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Resources, Reserves, and Consumption of Energy

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Abstract

Providing adequate energy for a growing human population that aspires to a higher standard of living while mitigating the effects of increased atmospheric carbon dioxide may be the defining issue of the twenty-first century. Presently, more than 92% of world energy comes from geologically based fuels (oil, gas, coal, and uranium), and this use has resulted in historically unprecedented increases in atmospheric CO_2 concentration. Without major technological or scientific breakthroughs, this trend will continue for the foreseeable future. Conventional oil resources of about 60 times current annual consumption are estimated in the form of reserves and potential additions to reserves. Significant opportunities exist for development of nonconventional hydrocarbon liquids. Proved natural gas reserves of more than 175 trillion cubic meters (TCM) are being consumed at a rate of about 3 TCM per year and numerous possibilities exist for new field discoveries, growth of reserves in existing fields, and development of unconventional resources. Coal reserves are adequate for hundreds of years of production at current rates, and nuclear fuels are abundant. Renewable energy sources have the potential to supply a large fraction of needed energy, but significant technological and logistical hurdles will first need to be overcome. As in the past, however, unforeseen technological advances may provide radical solutions to the world's energy needs.

Introduction

Most life in the oceans and on land ultimately depends upon the capture of sunlight by plants and marine phytoplankton for energy. For at least 250,000 years, modern humans and their hominid ancestors have expanded their use of energy by controlling fire, harnessing animals, and developing machinery to capture wind and water power (Smil 1994). Since the middle of the eighteenth

[1] Views expressed by the authors do not necessarily reflect those of the companies or organizations they represent.

century, society has been progressively transformed through the use of ancient concentrations of solar energy in fossil fuels. In the late nineteenth century, coal replaced firewood as humanity's principal fuel and drove the industrial revolution (Nakićenović et al. 1998). Petroleum from natural seeps had been used since antiquity for caulking, light, heat, and lubricants, but petroleum became a dominant force in world politics and economics in 1885 with the lightweight internal combustion engine of Gottlieb Daimler and Wilhelm Maybach (Eckermann 2001; Yergin 1991). Large-scale generation of hydroelectric power took off early in the twentieth century, and electricity from nuclear chain reactions appeared soon after World War II.

While the succession of fuels used in specific applications may be seen as increasingly efficient (Marchetti and Nakićenović 1979), the absolute quantities of energy expended have been rapidly rising. In 1945, the entire human population used about 50 exajoules (EJ) of energy. By 2007, primary energy consumption was 460 EJ per year (Figure 18.1).

Compared to the long geological timeframe of their accumulation, fossil fuels are being consumed within a few centuries. As a result, atmospheric CO_2 concentration has increased from a preindustrial level of about 280 parts per million by volume (ppmv) to more than 380 ppmv today. This higher value probably exceeds the upper limit of natural variation over the last 650,000 years. Moreover, the atmospheric concentration of CO_2 is currently rising by about 1.9 ppmv/yr and is expected to continue increasing for decades. Most atmospheric scientists and climatologists are convinced that anthropogenic CO_2 is changing the thermal properties of the atmosphere at rates unequalled in the historical record (IPCC 2007d).

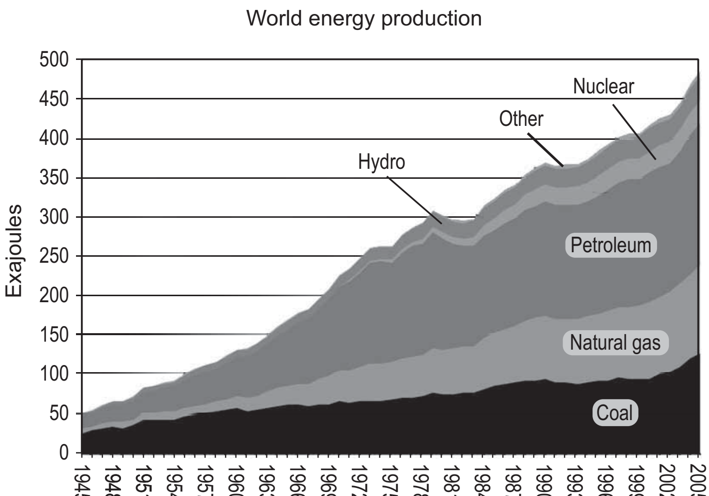

Figure 18.1 Global energy consumption by commodity since 1945, based on data from the U.S. Energy Information Administration (data from EIA 2007).

Recent high energy prices and concern about global climate change have increased calls for the development of renewable energy supplies, but the push for renewable fuels is not new; the amount of energy derived from them has grown considerably over the last half century (Figure 18.1). This increase, however, has thus far not quenched the global thirst for fossil energy. Every year since World War II, between 91–93 % of the world's commercial energy supply has come from the geologically based fuels: coal, oil, natural gas, and uranium (IEA 2008e). Without major scientific and technical breakthroughs or a coordinated multinational effort, these fuels will likely dominate the world's energy mix for the rest of the century.

Traditional fuels such as firewood and dung, used for cooking and heating near where they are collected, still comprise almost 10% of the world's energy consumption (IEA 2008a). Most of this consumption is in developing countries. Even in Nigeria, a major oil-exporting nation, almost 80% of the energy consumed is from combustible renewables and waste. This chapter will focus on commercial energy resources where the scale of production is for a mass market. The Energy Information Administration estimates that in 2006 about 36% of commercial energy consumed was from oil and other liquid petroleum. Coal contributed approximately 28% and natural gas 23%. Nuclear reactors generated almost 6% and hydroelectric installations a little more than 6% of global energy. Geothermal, solar, and wind installations together accounted for about 1% of global consumption. Calculations of the amount of energy produced for each fuel type vary somewhat between reporting agencies, such as the EIA, IEA and BP, depending on the factors used in the conversion of physical units to energy units.

Global energy consumption is unevenly distributed, especially on a per-capita basis (Figure 18.2). The Asia-Pacific region accounted for 34.3% of world consumption in 2007, led by China at 16.8% and Japan at 4.7%. More than 25.6% was used in North America, with the United States alone using more than 21% of the world total. Europe, Turkey, and the countries of the former Soviet Union together used 26.9%, with the largest single consumer being the Russian Federation at 6.2%, followed by Germany at 2.8% and France with 2.3%. All of Central and South America accounted for 5%, while the countries of the Middle East used 5.2%. The entire African continent consumed only 3.1% of primary energy production.

Fossil Fuel Resources

All fossil fuels produce energy when burned, but they are not readily interchangeable in the market sectors where they are used (IEA 2008c). Crude oil dominates the transportation sector because, when refined, due to its high volume density relative to other liquid and gaseous fuels, it is ideal for internal combustion and jet engines. Being a liquid, oil and its refined products can be

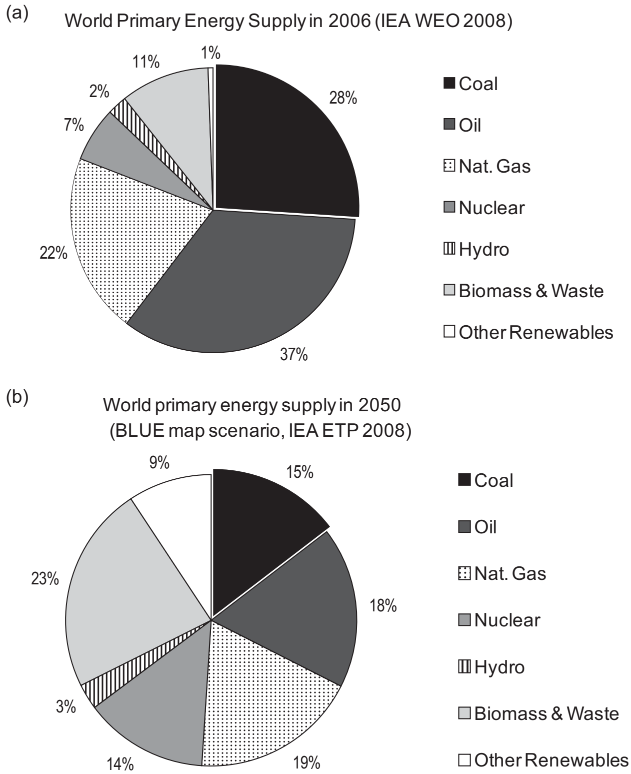

Figure 18.2 Total primary energy demand in (a) 2006 and (b) 2050 (IEA 2008c, e). In 2006, total primary energy use was 11,730 Mtoe. In 2050, it is projected to range from 15,894 (IEA BLUE Map Scenario) to 23,268 (IEA Baseline case) Mtoe. The "BLUE Map" scenario reflects an aggressive decarbonization scenario where greenhouse gases are reduced to 50% of their 2008 levels. Renewable energy accounted for 14% of the total in 2006 and up to 35% of the total in the 2050 scenario. These renewable percentages include traditional noncommercial biomass, which constitutes about 60% of today's biomass use but is expected to decrease over time.

transported at normal pressures and temperatures in pipelines, tankers, and vehicle fuel tanks. With the spread of the automobile, oil usage increased more rapidly than other fuels during most of the twentieth century.

Natural gas is a desirable fuel for electricity generation because, compared to coal, it yields approximately twice the energy per unit of released CO_2 with significantly less particulate and other criteria pollutant emissions. Just as electricity can be turned on and off, gas supply to a burner can be quickly regulated, making it an excellent fuel for domestic heating and cooking. Natural gas is still transported mainly by pipeline, so it is mostly consumed on the continent where it is produced. However, as the costs associated with ocean-going liquefied natural gas tankers and facilities decreases, gas is emerging as a true global commodity (EIA 2003, 2009).

Early in the twentieth century, coal dominated most energy markets, including transport (trains, steamships) and domestic heating. Its share subsequently declined until, by mid-century, coal seemed to be a fuel of the past for all but heavy industrial purposes. However, coal has found a new niche in the rapidly expanding electrical power sector, where it has proven to be by far the cheapest fuel for power plants in most parts of the world. As a result, coal consumption has recently been expanding more rapidly than any other fuel, mainly because of increased industrial growth in China (IEA 2007) (Figure 18.1). Current coal production is at an all-time high.

Fossil fuels also have a wide variety of uses beyond producing energy for homes, offices, industries, and vehicles. Most plastics, fertilizers, and many chemicals are derived from fossil fuels. Steel production depends upon fossil fuels, and natural gas is the basic feedstock for most hydrogen production.

Oil Resources

After a century and a half of exploration and millions of wells, the geological requirements for oil are reasonably well understood. Crude oil is a naturally occurring fluid mixture of complex long-chain organic molecules formed by the heating of organic matter within certain fine-grained sedimentary rocks. Typically, source organic matter originated as marine algae and plant debris deposited along with inorganic sediments as mud on the ocean floor.

Oil forms in a narrow range of temperatures; it generally cannot form until the original organic compounds are heated to at least 100°C. Above about 200°C, oil breaks down, or cracks, leaving mainly methane and CO_2 in its place. Crucially for petroleum generation, temperature increases with depth in the Earth's crust, commonly at rates of 15–30°C/km. Under favorable conditions, organic-rich marine mud is buried beneath younger sediments to depths of 3–6 km, where temperatures are appropriate for oil generation. Newly formed oil migrates out of the petroleum source rocks and into the water-filled pore spaces of adjacent sediments, from where it migrates to the surface and is lost, or it is trapped. Most traps are permeability barriers in subsurface structures (e.g., anticlines or fault blocks), in which porous reservoir rocks, such as sandstone or limestone, are juxtaposed with lower permeability sealing rocks, such as shale or salt. Oil exploration is the search for these petroleum-bearing traps. When oil accumulation has been demonstrated by drilling, production can only occur once a complex infrastructure of production wells, processing plants, pipelines, and market delivery systems is in place.

Despite a few interruptions from warfare, economic depression, and political upheaval, global oil production has increased steadily since the 1860s. Almost 5 billion cubic meters (BCM) of oil were produced during 2007 from wells in thousands of fields in more than 100 countries, led by Russia, Saudi

Arabia, and the U.S. Sometime during 2008, the landmark trillionth (1×10^{12}) barrel (~159 BCM) of oil was produced.

Although production is reliably tracked, proved reserves are not routinely reported. In many countries, including some of the largest producers, oil reserves are considered state secrets. Lack of transparent reporting has led to skepticism of officially stated reserves and given credence to predictions of imminent production declines (Simmons 2005). However, estimated world proved reserves are compiled and checked independently using best available information and considerable intelligence gathering by several organizations, including IHS Energy, BP, and the International Energy Agency. The estimates differ in detail, but they are similar in estimated overall volumes. Using the BP Annual Review (2008), for example, as of January 2008, world proved reserves of oil stood at approximately 197 BCM; the International Energy Agency estimated world reserves at 212 BCM. Neither estimate included Canadian heavy oil sands.

Proved reserves are strictly limited to the part of petroleum accumulations that can be produced at a profit under existing economic and operating conditions. Reserves recoverable at a 90% certainty are termed 1P reserves; 2P reserves are those estimated to have more than a 50% chance of being produced; and 3P reserves are commercially producible hydrocarbons deemed to have a 10% chance of commercial recoverability. Noncommercial resources, such as oil accumulations that are too small for profitable development, are contingent resources. Contingent resources could probably be produced under other economic circumstances.

The difference between international oil companies (IOCs) and national oil companies (NOCs) is extremely important when considering global resource availability. More than 90% of world oil and gas resources are controlled by NOCs that have responsibilities and purposes well beyond the profitable delivery of commodities. Most reserves reported by IOCs for purposes of financial accounting are 1P reserves that require demonstration of sufficient infrastructure for actual production of the stated reserve. Proved reserves should be synonymous with 1P reserves but in practice they commonly include some 2P reserves. Reserves reported by many NOCs, which appear in commercial databases, such as those of IHS Energy or the BP Annual Review, are usually 2P reserves.

Reserves have increased in lockstep with production. For example, in January 1996, world reserves were approximately 142 BCM and annual production was just over 4.1 BCM. Between January 1996 and January 2008 approximately 48 BCM were produced while reserves increased by nearly 56 BCM, suggesting that well over 100 BCM had been added to reserves during the twelve-year period. This paradoxical relationship of reserves increasing simultaneously with production is possible because of additions to reserves through (a) discoveries of new fields and (b) growth of reserves in existing fields.

Undiscovered Oil Resources

In 2000, the U.S. Geological Survey published the most recent global estimate of undiscovered oil and gas resources (USGS 2000). The World Petroleum Assessment (WPA-2000) was a geologically based study that relied on data from the beginning of 1996. The report included probabilistic estimates and detailed supporting data concerning the potential for volumes of conventional oil, gas, and natural gas liquids that might be added to proved reserves from new field discoveries in 128 petroleum provinces worldwide. The 128 provinces included the producing basins that account for more than 95% of the world's known oil and gas. The USGS study, which made no attempt to estimate potential outside of the 128 provinces and included only conventional resources, estimated that as of 1996 there was a 95% chance of discovering another 53 BCM of oil and a 5% chance of discovering 176 BCM. The median estimate, the 50% chance, was that 97 BCM of oil might yet be found in the 128 petroleum provinces.

More than 16 BCM were found in the 128 provinces during the eleven years following 1996 (IHS Energy 2007) and almost 3 BCM were discovered outside the provinces assessed by the USGS. If the recently discovered volumes are subtracted from the WPA-2000 estimates, a conservative interpretation suggests that as little as 36 BCM remain to be found in conventional accumulations in the 128 largest petroleum provinces. This also suggests that the estimated range of undiscovered oil resources is reasonable and that additional discoveries are to be expected. New discoveries are also likely in remote places that have not been well explored, including offshore in the Arctic, in deep water along the continental margins, and in areas, such as western Iraq, that have been inaccessible to exploration for various reasons.

Growth of Reserves in Existing Fields

Reserve growth refers to increases in successive estimates of recoverable oil, gas, or natural gas liquids in discovered fields, usually in fields that are already in production. Growth occurs for several reasons:

1. Better geological information may indicate previously unrecognized reservoirs, pools, or pay zones within an existing field.
2. Recovery efficiency may be improved by changing engineering practices, such as steam flooding, hydraulic fracturing, or infill drilling.
3. Estimated recoverable volumes may be revised upward based on changing economic or regulatory conditions.

In recent years, growth of reserves in existing fields has been volumetrically more important than new field discoveries. Between January 1996 and January 2004, approximately three barrels of oil were added to reserves of existing fields for each barrel added through new field discoveries.

Historically, only a fraction of the original oil in petroleum traps has actually been produced. In a recent study for the U.S. Department of Energy, Advanced Resources International (2006) estimated that while total cumulative oil production and remaining proved reserves in oil fields of the U.S. amounts to about 33 BCM, the oil remaining in the producing reservoirs probably exceeds 179 BCM. If correct, this analysis would indicate that after decades of production in the world's most intensely developed oil fields, the recovery efficiency was less than 19%, leaving the remaining 81% as a target for further development.

In its WPA-2000 study, using algorithms developed in oil fields of the U.S., the USGS estimated the potential for further growth of reserves in fields outside the U.S. to range from 30–164 BCM, with a median estimate of 97 BCM. The actual additions to reserves from field growth during the years since the WPA-2000 study (1996–2008) have already exceeded the lower range of the USGS estimates.

More recently Keith King, of ExxonMobil Corporation, made an independent estimate of the potential for reserve growth and reported the results at the American Association of Petroleum Geologists Hedberg Research Conference (Colorado Springs, November 2006) and at the International Geological Congress in Oslo, Norway in 2008 (King 2008). Using a different methodology and separate data from those used by USGS, King estimated that application of existing of technology to the world's largest fields could add 30–160 BCM to proved reserves.

Because of the large disparity between in-place and recoverable resources, the importance of reserve growth should not be underestimated. The quantities of unrecovered hydrocarbons are vast and given the historical impact of technology on recovery efficiency, it is likely that further technologic advances will allow substantial future reserve growth beyond that currently enumerated. Active research programs today on nanotechnology (Murphy 2009; Tippee 2009) and microbially enhanced oil recovery (CSIRO 2009), for example, could lead to substantial further increases in recovery efficiency.

Unconventional Oil Resources

In addition to the conventional oil resources discussed above, significant potential exists for additions to global reserves from so-called unconventional categories. Heavy oil resources, particularly in the Alberta Basin of western Canada and in the Orinoco Basin of Venezuela, are already being produced in large quantities. In Canada alone, almost 28 BCM were officially added to proved reserves in 2004, and Venezuela regularly wrestles with fellow OPEC members regarding what part of its large heavy oil resources to count against its production quota. Similar heavy oil resources may exist in many other basins worldwide, but their potential contribution to world oil reserves has not yet been systematically evaluated.

Additional oil resources also exist in the so-called oil shales, such as those of the Green River Formation in Colorado, Wyoming, and Utah. In spite of extreme abundance, confirmation of their practical potential is limited to a few small demonstration projects. However, because technologies already exist to extract oil from these rocks, they could undoubtedly be a major source of oil in the future, when more cost-effective methods of extraction are developed or if high oil prices were sustained.

One of the major concerns in developing heavy and extra-heavy oil resources is that extraction and upgrading technologies are energy intensive and result in higher life cycle greenhouse gas emissions than conventional oil resources. Mitigating these emissions through, for example, carbon capture and sequestration or the use of low carbon heat and power sources could be a focus of research and development for years to come.

Gas Resources

Methane (CH_4) is abundant in the solar system, constituting one of the principal components of the gaseous planets and existing in large quantities in the terrestrial planets as well. On Earth, CH_4 is understood to have three origins:

1. Thermogenic CH_4, formed from the thermal degradation of sedimentary organic matter, accounts for most commercial gas production.
2. Biogenic CH_4, generated by anaerobic microorganisms (the Archaea), is best known in low-pressure, disseminated settings, such as landfills, swamps (also from thawing Artic tundra), and the gastrointestinal tracts of mammals. In recent years, there has been an increasing recognition that the CH_4 in many shallow gas fields and coal beds (especially low-rank coals) is biogenic.
3. Primordial, abiogenic CH_4, which is presumably disseminated throughout Earth's crust and mantle, can be observed at times in volcanic emanations, but petroleum geologists are nearly unanimous in their view that abiogenic CH_4 makes little or no contribution to producible natural gas resources.

While large quantities of natural gas are formed with oil, gas also forms over a wider range of temperatures and depths as well as from sedimentary organic matter that is unsuitable for oil generation. As described above, if oil is heated sufficiently, it breaks down into simpler compounds, especially natural gas. Thus gas is expected to occur in larger quantities and over a wider range of conditions than oil.

The natural gas consumed by end-users consists almost entirely of CH_4. At the wellhead, however, natural gas usually includes a complex mixture of other light hydrocarbon molecules, such as ethane, propane, and butane. In addition, prior to processing, natural gas contains various other compounds, such as CO_2, water vapor, and nitrogen.

Natural gas is produced from oil wells, gas wells, and condensate wells. Natural gas produced together with oil is associated/dissolved gas. Natural gas produced from gas wells is nonassociated gas. Natural gas can also be produced from condensate wells that yield both natural gas and liquid condensate, which are separated near the well site.

In 2007, more than 2940 BCM of natural gas were produced worldwide; this amount is up from 1227 BCM in 1973. In 2007, ten countries accounted for more than 64% of world natural gas production: Russia (21.5%), the U.S. (18%), Canada (6%), Iran (3.5%), Norway (3%), Algeria (3%), The Netherlands (2.5%), Indonesia (2.3%), and China (2.2%). About 900 BCM of natural gas are imported and exported worldwide each year. The U.S. is the largest importer, bringing in about 130 BCM in 2007, followed by Japan (ca. 96 BCM), Germany (88 BCM), and Italy (74 BCM).

Prior to the last ten years or so, most proved reserves of gas outside of North America and Europe were discovered as a by-product of oil exploration and development. In recent years, proved global gas reserves have increased significantly due to purposeful exploration for natural gas. At the end of 1987, estimated world proved reserves of natural gas were approximately 107 TCM. As of 1997 reserves had risen to approximately 146 TCM, and at the end of 2007 world proved reserves of natural gas were estimated at approximately 177 TCM.

Approximately one-quarter of world reserves, between 44.6 and 47.8 TCM, are in Russia. Iran's reserves are ranked second, with 26.8–28.0 TCM, and Qatar, which shares the world's largest gas field with Iran, is ranked third in proved reserves, with about 25.6 TCM. In each of these three countries, natural gas occurs mostly in gas fields rather than in association with oil in oil fields. The U.S. has proved reserves of about 6.0 TCM. Many other countries are also rich in natural gas reserves, the leaders being Venezuela (~4.8 TCM), Norway (2.9 TCM), Iraq (3.2 TCM), Saudi Arabia (7.3 TCM), United Arab Emirates (~6.4 TCM), Algeria (~4.5 TCM), Nigeria (~5.3 TCM), and Indonesia (~2.8 TCM).

Future Additions to Conventional Gas Reserves

Natural gas exploration has not been pursued with nearly the level of investment and intensity nor for nearly as long as oil, and thus it is considered to be at a much lower level of exploitation. In its WPA-2000 study, the USGS estimated that as of 1996 there was a 95% chance of discovering another 14.8 TCM of associated/dissolved gas and 50.6 TCM of nonassociated gas. The USGS estimated that there was a 5% chance of discovering 57.7 TCM of associated/dissolved gas and 175 TCM of nonassociated gas. The median estimate of total gas (the sum of associated/dissolved and nonassociated gas), the 50%

chance, was that 122.6 TCM might be found in the 128 greatest petroleum provinces. In addition, the USGS study estimated that between 15 and 60 BCM of natural gas liquids would be discovered along with the associated/dissolved and nonassociated gas.

Based on IHS data, during the eleven years following 1996, about 18.9 TCM of conventional natural gas were found in the 128 provinces. If these volumes are subtracted from the USGS estimates, a conservative interpretation would suggest that as little as 46.4 TCM of gas remain to be found in conventional accumulations in the 128 greatest world petroleum provinces.

The reserves in existing gas fields are expected to grow; however, the volumes are difficult to estimate as gas fields are developed differently than oil fields and have much higher recovery efficiency. In 2000, using data collected since 1996, the USGS estimated the median gas reserve growth potential from already discovered fields to be approximately 93.5 TCM, with a statistical range of 29.7 TCM to 156.9 TCM at a 95% and 5% chance, respectively.

Unconventional Gas Resources

In addition to conventional resources, extremely large amounts of natural gas are known to exist in so-called unconventional reservoirs, including coal beds, low-permeability sandstones, and shales. In the U.S. alone, and excluding coalbed methane, the technically recoverable gas resources in unconventional reservoirs are estimated to exceed 7.7 TCM (USGS 2008b). While such resources are, as of the date of this writing (June, 2009), the most sought after gas plays in North America, they have hardly been touched on a global basis. As a result, no comprehensive quantitative estimate of such resources has been made outside of North America. Nevertheless, the developments in Canada and the U.S. may be instructive for initial thinking in regard to possible additions to gas reserves worldwide. It seems safe to assume that global unconventional gas resources are very large but as yet unmeasured.

Beyond conventional and so-called nonconventional gas resources are gas hydrates. Methane in hydrates overwhelms all other hydrocarbon concentrations in absolute molecular abundance, but how much of these resources can be considered technically recoverable is problematic. Recent work in Arctic Canada and Alaska, the U.S. Gulf of Mexico, India, and elsewhere indicate that conventional technology, with little or no modification, can produce gas streams from hydrates. Production tests in Canada have demonstrated the viability of such technological applications (Dallimore and Collett 2005).

Coal Resources and Production

Coal resources are widely distributed, but more than 75% of reserves are located in just five countries: the U.S. (28%), Russia, (19%), China (14%), Australia

(9%), and India (7%). At least some coal is produced in most countries, but China is easily the world's greatest producer and consumer, producing almost 55.9 EJ of energy from coal in 2006. For comparison, about 27.4 EJ of energy from coal was produced in all of North America, including the U.S., which produced more than 25 EJ. During the same period, Central and South America produced approximately 2.1 EJ. European coal production continues to fall, having declined from more than 11.6 EJ in 1996 to about 9.07 EJ in 2006. Eurasia, including Russia, first surpassed Europe in coal production in 2005 and produced more than 9.5 EJ in 2006, with its increase being driven by rising production in Russia. Africa produced almost 6.3 EJ of coal in 2006, nearly all of which (~6.2 EJ) was produced in South Africa.

Global proved reserves of coal are large compared to rates of production. As of 2002, global proved coal reserves coal exceeded 900 billion tonnes (WEC 2007a), which is approximately 200 years of supply at current annual production rates. Although coal reserves are not as thoroughly documented as are those of oil or gas, by almost any calculation they are sufficient for hundreds of years of production, even without large-scale development of new reserves from the much larger geological resource base.

The U.S. EIA projects a 65% increase in world coal consumption by 2030. Most scenarios foresee large increases in world coal demand with continued economic expansion in China and India. Consistently high oil and gas prices would offer continuing incentives for coal-fired electricity generation and for the development of coal-to-liquids processes for transport fuel as well.

The principal issue surrounding coal resources is emissions. Particulates, sulfur, and nitrous compounds from burning coal pose serious health problems and environmental degradation in some parts of the world, but these can be satisfactorily mitigated by processing coal before burning and by installing air pollution control systems to capture and remove pollutants from the stack gases in coal plants. Such systems are already installed on most coal-powered plants in OECD countries. A more fundamental problem is the high CO_2 emissions. As yet, no cost-effective means of mitigation has been developed to address greenhouse gas emissions from coal combustion. However, major efforts are currently underway to develop "clean coal" technologies to enhance the efficiency of power plants and to capture and geologically sequester the carbon products of combustion.

Nuclear Energy

Nuclear power facilities are similar to fossil fuel plants except that the source of heat generated for power comes mainly from the fission of unstable radioactive uranium, a nonrenewable but common metal found in rocks worldwide. The reactors rely on a particular isotope, U-235, for fuel. While common uranium, U-238, is 100 times more abundant than silver, U-235 is relatively rare.

Therefore, after uranium deposits are located and mined, the U-235 must be extracted, processed, and concentrated. Among the products of U-235 decay are neutrons that bombard other U-235 atoms, causing them to split. In sufficient concentration this process repeats itself naturally in an unstable chain reaction that can be controlled in nuclear power plants. The controlled chain reaction supplies heat to turn water into steam, which drives electric turbines.

Nuclear power is clean compared to burning fossil fuels. The plants produce no air pollution nor do they emit CO_2, although small amounts of emissions may be generated during uranium processing. The most significant issue in nuclear power concerns by-product wastes. Low-level radioactive waste in the form of tools, clothing, cleaning materials, and other disposable items are carefully monitored in most countries to ensure that they do not enter the environment. Spent fuel assemblies, however, are highly radioactive and pose a challenging situation for disposal, because they remain dangerous for hundreds or thousands of years.

In 2006, nuclear power constituted approximately 6.2% of worldwide total primary energy supply, more than 84% of which was generated in OECD countries. The leading producing countries are the U.S. (29.2%), France (16.1%), Japan (10.8%), Germany (6.0%), Russia (5.6%), Korea (5.3%), Canada (3.5%), Ukraine (3.2%), United Kingdom (2.7%), and Sweden (2.4%). The rest of the world produced the remaining 15.2%. After having increased consistently over the last few decades, nuclear power generation declined in 2007 in absolute terms by approximately 2%.

Viewed as a percentage of energy used, France was by far the largest user. Nuclear power plants generate more than 79% of France's domestic electricity. Sweden generates 46.7% of its electricity in nuclear plants, as does the Ukraine. The others include Korea (37%), Japan (27.8%), Germany (26.6%), U.K. (19.1%), U.S. (19.1%), Canada (16%), and Russia (15.7%). The rest of the world derived 7.2% of its electricity from nuclear power facilities. Uranium ore is mined in 18 countries, increasingly through a process of *in situ* leaching rather than traditional mining, which still accounts for more than 60% of production. More than half of the world's production is in Canada (23% of world supply), Australia (21%), and Kazakhstan (16%). Considerable amounts of uranium are in stored mine stocks, but since the early 1990s, mining is on the rise again. Following a number of corporate consolidations in the 1980s and 1990s, today just seven companies account for 85% of world uranium mine production.

Like coal, uranium is not considered in danger of geological exhaustion. Rather, the demand for uranium and the related ore pricing are the dominant forces controlling uranium production rates. Recently, development of additional nuclear generation facilities has increased demand and resulted in rising prices for uranium. Consequently, a number of mines have gone back into production.

Depletion of Geologically Sourced Fuels

Fossil energy resources are undoubtedly being consumed more rapidly than they are being replaced by geologic processes, but are they are becoming scarcer? Increased prices over time signal scarcity, but the long-term trend of prices may suggest that fossil resources are becoming less scarce (Simon et al. 1994). Short-term trends are influenced by factors, such as war, political decisions, and monopolistic behavior. Longer-term trends are difficult to define, as they require indexing relative to inflation, which is itself affected by energy prices. However, despite depletion of fossil energy resources, the percentage of take-home pay spent on energy by residents of OECD countries has fallen over the last fifty years and the number of people able to afford energy from fossil fuel has increased globally. Technological advances explain the apparent contradiction of resources becoming less scarce as they are being depleted.

From a geologic perspective, the amount of coal, oil, and gas in the ground is much larger than is suggested by resource assessments, which are defined (at least in part) by economic parameters. Still, fossil fuels are finite. In the long term, the world will have to draw an increasing amount of its energy from renewable sources.

Renewable Energy Sources

Renewable energy resources are produced from the direct (solar) or indirect energy (wind, biomass, wave, hydro) of the Sun, from nuclear decay deep within Earth's mantle (geothermal), or from the Moon's gravitational pull (tidal). These sources have recently been termed "perpetual resources" (WEC 2007a) though, even on the scale of several decades, at any location, tidal range, climate, and geothermal gradient can change the economic viability of such energy sources.

Geologically sourced resources are defined in terms of volumes of fuel that are known to exist or are inferred to exist within the Earth's crust and that are anticipated to be economically extractable within a foreseeable timeframe. In contrast, renewable energy resources are defined in terms of energy flows, such as the potential for energy production per year. Three types of renewable energy potential are commonly described:

1. Theoretical potential, which is a theoretical maximum energy flow rate.
2. Technical potential, which is the energy that can be captured using a certain set of technology assumptions.
3. Economic potential, which refers to the levels of renewable resources that could be converted at an economically viable cost.

In theory, there is more than enough renewable energy to provide for society's current and projected needs for primary energy. The amount of solar radiation that falls annually on Earth's land surface, for example, is about 10,000 times the annual global primary energy use. In practice, renewable energy use can be limited by intermittency, location, economics, and environmental and societal factors. Today, renewable energy comprises about 7% of global primary energy use and 18% of global electricity use (IEA 2008e). Hydropower accounts for 16% of electric generation, while wind, solar, and geothermal *together* contribute another 1%. Biomass and waste energy account for about 10% of primary energy use (IEA 2008e). Scenarios developed by the IEA suggest a growing role for renewable energy over the next decades (IEA 2008c), with 35–46% of electricity and of 17–25% of transport fuels from renewable sources by 2050 (Figure 18.3).

Solar energy is the most abundant energy resource available on Earth (WEC 2007a; IEA 2008c, e). Direct solar energy can be captured for heat, electricity, and fuels production. Commercially available applications include passive uses (e.g., space heating, cooling via reflection, and daylighting), hot water heating and cooling, process steam generation, and electricity production via solar photovoltaics or solar thermal electric systems. Other direct solar applications, still in very early stages of development, include photoelectrolysis of water to hydrogen, and photoreduction of carbon dioxide and water into methanol and other liquid fuels. Currently, solar energy provides far less than 1% of the world's total commercial energy, but its use is growing rapidly. Technical challenges to large-scale deployment of solar energy include land use issues and its intermittency; solar systems have an average annual capacity factor of about 15–35% depending on latitude, cloudiness, tilt and/or tracking, and collector efficiency. Most of the current installed capacity is in Europe (Germany, Spain), Japan, and the U.S. Solar energy is expected to provide 1–11% of total

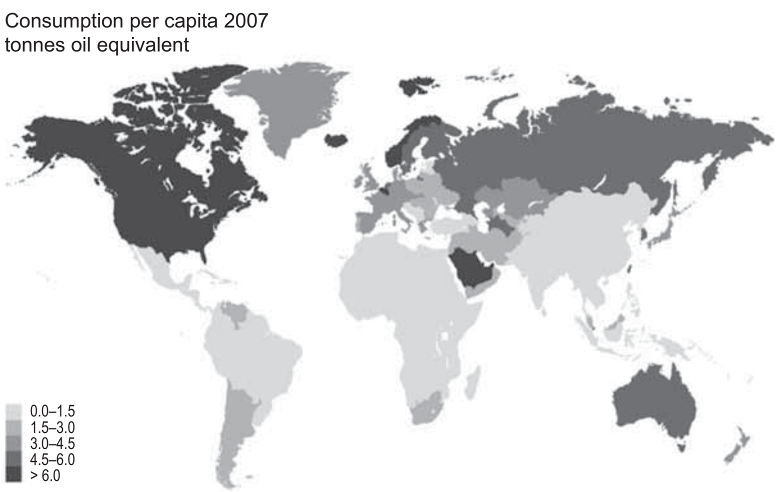

Figure 18.3 Global per-capita primary energy consumption, from the BP Annual Review of Energy (BP 2008).

electricity generation by 2050 (not including direct heat use) based on future scenario studies (IEA 2008c).

The global wind resource has been assessed in several recent reports (Archer and Jacobson 2005; De Vries et al. 2007; Grubb and Meyer 1993; UNDP 2000; WEC 2007a). It has been estimated that 0.25% of the solar radiation energy reaching the lower atmosphere is transformed into wind (Grubb and Meyer 1993), an amount many times current human energy consumption. Of course, only a small fraction of this energy can be captured because of technical, environmental, and societal constraints. The technical constraints include wind turbine efficiency, height, and losses due to air flow interference by adjacent turbines. Resource, environmental, and social constraints may restrict the siting of large turbines due to factors like visual impact, noise, conflicting land uses, wildlife impact, and inaccessibility. Intermittency could further limit how much wind power could be integrated with the electricity grid. The best wind resources are commonly located far from population centers, so transmission capacity is also a constraint. Scenario studies that account for these issues suggest that 2–12% of electricity in 2050 could be economically produced from wind power and integrated into the grid (IEA 2008c).

Currently, biomass energy and waste energy are used for heating, power generation, and production of liquid fuels (e.g., ethanol and biodiesel). In 2006, the global use of biomass energy was about 50 EJ per year (IEA 2008e). About 60% of biomass energy is consumed in developing countries as traditional, noncommercial fuels (fuel wood, crop residues, dung) for home heating and cooking. Modern biomass conversion for process heat, electricity, and fuels accounts for 19.4 EJ/yr (IEA 2008e). Estimates for future global biomass production vary widely depending on the assumptions about biomass yields, conversion efficiency to electricity or fuels, and land use restrictions (Hoogwijk et al. 2004). Several issues contribute to the uncertainty in long-term contributions of biomass to the energy system. These include competition for water resources, environmental impacts of fertilizer and pesticide use for energy crops, biodiversity effects of energy crops, and competition for land between bioenergy crops and feed and food production. In a recent review, the IEA estimated that the global potential for sustainable primary biomass energy production was 200–400 EJ per year.

Geothermal energy projects convert the energy contained in hot rock into electricity, process heat, and space heating/cooling by using water to absorb heat from the rock and then transport it to the Earth's surface. Conventional flash, direct-steam, and binary geothermal plants provide base load power in 24 countries. Approximately 75% of the worldwide capacity is produced from the 20 sites which have more than 100 MW_e installed. Unconventional geothermal resources (e.g., hidden systems, deeper systems, and enhanced or engineered systems) are generally still in early phase development. Estimates for total worldwide economically recoverable geothermal energy for power and heat production range from 2–20 EJ/yr (556–5556 TWh/yr) (Jacobson 2008;

Jaccard 2005). The worldwide electrical power output from geothermal sources was 60 TWh/yr in 2006, or about 0.3% of the world's electrical output (IEA 2008e). As more fields, both conventional and unconventional, are exploited, geothermal power generation is expected to triple by 2030 (IEA 2008e).

Hydroelectricity is currently the largest renewable source for electricity generation, accounting for about 3035 TWh per year, or 16% of global electricity production (IEA 2008e). Hydroelectricity can be generated using large dams, small hydropower plants, or pumped water storage. The global hydropower resource has been assessed in several recent reports (Archer and Jacobson 2005; De Vries et al. 2007; IEA 2008e; UNDP 2000; WEC 2007a). Hydropower resources are distributed unevenly throughout the world. Much of the unrealized hydropower potential lies in developing countries in Latin America, Asia, and Africa. Historically, about 60–70% of hydropower resources have been developed in the industrialized regions of Europe and the U.S. Challenges include social and biodiversity impacts of dams due to flooding and aquatic life flowing through water turbines. Using this as a guide, the global economic potential has been estimated at 6000–9000 TWh/yr (UNDP 2000; IEA 2008c, e). According to recent IEA scenarios, hydropower could grow by a factor of 1.7 by 2050 (IEA 2008c), mostly in developing countries.

Although conventional hydropower has been widely tapped across the globe, ocean and river energy (i.e., the kinetic energy generated by ocean waves, tidal currents, and river flows) and the thermal energy stored in ocean temperature gradients are largely unexploited. The technologies to harness these energy sources are still in various stages of development, with a handful of applications undergoing sea trials and nearing full-scale deployment. However, they all face challenges due to the harsh environmental conditions of the open ocean, intermittency, and reliability in connecting the devices to onshore electrical grids. The total resource meeting the world's shorelines in the form of ocean waves is estimated at about 23,600–80,000 TWh/yr (IEA 2006b; Jaccard 2005; WEC 2007a), of which only about 28 TWh/yr is potentially economically recoverable. The global tidal power potential in sites with good power densities is estimated to be between 800–7000 TWh/yr (IEA 2006b; Jacobson 2008), of which up to 180TWh/yr may be economically converted into electricity. Ocean Thermal Energy Conversion (OTEC) is by far the largest ocean energy resource. However, OTEC is challenged by a mismatch between resource location and load, by low conversion efficiencies, and by the need for deep-water deployment of hardware. Salinity gradient technology uses the osmotic pressure differential of seawater and freshwater, which represents an equivalent of a 240 m hydraulic head. The global primary power potential is estimated at about 2000 TWh/yr (IEA 2006b). However, salinity power technologies are still in very early stages of research and development and will likely have limited potential for the foreseeable future.

A major shift to renewable energy use could reduce the need for geologically based fuels but it would also increase the need for other geologically based commodities, substantially changing existing material flow patterns. For example, Schleisner (2000) calculated that for an onshore wind-farm in Denmark, each 500 kW turbine required 64.7 metric tons of iron and steel, 1.4 tons of aluminium, 0.35 tons of copper, 2 tons of plastic, and 282.5 tons of concrete. If wind power is to supply a major part of the world's energy in the next decades, there will be substantially increased demand for all these commodities. Similarly, increasing solar power will require vast amounts of silicon wafers and a dramatic rise in production of rare metals such as cadmium, tellurium, indium, and gallium. Large-scale increases in biofuels will require more farm equipment and fertilizers, which ironically will require additional natural gas for production.

Conclusion

The stock of energy resources to be passed onto future generations increased during the twentieth century due to technological advances, most of which were unforeseeable at the beginning of the century. For that trend to continue, substantial technological advances are necessary in many areas over the coming decades.

Global production of energy from renewable sources has increased approximately 15-fold over the last fifty years, but the percentage of the world's energy consumption from these sources has remained between 7–8% as consumption of other energy resources has also markedly increased. Renewables offer the promise of a world with lower emissions of greenhouse gases, but major breakthroughs will be needed for them to become cost-competitive. Conflicting land and water use, problems related to material flow, and costs of transportation and infrastructure are major hurdles that need to be addressed for all forms of energy production and transportation.

Fossil fuels are likely to remain a major part of the world's energy mix for the entire twenty-first century, and they will provide the bridge to a sustainable energy future. The continued use of fossil fuels will require major advances in energy efficiency and in technologies to capture and store carbon in order to mitigate greenhouse gas emissions and related effects of climate change. Nuclear power offers a proven source of energy without carbon emissions but has its own environmental and safety problems that must continue to be addressed for appreciable expansion.

Finally, it is possible that, as in the twentieth century, unforeseeable technological advances may provide radical solutions to the world's energy needs. For example, research in fusion and superconductivity has continued for many years without realizing the promise of cheaper energy supplies, but a breakthrough could assure sustainable energy sources for centuries to come.