moved the world. Not only do cars, trucks, and buses take people to work, school, and the store every day, but the global flow of commerce also runs on oil-based fuels. Every product must be brought from where it is mined, made, or grown to where it is used or consumed—often a long journey, usually powered by oil.

Technically, petroleum, or oil, is a naturally occurring organic substance consisting of various hydrocarbon compounds formed from burial and thermal decay of marine plants and microorganisms over geologic time. The chemistry of oil varies from one deposit to another, depending on the source material, burial depth, diagenesis, thermal gradient, and other factors. Oil can range from highly viscous, like the oil sands of Canada, to very fluid. Produced crude oil can be refined into a suite of products including transportation fuels, petrochemicals, lubricants, feedstocks for plastic, fertilizers, paints, asphalt, medicines, and many other products.
Figure 4. Power generation by fuel type and geopolitical region, forecast to 2030. Source: ExxonMobil Corporation (2010).

Figure 5. Vehicle sales in the United States and China. Sources: China Association of Automobile Manufacturers (2011); Olathe Toyota (2012); U.S. Bureau of Transportation Statistics (2012).
Oil is a unique transportation fuel packing a huge amount of energy into a compact, lightweight, liquid form—easy to transport, easy to store, and easy to pump into a gas tank. And while it is used mostly for transport, it can also be used for heating, power production, and as an incredibly versatile chemical feedstock. Even today, oil is still remarkably cheap considering the cost of extraction, refining and transportation, and the many social and economic benefits it provides.

**Resources.** Oil resources, also called original oil in place (OOIP), represent the total volume of oil stored in the ground. Oil reserves are the amount of oil than can be produced with known technology at a given price. Although oil resources do not physically change on human time scales, our ability to estimate resources does change with technology and knowledge of new types of oil deposits. And reserves change routinely—commonly upward—with improved technology and price variations.

Oil reserves and present-day production are not evenly distributed across the globe (Fig. 6). In fact, 90% of the world’s current oil reserves are held by only 12 countries. The Middle East contains ~48% of the world’s oil reserves, with Saudi Arabia alone representing ~25%. Venezuela and Russia have the greatest reserves outside of the Middle East, with 8% and 5% respectively. The United States, China, Nigeria, and Mexico each have between 2% and 3% of the world’s oil reserves (BP Statistical Review of World Energy, 2012).

As we look to the future of oil, we see a gradual transition from conventional oil production from sandstone and carbonate reservoirs with relatively high porosity and permeability, to so-called unconventional reservoirs such as shale and other mudstones with very low porosity and permeability. The resource potential in unconventional reservoirs (heavy oil, oil shale, and shale oil) exceeds what has been produced to date from conventional reservoirs by 2x (Fig. 7). Other potential unconventional reservoir oil alternatives (gas to liquids and coal to liquids) represent another 2x of what has been produced to date.

The production potential is substantial, representing up to 4 million barrels of oil per day (MMpd) by 2020 from U.S. shale oil alone (Fig. 8). For reference, current U.S. production of oil is ~5.5 MMpd and peaked in the early 1970s at ~10 MMpd.

Unconventional oil reservoirs usually require special completion techniques, such as horizontal drilling and hydraulic fracturing in the case of shale oil or steam-assisted gravity drainage (SAGD) in oil sands, to allow the oil molecules to flow from the very low permeability rock into the wellbore. As such, given present-day technology and oil price, unconventional reservoirs are more expensive to develop than conventional reservoirs, ranging from $40 to over $70 per barrel in the current shale oil plays in the United States (Fig. 8) and $60 to $70 in the oil sands of northern Alberta, Canada (Tinker and Lynch, 2012).

**Technology and the role of geosciences.** In terms of achievement in advanced technology, the oil and gas industry rivals the military, National Aeronautics and Space Administration (NASA), and medicine, and any sort of attempt at comprehensive review here would be inadequate. Several key technologies will be discussed and not repeated later in the section on natural gas. The discovery and production of conventional oil includes exploration, drilling, transportation, refining, and production of petrochemicals; these processes involve a gamut of geologic expertise throughout. As production of oil transitions from conventional reservoirs to unconventional reservoirs, the technical challenge becomes more difficult, requiring comprehension from the nanopore, micropore, and macropore all the way up to the massive reservoirs.
Figure 7. Estimate of oil resources by resource type against the cost to produce a barrel of oil. The vertical white line separates oil produced to date from remaining potential resources. MENA—Middle East North Africa; EOR—Enhanced Oil Recovery. Source: IEA World Energy Outlook (2009).

Figure 8. Forecast of liquids production from U.S. shales. MMpd—million barrels of oil per day. Source: Morse (2012).
way to kilometric-scale natural and induced hydraulic fracture arrays, which in spite of their size are extremely challenging to observe. Scientific inquiries into these aspects of the geology of shales and other mudstones include an array of new approaches and methods: organically hosted nanoporosity, molecular-scale flow in porous media, micro sedimentology and stratigraphy, and the role of mechanical stratigraphy and natural fractures in the growth of hydraulic fractures. These scientific fields are in their very early stages.

On the upstream side, geoscientists are applying new technology to advance understanding of outcrops, rock cores cut in wellbores, and petrophysical and geophysical data. Again, an exhaustive examination is impossible, but some examples will serve to highlight advances being made. In outcrop analysis, ground-based light ranging and detection (lidar) allows for the collection of extremely high resolution (2-cm vertical accuracy) topographic data (Bellian et al., 2005). The data can be rendered in 3D and used to map stratigraphy and structure, among other things (Janson et al., 2007). In addition, the full-spectrum waveform can be collected, analyzed, and mapped, providing significantly enhanced and “continuous” data density (5 cm by 5 cm) that can be used with other rock observations to significantly improve understanding of lithofacies distribution, heterogeneity, and relationship to structural features such as fractures (Bellian et al., 2007). For unconventionals as well as many other fractured reservoirs, a key recent development is the appreciation of the importance of mechanical and fracture stratigraphy and their sometimes complex or nonintuitive relationship to lithostratigraphy (Laubach et al., 2009). These concepts are central to understanding how the rock responds to engineering perturbations such as drilling and hydraulic fracturing.

In well cores, advanced tools such as atomic force microscopy (AFM) document nanometer-scale pore systems, prompting modeling attempts to define fluid flow behavior that may take researchers beyond Darcy’s Law (Javadpour, 2009). High-resolution scanning electron microscopy (SEM) allows scientists to image pore throats just a few nanometers across in mudstones (Loucks et al., 2009, 2012), and when SEM is combined with cathodoluminescence, the paragenetic history of cementation phases (Laubach et al., 2004). Combined with fluid inclusion analysis, this permits researchers for the first time to determine fracture timing (Becker et al., 2010) and thus rigorously test predictive models of fracture growth and permeability (Olson et al., 2009), key elements in unconventional reservoirs. These analysis tools are combined with structural, geomechanical, and geochemical modeling approaches in the field of structural diagenesis (Laubach et al., 2010) to unravel the properties of these diagnostically and structurally complex rocks. In addition, the use of element and isotope chemostatigraphy is providing significant advances in defining variations in depositional environments, depositional processes, sediment flux, redox conditions, and diagenesis in cores and outcrops (Rowe et al., 2008).

Well logs are devices that measure various acoustic, electrical, nuclear, and magnetic properties of the subsurface rock by dragging a tool combining a signal source and receiver on a wireline up the wellbore. The recorded data are deconstructed by petrophysicists using sophisticated algorithms to provide remarkable understanding of the rock fluid system. Recent advances are improving geophysical measurement while drilling (MWD: geophysical downhole measurements that are transmitted to the surface while drilling a well). Although 3D reservoir modeling has been around for nearly 20 years (Tinker, 1996), researchers are now combining high-resolution outcrop measurements from lidar with advances in core analysis, petrophysics, and geophysics to develop structurally and stratigraphically complex 3D and 4D (time series) numerical models of the subsurface (Bellian et al., 2005; Janson et al., 2007). Such models are used to help with exploration, development, and advanced recovery of oil and natural gas.

Geophysicists use a variety of sound sources, including vibrating trucks and small explosions, to send vibrations into the ground and capture the reflections created by subsurface impedance contrasts. Geophysical data record velocity, distance, and direction of the primary and secondary waves, which are deconvolved using extremely sophisticated algorithms and massive supercomputers. The subsequent images of the subsurface allow geologists and geophysicists to interpret and model the extremely complicated structural and stratigraphic history. Advances in geophysical acquisition include such things as independent simultaneous sourcing, whereby several sound sources distributed in random arrays are activated “simultaneously,” resulting in faster data acquisition, greater data density, and improved imaging (Fomel and Jin, 2009); and 4D seismic, whereby several 3D seismic surveys are run with similar parameters over calendar time, allowing examination of changes in the rock/fl uid system happening on the developmental time scale (Lumley, 2001).

A new area of subsurface data collection being led by the Advanced Energy Consortium at the Bureau of Economic Geology at The University of Texas at Austin is driving pre-competitive research in subsurface micro- and nanotechnology, with an emphasis on sensors and materials, to reveal directly the location of fluids and/or measure the subsurface interwell chemical and physical properties, improving reservoir illumination and enhancing recovery from existing oil and gas fields (Halford, 2012). Data collected from these interwell sensors will add a new source of information to existing seismic, well log, and core data.

In the downstream, offshore wells are being drilled in nearly 2 miles of water depth and another 3–5 miles of sediments and rocks. Wells are also being drilled in remote arctic areas and extreme desert conditions, and from high elevations down to coastal jungles in hurricane-prone regions. The drill string can target a specific depth window several miles below the surface, then turn and drill horizontally for several thousand feet and be “geo-steered” in real time to stay within a 10-foot-tall window of rock. Multiple wells are being drilled from the same surface pad. Remote vehicles and infrastructure are routinely placed on
the ocean floor and pipelines take liquids along the seabed to the shoreline. Suffice it to say that the downstream sector of the oil and gas business is an engineering-dominated, high-risk, capital-intensive, and indispensable global industry.

**Benefits and challenges.** The energy density of oil is extremely high, which means that, compared to other fuels, oil contains a lot of energy in a relatively small volume. It is also fairly low in mass. The process of oil refining is well understood and the global infrastructure for oil is highly developed. But oil has several disadvantages compared to other fuels.

Because of its chemistry, the combustion of oil products releases sulfur dioxide and carbon dioxide (CO₂) into the atmosphere; roughly one-fourth of global CO₂ emissions come out of vehicle tailpipes (IEA, 2005). Oil also contains benzene, which can have negative health effects. Oil supply is vulnerable to hazards such as severe weather, earthquakes, and war. As the number of cars increases (Fig. 5), the demand for oil also increases. New reserves are typically found in more extreme locations and are therefore more expensive to produce. Oil from politically unstable regions is subject to volatile prices. The world’s largest oil-consuming countries spend billions of dollars and huge political capital each year trying to maintain stability in oil-producing regions. The environmental threat from accidents can be severe. The potential exists for leakages and spills from supertankers, pipelines, oil platforms, and oil wells. Remediation of serious accidents is difficult, time consuming, and expensive.

But the biggest challenge with oil is that it is virtually the only transport fuel: 97% of global transportation runs on it. This near absence of substitutes gives oil an excessive influence on the global economy, which can be good when low oil prices help the economy but bad when high oil prices are followed by recession. Even today, any severe shock to the global supply of oil could cripple the world economy. The solution, as in a financial portfolio, is to diversify into other transportation fuels. As oil prices rise in the future, alternatives will become more competitive, and will capture a greater share of the market. In the meantime, sources of unconventional oil in sands and shales will help to keep oil affordable longer, allowing this transition to happen smoothly.

**Transportation: Oil Alternatives**

The high energy density of gasoline, diesel, and jet fuel is hard to match. Biofuels offer a liquid alternative, as do compressed natural gas (CNG), liquefied natural gas (LNG), and gas-to-liquids and coal-to-liquids refining, but each of these has challenges. Non-liquid transportation alternatives include electric vehicles and fuel cells and will be discussed in the section on electricity.

**Biofuel**

**What is it and how is it used?** Biomass is organic material containing energy from the sun that has been stored chemically. Plants absorb solar radiation through photosynthesis and convert it into chemical energy in the form of glucose, a sugar. Burning biomass releases stored chemical energy as thermal energy (heat). Biomass can also be converted to other, more convenient forms, often known as biofuels. Sugar can be fermented to make alcohol, a flammable liquid fuel. Plant oil or algae can be converted into diesel (U.S. EIA, 2012b).

The two most common types of biofuels are ethanol and biodiesel. Ethanol is a clear, colorless liquid commonly found in alcoholic beverages produced through fermentation and distillation. Biodiesel is made from vegetable oils and animal fats. Both ethanol and biodiesel are used primarily for transportation in internal combustion engines and thus can serve as a substitute for fossil fuels.

Typically, biofuels are blended with a petroleum-based fuel. Any gasoline-powered vehicle can use a fuel mixture that contains up to 10% ethanol without suffering damage to the engine or fuel system. Cars and light trucks built after 2007 are able to handle up to 15% ethanol. Some vehicles, known as flexible fuel vehicles, are able to use fuel mixtures that are up to 85% ethanol. In 2011, almost 14 billion gallons of ethanol were added to the ~135 billion gallons of gasoline consumed in the United States (U.S. EIA, 2012b). Biodiesel use is relatively small compared to that of ethanol. In 2011, slightly over 950 million gallons of biodiesel was produced in the United States (U.S. EIA, 2012b). Diesel-based fuels that contain up to 20% biodiesel can be used by most diesel-powered vehicles.

**Resources.** Almost any plant-based material can be an ethanol feedstock, but some plants are easier to process into ethanol than others. Today, ethanol is produced from three main types of feedstocks: starch-based, sugar-based, and cellulosic. Starch-based feedstocks are grains, such as corn, sorghum, wheat, and barley, which contain long, complex chains of sugar molecules. Due to its abundance and low price, corn is the feedstock for ethanol production in the United States (Texas Comptroller of Public Accounts, 2008). Sugar-based feedstocks, which include sugar cane and sugar beets, contain smaller, simple sugar molecules. Sugar-based feedstocks are more commonly used outside of the United States. With an ideal climate for the cultivation of sugar cane, Brazil is the world’s second-largest ethanol producer (after the United States) and can produce ethanol that is cheaper than gasoline. However, for most countries, ethanol is relatively expensive to produce and has the disadvantage of requiring significant amounts of farmland, water, fertilizer, and energy to produce.

The newest biofuel process breaks down the cellulose of the plant, its woody structure, into sugars that can be fermented. The most promising feedstocks have been perennial grasses that can be planted once and then harvested for many years (Fig. 9). Such grasses can grow on land that may not be suitable for food crops, and need less water and fertilizer. In colder climates, fast-growing shrubs and trees are well suited; lumber and food wastes are also very promising potential feedstocks. But so far cellulosic fuel is experimental and has been hard to scale up into pilot plants. There are no large-scale commercial plants in the world,
in part because of uncertainties about the potential profitability of cellulosic ethanol (Bullis, 2012).

There is a limit to the capacity of soil and water to grow biomass. Biofuels currently make up only a small fraction (0.2%) of the gasoline consumed worldwide. But the contribution of biofuels is expected to grow, with positive impacts including reductions in greenhouse gases, improved energy security, and new income sources for farmers (de Fraiture et al., 2008). However, unless significant improvements in yields are realized, the increased production of biofuels will result in more land used for feedstock production. “It is estimated that 3.7 million additional acres will be required to produce 15 BGY [billion gallons per year] of corn ethanol in the United States in comparison with their baseline estimate of 12 BGY ethanol from corn in 2016. This increase in land use, especially the increase in the use of marginally productive lands, is likely to also result in increased water, fertilizer and pesticide use, and soil lost to erosion” (Powers et al., 2010, p. 255).

**Technology and the role of geosciences.** Two types of facilities exist for the production of ethanol from starch-based feedstocks—dry mill and wet mill—the main difference being in the initial treatment of the grain. Dry mill is the most common production method in the United States, owing to the lower cost. The process of producing ethanol from sugar-based feedstocks is simpler because they do not need to be heated and require no added enzymes. Instead, they need only to be treated with yeast, which eats the simple sugars contained in the feedstocks to produce ethanol. Producing ethanol from cellulosic feedstocks is more complicated because it is difficult to break down the long chains of sugar molecules that comprise cellulosic materials into usable sugars that can be treated with yeast. Current methods for treating the feedstocks include treatment with an acid such as sulfuric acid, heat treatment, and exposure to expensive, specially selected enzymes. Biodiesel is produced by chemically reacting alcohol (commonly methanol) and the animal fats in biodiesel feedstocks. Substances are added to the mixture to speed up the chemical reaction, which creates organic chemical compounds called esters, the main components of biodiesel.

The role of geosciences in biofuels revolves in part around water, soil science, hydrogeology, fertilizers, weather, climate, and other aspects of agriculture to produce feedstocks. Remote sensing such as airborne lidar and satellite-based instruments (e.g., Interferometric Synthetic Aperture Radar [InSAR]) are also being used to measure biomass, monitor crops, and study moisture patterns. Since the 1950s, global irrigated agriculture has expanded by 174%, accounting for 90% of fresh-water consumption (Scanlon et al., 2007). Feedstock water requirements range from “500 to 2000 liters of water per liter of ethanol produced to approximately 1000 to 4000 liters of water for soybeans per ethanol-equivalent liter of biodiesel. By contrast, ethanol conversion facilities use only 2–10 L of water per liter of ethanol produced” (Powers et al., 2010, p. 256). However, biomass production for energy will also compete with food crops for scarce land and water resources, already a major constraint on agricultural production in many parts of the world (de Fraiture et al., 2008), especially regions where water supplies are already stressed.

**Benefits and challenges.** Biofuels offer a number of benefits over fossil fuels. They can reduce dependence on imported fossil fuels and thus reduce net carbon dioxide emissions. Biofuels are biodegradable and safer to handle than fossil fuels, making spills less hazardous and easier to clean up. In time, biofuels may reach cost parity with fossil fuels. If so, however, the sheer acreage required to fuel global transportation will be a limiting factor (NCEE, 2012).

In addition to the large water demands, there are a number of disadvantages to certain biofuels, such as corn ethanol, which could result in higher food costs and potential food shortages (Timilsina et al., 2012). More land will be needed to grow more crops, which could contribute to deforestation and soil erosion. Finally, biofuel production can produce strong and noxious smells, which are undesirable to nearby communities (U.S. EPA, 2011).

**Natural Gas**

**What is it and how is it used?** Natural gas is the general name for several forms of produced gas, dominantly methane, but also including propane, butane, pentane, and other natural gases in lesser amounts. Natural gas is the most versatile of the primary energy sources, because it can be used to generate electricity; for heating, cooling, and cooking; and directly in vehicles as CNG or LNG. As a source of energy, natural gas is readily combustible, gives off few emissions, and is abundant in the United States and globally. Common household uses include cooking, space heating, cooling, and drying. More than half of the homes in the United States are heated by natural gas, and an increasing number of homes are cooled by gas-powered air conditioners (American Gas Association, 2008). Between 1986 and 1999, the number of newly constructed single-family homes...
With increasingly stringent controls on emissions, the advantages of cleaner-burning and now very affordable natural gas are becoming more widely recognized.

**Resources.** The earlier discussion in the section on oil regarding resources and reserves applies for the most part to natural gas and will not be repeated. The U.S. Energy Information Administration calculates that in the United States there are 2543 trillion cubic feet (Tcf) of technically recoverable resources (U.S. EIA, 2011a). This includes undiscovered, unproved, and unconventional natural gas. The National Petroleum Council suggested in 2011 that technically recoverable resources ranged from a low of 1700 Tcf to a high of 3600 Tcf (Fig. 11). Through time, even after accounting for natural gas consumption, reserve estimates continue to climb, which means that new reserves are being discovered and known resources are being converted to reserves at a pace greater than consumption.

The largest conventional natural gas basins in the United States are located in Texas and the Gulf of Mexico. Recently, natural gas has begun to be extracted from unconventional reservoirs such as coal, tightly cemented sandstone, and shale. Globally, these unconventional reservoir resources are estimated to exceed 4x or more the total conventional reservoir resource base (Fig. 12). Other potential sources, such as sour gas, arctic gas, and deep-water gas, could add an additional 4x, and methane hydrates could add significantly more.

In the United States, unconventional gas reservoirs today account for over half of annual natural gas production (Fig. 13). Shale gas is the most recent of the unconventional gas reservoir types to be developed, today accounting for 25% of U.S. natural gas production (Fig. 14).

Shale gas reserves and production are growing rapidly, and current and prospective shale plays are located across North America (Fig. 15) and in many sedimentary basins around the world.

As with unconventional oil reservoirs, unconventional gas reservoirs, such as shale, usually require horizontal drilling and hydraulic fracturing to maximize recovery and, therefore, unconventional gas reservoirs are more expensive to develop than conventional reservoirs.

The U.S. Energy Information Agency estimates world proved conventional natural gas reserves to be ~6675 Tcf. The Middle East represents 40% of the world total (~2686 Tcf). Europe and the former Union of Soviet Socialist Republic countries possess 35% of total world reserves (~2331 Tcf). In comparison, the United States accounts for ~4% of the world’s reserves, yet produces and consumes ~25% of global natural gas production annually (U.S. EIA, 2011c). Global estimates of unconventional natural gas resources are not yet robust, but, based on U.S. experience to date, the potential far exceeds conventional natural gas. A current study being conducted at the Bureau of Economic Geology and funded by the Alfred Sloan Foundation focuses on U.S. shale gas. This study brings engineers, geoscientists, economists, and industry experts together to assess the resource, reserve, and production outlooks for four of the largest U.S. natural gas shale basins and represents the most comprehensive public study known to date.
Figure 11. U.S. technically recoverable natural gas resources (i.e., those resources that can be recovered without regard to economic constraints). Note: The Minerals Management Service no longer exists. Its functions are administered by the Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE). Source: NPC (2011).

Figure 12. Natural gas resources as a function of production cost. Source: IEA World Energy Outlook (2009).
Figure 13. U.S. annual natural gas production in trillion cubic feet (Tcf) with unconventional reservoirs (tight, coalbed, and shale) representing over 50% of U.S. production. Source: U.S. EIA (2012a).

Figure 14. U.S. annual natural shale gas production in trillion cubic feet (Tcf). Source: Boyer et al. (2011).
Technology and the role of geosciences. The role of technology and geosciences discussed in the section on oil applies almost in whole to natural gas and will not be repeated. In addition, extensive natural gas resources are known to exist as clathrates or hydrates (natural gas locked in ice) in onshore permafrost regions and near continental margins at ocean depths between 1000 and 15,000 feet where temperature, pressure, and organic conditions are the most favorable (World Ocean Review, 2010). Geosciences are needed to characterize these vast hydrate deposits geophysically, and to understand the rock physics in order to eventually realize engineering solutions to produce the resource.

Methane is a greenhouse gas, released naturally in seeps and by animals as part of the digestive process, as well as from oilfield operations. Methane is found in subsurface formation waters globally, but in varying, usually very low, concentrations. Because natural gas represents such a vital global energy resource, geoscientists will be studying natural gas for the next century or more.

Benefits and challenges. The use of natural gas has certain advantages: natural gas is one of the cleanest burning fossil fuels, emitting 45% less carbon dioxide during combustion than coal and 30% less than oil (U.S. EIA, 1999). Importantly, the combustion of natural gas does not produce soot, ash, mercury, or much sulfur or nitrogen. Natural gas has a high heating value, ~24,000 Btu per pound, and can be transported fairly easily via pipelines and in the form of LNG on transoceanic tankers. Natural gas can be compressed or liquefied and used as fuel in vehicles, with cleaner properties than gasoline or diesel. Some of the byproducts from refineries can be used in the production of pharmaceuticals, industrial chemicals, paints, plastics, and ammonia for fertilizers. Natural gas dissipates quickly in air, does not pool like heavier hydrocarbons and, in small volumes, is nontoxic to humans. Importantly, owing to increased production from unconventional gas reservoirs in North America, natural gas is now very affordable on a Btu basis relative to all other fuels, and for this reason it has replaced coal in power production to such an extent that, combined with the economic slowdown, the United States has reduced CO$_2$ emissions by over 10%, down to 1992 levels (U.S. EIA, 2012d)—a reduction deeper than any other developed nation, even those with carbon taxes or cap-and-trade policies, has achieved.

Natural gas also has disadvantages. Like all fossil fuels, natural gas is nonrenewable. The infrastructure required for natural gas, in particular interstate, intrastate, and distribution pipeline networks, is costly. Natural gas is directly flammable, and when gas leaks in confined spaces, there is a strong potential for explosion.
Environmentalists are mostly positive about natural gas, but some are concerned about hydraulic fracturing. The oil and gas industry has been practicing hydraulic fracturing for 60 years, but never before on the current scale. There is concern among some members of the public that hydraulic fracturing poses a risk of contaminating water supplies. The data regarding hydraulic fracturing indicate that there are very few, if any, cases in which a hydraulic fracture was propagated from the deep reservoir zone to a near-surface aquifer (Anderson, 2012; Rao, 2012). Nonetheless, there are on occasion local surface environmental issues associated with all oil and gas operations, including hydraulically fractured wells. These can include truck spills, storage pit or tank leaks, surface casing leaks, and natural gas leaks associated with pipeline and valves (O'Sullivan and Paltsev, 2012; Rao, 2012). Methane, the major component of natural gas, is a powerful greenhouse gas, 21 times more heat absorbive than carbon dioxide. This is countered, somewhat, because the lifetime of methane in the atmosphere is ~12 years, whereas carbon dioxide, although less heat absorbive, lasts for 5–200 years (IPCC, 2001). Regardless, for many reasons, it makes sense to minimize methane emissions.

By definition, hydraulic fracturing causes small earthquakes in the subsurface, but these are rarely felt at the surface. There can be larger, but to date nondamaging, earthquakes associated with reinjection of produced fluids. Again, these are local, not regional events but there must be continued public education, industry transparency, and cooperation between natural gas producers and regulators to reduce these risks and continue to improve what has actually been a good safety and environmental record.

In addition to biofuels and natural gas, there are other potential alternatives to oil products in the transportation sector. These include plug-in hybrids, fully electric vehicles, and vehicles powered by fuel cells that produce hydrogen. These technologies will not be discussed further here, other than to note that fuel cells use natural gas as feedstock and batteries require rare-earth elements, so all involve geosciences to some degree.

**Electricity: Coal**

Coal is a globally abundant, affordable, and reliable source of fuel for electricity generation. Not surprisingly, coal is the most widely used fuel for electricity generation.

**What is it and how is it used?** Coal is an organic sedimentary rock, consisting mostly of carbon with some hydrogen, sulfur, oxygen, and nitrogen. Coal is formed by the compaction and hardening of plant remains, deposited most commonly in coastal swamps, eventually forming a soggy, dense material called peat, which can later form coal. Coal typically occurs in seams a few meters thick, often interbedded with shales and sandstones, although some coal seams can reach thicknesses of more than 30 m. Coal seams can extend for hundreds, and sometimes even thousands, of square kilometers.

Power plants use the heat from burning coal to boil water, making steam that turns turbines and drives electric generators. In the United States, there are more than 500 coal-fueled power plants; this number has been decreasing as older plants are replaced by natural gas plants, reaching the point in 2012 at which coal and natural gas were used in equal proportions (~32% each) for power generation (U.S. EIA, 2012i). Globally, percentages of coal for power are higher, around 40%, but vary substantially by region (IEA, 2011).

**Resources.** The United States has an estimated 260 billion tons of coal deposits that can be recovered and used (U.S. EIA, 2010). This represents ~30% of the world’s known reserves (U.S. EIA, 2012h)—enough to last more than 200 years, based on the rate at which coal is used today. The amount of coal produced in the United States in 2011 was just over one billion tons (U.S. EIA, 2012f).

In the United States, coal production is spread across three regions (Fig. 16). The Appalachian Coal Region contains much of the nation’s high-quality, Paleozoic bituminous coal and almost all of its anthracite. Coal in the Western Coal Region is mostly Mesozoic lignite and bituminous. This area includes Wyoming and the Powder River Basin and contains the largest coal mines in the world. Low-quality Cenozoic lignite is abundant in the Interior Coal Region, with Texas being the largest producer. Coal is mined in 26 states with almost 41% of all the coal produced in the United States coming from Wyoming (443 million tons in 2010). The next-highest coal-producing states are West Virginia (135 million tons), Kentucky (105 million tons), Pennsylvania (59 million tons), and Montana (45 million tons) (U.S. EIA, 2010).

**Technology and the role of geosciences.** Coal found at depths less than 50 m can be extracted by surface mining, which accounted for 68% of the coal produced in the United States in 2011 (Fig. 17) (U.S. EIA, 2012c). Topsoil is removed first and set aside to be used later in reclaiming the land. Explosives are used to break up rock above the coal seam and draglines, wheel excavators and huge shovels expose the coal. The coal is drilled, fragmented, loaded into gigantic trucks, and hauled to nearby trains to be transported to power plants. The mine moves across the landscape several thousand feet a year as mined rock is returned to the site, the topsoil is replaced, and vegetation is replanted to reduce the environmental impact.

Underground mining methods are used where coal seams lie at depths greater than 50 m. Coal is removed from the ground through networks of tunnels and passages. The most common type of mine is the shaft mine, which involves cutting vertical shafts to the coal. Underground mining operations rely on heavy tunneling and extracting equipment. For example, longwall mining machines have massive shearsers that cut coal from a wall face; the coal then falls onto a conveyor belt for removal.

The location of most coal resources is reasonably well known, so mining for coal does not require extraordinary geologic expertise. However, to make coal “clean,” CO₂ must be removed either pre- or post-combustion and then stored or sequestered. This is called carbon capture and storage (CCS). Although terrestrial and oceanic storage of CO₂ is possible, by far the greatest
Figure 16. Coal type and production in the United States, in million short tons per year. Source: U.S. EIA (2012c).

potential for large-scale sequestration is geologic: injection and trapping of CO₂ in rock pore space filled with saltwater brine. Geologic sequestration involves geologic input throughout, including structural and stratigraphic mapping, sedimentology, stratigraphy, petrophysics, geochemistry, seismic imaging, reservoir characterization, modeling, and simulation.

The U.S. Department of Energy (U.S. DOE) created seven regional partnerships in the early 2000s to study various sequestration options. Some of the partnerships have done pioneering work in monitoring and modeling large-scale injection. Some international work in Canada, Australia, Europe, and Asia has also pushed the science and engineering (Global CCS Institute, 2009). The Gulf Coast Carbon Center has led a number of important “firsts,” including the first brine injection in Frio I and II, and, at Cranfield, the first injections to surpass 1 million and, later, 3 million tons (Hovorka et al., 2006, 2013).

An affordable and safe process for injection and long-term storage of billions of tons of CO₂ every year is required if the world is to someday capture and store enough CO₂ to have an impact on the climate system. Barring a price on carbon via a tax or cap-and-trade scheme, the best impetus for carbon storage is the Gulf Coast Carbon Center has led a number of important “firsts,” including the first brine injection in Frio I and II, and, at Cranfield, the first injections to surpass 1 million and, later, 3 million tons (Hovorka et al., 2006, 2013).

An affordable and safe process for injection and long-term storage of billions of tons of CO₂ every year is required if the world is to someday capture and store enough CO₂ to have an impact on the climate system. Barring a price on carbon via a tax or cap-and-trade scheme, the best impetus for carbon storage is likely to be via the process of enhanced oil recovery (EOR), which uses CO₂ to change the viscosity of oil in a reservoir and alter the wettability of the rock-fluid system. This has been called CCUS (carbon capture utilization and storage) by the U.S. Department of Energy. Certainly some CO₂ will be permanently stored in oil fields as CO₂ displaces oil (MIT Energy Initiative and Bureau of Economic Geology, 2010). But more importantly, by coupling CCUS with an initial economic driver, EOR, much of the expensive surface infrastructure such as compression, pipelines, and injection wells will be paid for by the oil and gas industry. Once this infrastructure is in place, the further injection of CO₂ for the sole purpose of storage will be affordable and practicable. In this way, CCUS has the potential to become an outstanding example of a partnership between government, industry, and academia, by which needed compromises are reached and all sides benefit—a positive model for how to address other major energy challenges.

**Benefits and challenges.** Nearly every major country has an available domestic coal reserve. Coal is easy to mine, transport, store, and turn into electricity. Because coal is available, it is cheap; coal electricity is the cheapest in the world, although natural gas is now competitive with coal in the United States. Because electricity goes into every product and service, cheap electricity makes everything else more affordable, an extremely important advantage to developing countries.

But coal has some downsides too, and the biggest is that it is “dirty.” For example, in surface mines, removed rock overburden is stored near the mine until it is used to fill the pit. In many cases, this rock contains pyrite (FeS₂), which can form sulfuric acid that flows into streams and rivers, impacting fish, plants, and aquatic animals. This FeS₂ can also percolate into the ground, leaching heavy metals from rock and depositing them in the groundwater system (U.S. EIA, 2012f). Underground mines can collapse, and

natural gas and coal dust released during mining can be harmful to human health.

The burning of coal emits sulfur dioxide (SO₂) and nitrous oxides (NOₓ). These oxides react with water vapor in the air to form droplets of sulfuric and nitric acid that cause damage to vegetation and create acidic streams and lakes. Coal-fired power plants emit carbon dioxide, and there is not a single coal plant in the world that captures and sequesters its CO₂. As a result, nearly half of all humankind CO₂ emissions are produced by coal combustion. Burning coal produces particulates and large volumes of ash. The best coal plants capture some of this ash, but many do not. Efforts are being made to control the gases emitted by coal-fueled power plants. For example, scrubbers are currently used in most coal plants to remove some of the most harmful pollutants, especially sulfur dioxide and some of the mercury.

**Electricity: Alternatives to Coal**

Although coal is not easy to replace, there are several viable options including natural gas, hydroelectric, geothermal, wind, solar, and nuclear. Natural gas was discussed in the transportation section, so we will begin with hydroelectric.

**Hydroelectric Energy**

**What is it and how is it used?** Hydroelectric energy, also referred to as hydroelectricity, hydropower, or simply hydro, is generated by converting the kinetic energy of flowing water into mechanical and then electrical energy. As with coal and natural gas, the process involves the use of turbines, but instead of using heat from combusting coal or natural gas, hydro uses moving water.

**Resources.** There are three main sources of hydroelectric power: waves, tides, and rivers. Waves contain an enormous amount of energy because of their constancy. New technologies to capture wave energy are currently under development. These include channeling waves into catch basins and using devices anchored to the ocean floor. But waves are a low-density form of energy, meaning a lot of area is required to generate a substantial amount of electricity (EPRI, 2011).

Tidal energy comes from the Earth’s rotation and from the gravitational interactions between the Earth and the Moon. Earth experiences two high tides and two low tides every day. Tidal systems typically involve a barrier that is built across the mouth of a bay where water is trapped at high tide and then released at low tide and used to drive a turbine. Large-scale tidal power plants are in operation in France and South Korea. Like wave power, tidal power will likely never be more than a regional electricity supplement (Georgia Tech Research Corporation, 2011).

There are two basic types of stream and river systems used in hydroelectric power plants to produce electricity. One utilizes the natural flows of streams and rivers and the other is based on falling water. The first, called a run-of-the-river system, diverts water from a river into a canal or large pipe, called a penstock, where the water turns a turbine. These systems are subject to seasonal variations in river flow.
The second system is called a falling-water system, or a dam, and requires the right combination of water and landforms, ideally with consistent rainfall. Under the force of gravity, water falls through a penstock and turns a turbine. Hydroelectric power plants range in size from small systems for a home, farm, ranch, or small community to large plants that supply electricity to consumers on a regional scale. The amount of electricity produced by a hydroelectric power plant is directly related to the height of the dam, the volume of water available to flow through the dam, and the rate at which the water flows. The greater the volume of water in the reservoir and the faster it flows through the dam, the more electricity the plant can produce. The largest dam in the world, the Three Gorges Dam in China, has a capacity that exceeds 20,000 megawatts (MW). The largest hydroelectric power plant in the United States, the Grand Coulee Dam in Washington State, produces almost 7000 MW of electricity. Today, there are hundreds of hydroelectric power plants across the United States (Fig. 18). In 2011, almost 8% of total U.S. electricity was generated from stream-fed hydroelectric power plants (U.S. EIA, 2012e).

**Technology and the role of geosciences.** Hydro can provide always-on baseload power, or can follow electricity demand by the minute. Although hydroelectric dams are expensive to build and have a high environmental impact, they are cheap to operate and may last for a hundred years. The best location for a dam is where a river passes through a constriction such as a canyon or gorge. Geosciences help to determine whether the bedrock on which a dam is to be built is stable and strong enough to support the weight of the dam and the reservoir, along with the pressure of the water stored in the reservoir. In Norway, rather than being built as standard dams, hydro plants are built inside excavated chambers located inside a mountain at depths ~500 m; the turbines are powered by surface water gathered from streams by a pipeline network. But in most places, the topography is not suitable for such a system.

As population and development increase, so does the demand for water for all applications, including industry, power generation, and agriculture. Compounding the critical role of water, climate change could bring more droughts and hotter summers to many regions. Hydrogeologists are needed to help understand regional water systems. The spots suitable to build hydroelectric dams are limited. In the developed world, nearly all of these suitable spots have been used. The big hydro projects in the future will be in China, India, and elsewhere in the developing world. But there, as everywhere, damming a river has environmental, social, and economic impacts that not everyone is ready to bear.

**Benefits and challenges.** Using moving water to generate electricity offers a number of advantages over other energy sources. Hydroelectric power plants produce little air pollution compared to power plants that burn fossil fuels. Also, there is limited emission of thermal pollution compared to nuclear plants. Because they do not need to wait for water to be heated into steam, hydroelectric power plants can start generating electricity quickly and can make rapid adjustments in power output to match rising and falling demands. Additionally, reservoirs created by hydroelectric power plants offer a variety of recreational

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**Figure 18.** Hydroelectric power plants in the continental United States. Source: U.S. DOE (2004).
opportunities such as fishing, swimming, and boating. Other benefits may include drinking water supply, flood control, and water for irrigation (USGS, 2012).

Hydroelectricity has some negative impacts as well. Hydroelectric power plants that require the use of dams can greatly affect the flow of rivers, altering ecosystems and affecting the wildlife and people who depend on those waters. For example, the reservoirs created by dams may flood agricultural land, archaeological sites, and inhabited areas. Hydroelectric power plants affect fish populations as well. Dams can obstruct the migration of certain fish upstream to their spawning areas. Another problem is that the sediments carried by rivers and streams accumulate in reservoirs behind dams. Eventually, a reservoir will fill up with sediment, rendering the hydroelectric power plant inoperable. On occasion, dams can break, producing potentially devastating floods (U.S. EPA, 2012a).

Geothermal

Although geothermal energy is discussed here as an alternative to coal for power generation, it also has a major direct use in heating and cooling. Both will be discussed.

What is it and how is it used? Geothermal energy, the heat of Earth’s interior, can be found beneath our feet everywhere. But extracting enough of it, at an affordable price, is a challenge. The heat is utilized in two main ways. High-temperature geothermal is used to turn a steam turbine and make electricity. Like hydropower, geothermal electricity can be always-on baseload power, or can be ramped up quickly to follow demand. Higher-temperature geothermal energy can also be used to heat or cool buildings on a utility scale (widely done in Iceland) and lower-temperature geothermal energy uses the constant temperature of the near-surface to heat and cool buildings. Today, the installation of such distributed systems is typically more expensive than other heating and cooling options.

Resources. In some parts of the world, extreme heat from deep within the planet (up to 200 °C; 430 °F) rises nearer the surface. In these places, geothermal energy is fairly easy to tap, but these high-temperature geothermal areas are rare. Iceland is the best example: rich in geysers and hot springs, Iceland derives 66% of its energy supply from geothermal (National Energy Authority, 2012). Indonesia, Italy, California, and Hawaii all have exploitable high-temperature geothermal resources. In other places, old oil wells allow access to hot water. Researchers are also experimenting with drilling new wells, fracturing the surrounding rock, and circulating water as a means of power generation.

According to the International Geothermal Energy Association, both the capacity and production of geothermal energy increased by 20% worldwide between 2005 and 2010 (Jennejohn et al., 2012). The online capacity in the 24 major producing countries was 10,715 MW and is expected to rise to 18,500 MW by 2015.

While Iceland can supply most of its (relatively small) electricity needs from geothermal, it is the United States that ranks number one in both the capacity and production of geothermal energy (Fig. 19). In 2010, the United States had a capacity of 3086 MW (Jennejohn et al., 2012). This nearly equals the combined capacity of second-ranked Philippines (1904 MW) and third-ranked Indonesia (1197 MW). The development of geothermal resources in the United States has been stimulated by an increased focus on energy independence and clean energy production. Nine U.S. states produce geothermal energy: Alaska, California, Hawaii, Idaho, Nevada, New Mexico, Oregon, Utah, and Wyoming. In addition, Colorado, Louisiana, Mississippi, and Texas are developing geothermal installations. Yet, in 2010, geothermal energy contributed less than 0.4% of the total electricity produced in the United States (U.S. EIA, 2011b).

Owing to its geologic setting, California is the largest producer of geothermal energy in the United States with nearly 2600 MW of installed capacity (NREL, 2010). This is greater than any other country in the world. Geothermal energy supplies ~5% of California’s energy needs, enough for ~725,000 homes, or a city about the size of San Francisco.

Technology and the role of geosciences. A variety of techniques are used to explore for geothermal resources. For any potential site, an accurate geothermal model is needed to evaluate its scale, heat production, and expected lifetime. Many of the tools used are similar to those employed in exploration for oil and gas. In early stages, exploration involves field studies, mapping of bedrock and hydrology, and examinations of porosity and permeability. Geochemical studies are used to determine the expected temperature at depth, the uniformity of the water supply, and the source of the water that naturally recharges the system. Studying isotopes helps determine the characteristics of hydrothermal waters at depth. Geochemical studies combined with geological and hydrological studies provide valuable insights before the use of more expensive geophysical methods.

Geophysical methods are employed either at the surface or down boreholes. Measurements include temperature, electrical conductivity, magnetism, density, and response to seismic waves. Sensitive electrical measurements are very important for the detection of hydrothermal fluids. The application of these can often provide a good estimate of the temperature at the top of the reservoir. In the final phase of exploration, wells are drilled in key places and the data from wells are used to test the models and hypothesis made earlier during the investigation. Similar methods can be used to identify potential earthquake hazards associated with geothermal production.

The fundamental collection mechanism in liquid hydrothermal systems is the sampling of hot water, which rises because it is less dense than the fluids that surround it. Another technique is to drill a borehole to penetrate a hot body of rock and hydraulically fracture the rock by injecting water under great pressure. After this, a second well is drilled to allow the hot fluids to rise to the surface.

There are three main types of geothermal power plants (U.S. EIA, 2012g). Dry steam power plants use steam from the ground directly to turn a turbine (Fig. 20). Flash steam power plants use
Geothermal resource of the United States

Locations of identified hydrothermal sites and favorability of deep enhanced geothermal systems (EGS)

Figure 19. U.S. geothermal potential. Source: NREL (2009).
boiling geothermal water collected in a reservoir, where it flashes to steam under reduced pressures. Binary steam power plants use hot geothermal water to heat another fluid that has a lower boiling point than water. This fluid vaporizes to steam and drives the turbines. Binary plants are the most common because they can utilize lower-temperature geothermal fluids.

Direct heat is one of the oldest uses of geothermal energy and is used for bathing, space and district heating, agricultural applications, aquaculture, and some industrial uses. In agriculture, geothermal fluids are used to heat greenhouses. Livestock can be housed in a temperature-controlled environment that is beneficial to their health. Sanitation and sterilization are efficient uses of hot fluids. In aquaculture, controlled breeding temperatures are an essential factor for maintaining yields. Other potential industrial uses include process heating, evaporation, drying, distillation, washing, de-icing, and salt extraction.

Benefits and challenges. Geothermal power can be used directly as a source of heating, for cooking, and for health. Electricity can be produced cleanly without burning fossil fuels. Geothermal plants are relatively small compared to coal, nuclear, and natural gas power plants and are also cheaper to build and operate (U.S. DOE, 2012c). Geothermal energy is relatively inexpensive. Geothermal plants are largely self-sustaining and are not dependent on the global price of oil. Suppliers of geothermal power are often assisted by tax cuts by governments because geothermal energy promotes energy independence.

Several disadvantages to geothermal exist, although none are prohibitive. Geothermal plants can pose a threat of release of hydrogen sulfide and some geothermal fluids contain high concentrations of chemicals such as boron, fluoride, or arsenic (U.S. EPA, 1980). Small-scale ground-source heat pumps are initially expensive, making them prohibitive to many households. There are recent examples of earthquake concerns associated with geothermal plants (Moseman, 2009). Perhaps the biggest disadvantage to geothermal is that the geologic conditions required to produce geothermal energy do not occur everywhere.

Wind

What is it and how is it used? Air is a fluid and tends to move from areas of high pressure to areas of low pressure; the greater the differences in air pressure, the greater the motion. We know this as wind. The motion caused by wind can be used to turn a wind turbine and lift water or generate electricity.

Change in pressure is caused by the uneven heating of Earth’s surface by the Sun. When an area of Earth’s surface is heated, some of the heat will be transferred to the air above the surface where it will expand and become less dense, causing the air pressure to decrease. If an area nearby is heated less, the air above will become cooler and condense. The air pressure will increase and flow underneath the warm, less-dense air nearby. The lighter and less-dense air will rise. These movements create wind.

Winds caused by the unequal heating of Earth’s surface within a small area are known as local winds; they blow over short distances. Large-scale winds, such as monsoons, blow over large regions and are caused by large and consistent differences in air pressure between land and water that occur with the seasons. Global winds are winds that blow steadily over thousands of kilometers caused by unequal heating of Earth’s surface—hot near the equator and cool at the poles—and generally circulate air from the equator toward the poles.

Resources. A preferred location for a wind turbine is one where the wind is strong and constant. A number of factors must be considered. Generally, wind speed increases with altitude.
Ground obstructions, such as trees and buildings, act as wind-breaks and reduce the speed of surface winds. The best places to site wind turbines are exposed high areas, such as the tops of smooth, rounded hills or small mountains. Other good places are open plains, coastal areas, and offshore.

Today, the installed or nameplate capacity of the tens of thousands of wind turbines installed across the United States is close to 50,000 MW (American Wind Energy Association, 2012a). Texas leads with installed capacity of over 10,000 MW, followed by Iowa, California, Illinois, Minnesota, and Washington (Fig. 21). The electricity produced by all turbines throughout the United States is enough to power the equivalent of more than 9.7 million homes (American Wind Energy Association, 2012b).

**Technology and the role of geosciences.** The most common method for creating electricity from wind is through a wind turbine. Wind turbines convert the moving energy of the wind to mechanical energy, which is then used to produce electrical energy. Most turbines consist of a set of blades connected to a rotating driveshaft. The mechanical energy of the driveshaft is transferred through a gearbox to an electric conductor (coils of copper wire), which causes electrons to flow, generating an electrical field.

There are two main designs of wind turbines. The most common is the three-blade horizontal-axis turbine, which resembles an airplane propeller. Less common is the vertical-axis turbine. Generally, the electricity produced by a turbine is proportional to its size. For example, a household might use a small, 100 kW turbine with a blade length of one meter. Large commercial turbines can have capacities up to 5 million watts (5 MW) and blades between 40 and 50 m that sit atop towers up to 80 m tall.

Wind power plants, or wind farms, have a few dozen to several hundred commercial wind turbines and can cover tens of km² or, for the largest ones, more than 150 km² (Fig. 22). The electricity produced by the turbines is supplied to a power grid, often over long distances requiring major transmission lines. Geoscientists who understand climate, weather, and geomorphology are involved in development of major wind farms.

**Benefits and challenges.** Wind energy has a number of benefits. Once installed, wind is clean in terms of emissions, and most countries have some useable wind resource. Wind turbines are simple and relatively easy to build. Wind turbines are modular and can be built quickly and expanded as needed. And although the total land required is substantial, 95% of the land below the turbine can be used for other purposes, such as farming or cattle grazing. Wind’s most important benefit is that it is affordable—about the same price as natural gas or coal in the United States (U.S. EPA, 2012b).

But wind has a few downsides. Some people do not want to look at wind turbines. And the closer they are the less people want to look at them. Siting the turbines offshore removes them from sight but makes wind power much more expensive. If turbines are built far from cities, as in the Great Plains, then long-distance transmission is required, adding cost. In addition, the moving blades of a wind turbine can be noisy, cast shadows, and, depending on the technology and location, be harmful to bird and bat populations. On occasion, wind turbine motors ignite, and towers fall down. The biggest challenge is that wind is intermittent—power can only be generated when the wind is blowing. This necessitates a fast-starting power source, usually natural gas power plants, to back up wind power (U.S. DOE, 2011) or significant advances in energy storage.

**Solar**

Although solar energy is discussed here as an alternative to coal for power generation, it also has a major direct use in heating. Both will be discussed.

**What is it and how is it used?** The Sun, 330,000 times more massive than Earth, produces energy by joining hydrogen atoms into helium in its core, a process known as nuclear fusion; thus solar energy is really nuclear energy. These nuclear reactions make the Sun very hot, over 5500º C at its surface, and release enormous amounts of electromagnetic radiation. Visible light represents 43% of the total radiation emitted by the Sun, and ~50% of the energy emitted by the Sun is spread over wavelengths longer than those of visible light, mostly infrared. Wave-lengths shorter than visible light, including ultraviolet radiation, account for the remaining 7%. A variety of technologies are able to capture and convert solar energy into other useful forms of energy, such as heat and electricity.

**Resources.** Every place on Earth receives solar radiation, in amounts that vary with latitude, season, time of day, landscape, and weather. Latitude determines the angle at which solar radiation is received. Solar radiation hits the area around the equator at an angle of nearly 90º. Near the poles, solar energy strikes the surface at a much lower angle, which spreads the energy over a larger area. Solar radiation is also affected by the axis of Earth’s orbit around the Sun, which causes different parts of Earth to be tilted toward the Sun over the course of a year; closer in the summer and farther in the winter. The rotation of Earth causes daily variations in solar radiation; topography and weather, especially clouds, also impact solar radiation. The southwest United States receives more solar radiation than other U.S. regions because it is closer to the equator and often has little cloud cover (Fig. 23).

**Technology and the role of geosciences.** In order for solar radiation to be used as an energy resource, it must be converted into other types of energy. It can be converted to thermal energy and used for a variety of purposes, including heating homes, buildings, and water. In passive solar heating systems, buildings are designed to receive large amounts of sunlight through large, south-facing windows with overhangs. In winter the sunlight shines directly through the large windows and in summer the high Sun is blocked by the overhang. Active solar heating systems use a collector, commonly a large, flat panel, to absorb solar radiation. Air or a liquid is pumped through the panel, where it is warmed and used to heat the building or for washing dishes or clothing.

In active systems, solar radiation is converted into electricity, either via concentrated solar power or photovoltaic cells. Solar
Figure 21. Installed wind capacity. Source: NREL (2012).

Figure 22. The Roscoe Wind Farm in Texas has more than 600 hundred wind turbines. Source: Tinker and Lynch (2012). Photo courtesy Wilson Waggoner.
towers use large mirrors to focus the Sun’s energy and boil water, making steam to turn a turbine. Parabolic trough mirrors reflect and concentrate solar radiation onto pipes containing synthetic oil, which heats up and circulates next to water pipes; the water boils and generates steam (Fig. 24). In other words, in mirrored systems, solar radiation is converted to thermal energy in steam, mechanical energy in the turbine, and finally electrical energy through the generator.

Concentrated solar power technology is relatively new. Today, there are around ten such plants in the United States, including several in California and Arizona, one in Nevada, one in Florida, one in Colorado, and one in Hawaii (NREL, 2011). Solar radiation can also produce electricity directly through photovoltaic cells, commonly known as solar cells. Photovoltaic cells are composed of thin, transparent layers of boron and phosphorous-enriched silicon. Simple photovoltaic systems are commonly used to provide power for small consumer items such as toys, calculators, and wristwatches. Larger systems provide electricity for other purposes, including water pumps, road and traffic signs, and communications satellites. These systems are sometimes installed on the roofs of houses and buildings or as parking lot shade canopies (Fig. 25). The most complex and largest systems are those used in photovoltaic power plants. Today, there are only a handful of commercial plants in the United States, including ones in California, Nevada, New York, Arizona, and Florida. Several more have been proposed.

Geoscientists are needed for the exploration and production of an array of necessary raw materials such as silicon, gallium, cadmium, and copper.

**Benefits and challenges.** Solar energy has a number of advantages over other sources of energy. First, solar energy systems do not produce air pollutants. This includes active and passive solar heating systems, concentrated solar power systems, and photovoltaic systems. Second, following set-up and maintenance costs, the solar radiation is free. Third, photovoltaic panels are relatively simple and durable, require little maintenance, can
be installed quickly and in any size to meet the needs of consumers and photovoltaic cell costs continue to decrease. In remote locations, photovoltaic systems can be a more feasible option for local electricity generation than running long wires to connect to an electrical grid (National Resources Defense Council, 2012).

There are also several disadvantages to solar power, the greatest of which is intermittency, which necessitates a backup energy source. Another challenge is cost, and this is driven by inefficiency. The efficiency of most commercial photovoltaic panels and arrays in converting solar radiation to electricity ranges from 5% to 15%. And although photovoltaic technology continues to improve, there are technological and physical limits. Finally, population centers are not always located where the sun shines most, and transmission lines are expensive (U.S. EPA, 2012d).

Nuclear

What is it and how is it used? Nuclear energy is more powerful than any other energy source. Enormous forces hold together the nuclei of atoms. The heat produced from splitting atoms—fission—is used to boil water, make steam, and generate electricity. The United States generates ~20% of its electricity from nuclear; for France the figure is 80%. Most other developed countries produce a small percentage from nuclear. Compared to the huge amount of electricity it produces, the fuel costs almost nothing and nuclear plants have essentially zero emissions. Nuclear power is presently producing electricity, largely without incident, in more than 400 power plants worldwide (U.S. EPA, 2012c).

Resources. The most common fuel for nuclear power generation is uranium, which is extracted from mined uranium ore. The worldwide production of uranium in 2009 amounted to just over 50 thousand tons. Kazakhstan, Canada, and Australia account for 63% of world uranium production (World Nuclear Association, 2012b). Uranium is mined in open pits, in underground mines, or in leaching operations. When first mined, uranium contains numerous isotopes, not just the U-235 used in fission. As a result, the uranium must be enriched before it can be used as fuel in a nuclear reactor. According to a study by Massachusetts Institute of Technology (Deutch et al., 2009), the global supply of uranium ore is capable of supplying 1000 new reactors over the next 500 years.

According to the European Nuclear Society, as of 2012, there are 435 nuclear power plants (also referred to as sites) worldwide and many plants contain several reactors. The installed electric net capacity is ~368 gigawatts (GW). Between 1951 and 2010, a total of 67,240 billion kWh of electricity was generated (European Nuclear Society, 2012). The United States has 104 nuclear reactors, which nearly equals the total of the next two countries combined, France (58) and Japan (50). Sixty-four reactors are under construction globally with a total capacity of 61 GW. By way of comparison of density and scale, 61 GW exceeds the total installed nameplate wind capacity in the U.S. (50 GW) and is 3× the actual wind generating capacity. Of the 64 plants under construction, 26 are in China and 11 are in the Russian Federation (IAEA, 2012).

Technology and the role of geosciences. A nuclear reactor is the part of a nuclear plant in which nuclear fission occurs. The reactor contains very few parts. Fuel rods, each ~3.5 m in length, contain hundreds of pellets of uranium fuel, each ~1 cm long. Fuel rods are bundled into assemblies of several hundred. Within the reactor core are “control rods” composed of materials, such as cadmium, which absorb neutrons. When control rods are lowered into the core, they absorb neutrons and slow down the nuclear reactions in the uranium fuel. Water is also used in the core as a moderator to slow down the speed of very fast moving neutrons so they can be captured by the nuclei of the uranium.

There are several types of nuclear power plants. Pressurized water reactor (PWR) plants are the most common. In PWRs water is used as a coolant to absorb the heat released by nuclear
fission. The water is kept under very high pressures and temperatures (100 °C) so that it does not boil off. The heated water becomes radioactive and must remain isolated as it flows through a heat exchanger where the heat is transferred to nonradioactive water. The hot, clean water is then moved to a turbine to generate electricity. The hot water is then moved into large cooling towers and air cooled into steam or into a reservoir for circulation and cooling (Fig. 26).

In boiling water reactors (BWRs), radioactive water drives the turbine directly. This allows the core to be kept under lower pressure. Over time, the turbines become radioactive and must be carefully disposed of when the reactor is dismantled. In heavy water reactors (HWRs), deuterium, an isotope of hydrogen with one neutron, is used. This allows unenriched uranium to be used as fuel because deuterium is very efficient at controlling the bombarding neutrons that split the uranium atoms.

Nuclear power plants have several important safety features, but like any major facility, can never be 100% safe. The fuel remains bound in ceramic pellets until it is used. The fuel rods are placed within a steel pressure vessel with walls up to 30 cm thick. The walls of the plant are made of reinforced concrete at least 1 m thick to reduce the risk of an impact on the exterior affecting the core. Nuclear power plants have complex systems to ensure their safety from mechanical, computer, or user error. They have backup water systems to ensure continuous cooling of the fuel as well as backup generators in case of a loss of power.

Sources of uranium, plutonium, thorium, and many other mined products rely on geosciences, as does the diesel required in the engines used for backup generators. And, of course, eventually geologic repositories will be required to store the low-level and high-level wastes.

**Benefits and challenges.** Nuclear energy has many advantages. It is incredibly efficient, extremely dense, very affordable per kilowatt-hour, and essentially emissions free. For comparison, one pellet of uranium weighing about ¼ ounce is equivalent to nearly one ton of coal in energy potential.

Challenges for nuclear include plant and mining safety, handling of spent fuel, proliferation, and cost to build. As with other mining operations such as coal, accidents do, on occasion, occur in the mining of uranium. In 50 years, there have been three significant nuclear power plant accidents worldwide. Considering there are 400 nuclear reactors worldwide, nuclear reactors have a remarkably good safety record (Muller, 2012). Still, because of the radioactive nature of the fuel, the coolants, and waste products, any leak could have potentially far-reaching and long-term effects on the environment and humans.

France recycles and reuses spent fuel. The United States stores spent fuel on site in dry casks and pools containing spent fuel-rod assemblies. A permanent geologic repository does not yet exist but is close to reality in France. The concern with proliferation focuses on preventing radioactive material from falling into the hands of terrorists or other malicious parties, who could somehow utilize it for nuclear weapons. In reality, nuclear material is hard to handle, closely guarded, not pure enough, and the technology is complex. Nonetheless, it still must be handled with great care. The final major challenge for nuclear is cost. Nuclear plants must be incredibly robust, and therefore they are much more expensive than a natural gas or coal plant of equivalent size.

**LOOKING FORWARD: EFFICIENCY AND CULTURE**

The world contains abundant energy resources. Extracting and utilizing these resources in an affordable, environmentally sound, and dense enough form is the challenge, and involves the geosciences extensively. Coal mining and large-scale geologic carbon sequestration will rely on advanced subsurface...
characterization and monitoring. The subsurface understanding required for fossil-fuel exploration and extraction ranges from nanopores to tectonic plates; it utilizes advanced fieldwork and seismic imaging; it requires ever-greater laboratory experimentation. Nuclear energy relies on sources of uranium, plutonium, thorium, and many other mined products. And eventually, geologic repositories will be required to store the waste products of nuclear power generation. Production of biofuels involves soil science, hydrogeology, fertilizers, weather, and climate. Harnessing geothermal energy involves the ability to characterize the subsurface resource. Generating power from tides and waves involves oceanography and analysis of coastal change. Utilizing wind depends on geomorphology as well as the mining of copper, carbon, and other materials. Solar energy requires silicon, gallium, cadmium, copper, and other materials.

As large-scale energy-storage solutions develop, input from the geosciences will range from characterizing the subsurface for compressed-air storage options to mining rare-earth elements for chemical batteries. Finally, the “above-ground” environmental challenges from mining and production to climate change require that environmental geologists, climate scientists, biologists, economists, and policymakers come together to educate the public and make it possible for industry, government, academia, and NGOs to work together to develop and deliver balanced solutions.

Energy consumption trends are relatively stable through time, in part because the scale of energy infrastructure is so massive that change is very slow. It often takes a decade to build energy facilities such as power plants, refineries, and petrochemical plants, longer to pay off the debt, and the facilities then last for 25, 50, or even 100 years. Even if a game-changing innovation took place today, rolling it out at scale would likely take 10–20 years. It took Iceland 35 years to get half its energy from geothermal; France, 30 years to get 80% of its electricity from nuclear; and Denmark, 35 years to get 20% of its electricity from wind.

The scale of energy exists for two primary reasons: population and per capita consumption. In other words, people are the challenge and people must be the solution. Governments and societies will manage scale by managing demand, through some combination of using energy more efficiently and conserving energy. Efficiency means using less energy to do the same work. Efficiency can make conventional facilities, such as a coal plant, power more people. Efficiency can make solar panels have greater impact. Efficiency lowers demand, which means less energy infrastructure, land, water, imports, carbon emissions, and capital required. So why isn’t efficiency being deployed more broadly and rapidly? First, it is hard to incentivize energy producers to produce less energy. Second, some efficiency measures have an up-front cost, which may take a few years to pay back. Finally, there is a rebound effect, which means that greater efficiency often creates some offsetting increase in demand, because the per-unit cost of consumption falls with efficiency.

Whereas efficiency is mostly what technology can do to make existing systems use less energy, conservation means using less energy, by choice. In other words, conservation involves a change in the way people think and act about energy. If energy awareness becomes a cultural norm, then efficiency and conservation will too. Changes in culture are not easy and rarely happen quickly unless driven by crisis. Energy needs to be different. A severe energy crisis would have negative consequences on the economy and, by extension, the environment. It is not a good option.

A change in culture—the way societies think about energy—and the increasing efficiency and conservation that would result from such a change would help to avert potential energy crises. It is time to become educated about energy and use that knowledge to become more efficient. The stakes are simply too high to permit inaction and complacency.

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