Chapter 2
The Future of Energy I: Fossil Fuels*

There are three different types of power: backbone power, green power, and mobile power. *Backbone power* is the primary energy source that is always there when we need it. *Green power* comes from renewable energy sources which do not pollute. *Mobile power* drives our cars, planes, and other vehicles and has the special requirement of transportability. We will discuss each of these in turn.

Backbone Power

Only 40% of the world's energy use is in the form of electricity; the rest is used for heating and manufacturing. But it is the electric power that governs our way of life in developed countries. During a hot summer day, you have probably experienced a rolling blackout. Night falls and you light a candle. So far so good, and it might even be romantic; but it is too dim to read by. You turn on the radio to find out what the problem is. It does not work. You want to watch TV or play a disk, but those do not work either. You try to call your neighbor to talk about it, but the phone does not work either. Now, where is that phone that connects directly without a power brick? Well, I have all this time to surf the web, you think. The computer is dead as a door nail, and so is the modem. A cup of hot tea would calm your nerves, but… oops! The stove is electric, and so is the hot water heater. Maybe we can take a drive in the moonlight until the power comes back on. But the garage door would not open. There is nothing to do. During the 10-h New York blackout in 1965, people did what came naturally; and the maternity hospitals were jammed nine months later…or so it was reported. This story has been debunked since then.

Heating of homes uses mostly oil and gas, but reliable electric power is still needed in a pinch. Mrs. Johnson, a widow, lives alone in her house in suburbia. The snow is so deep that oil trucks have difficulty in making deliveries. The electricity goes out when a large generator goes down in the public utility. A fierce storm rages outside, and there is no sun. The gusting wind does not provide enough wind power to make up for the

*Numbers in superscripts indicate Notes and square brackets [] indicate References at the end of this chapter.

F.F. Chen, *An Indispensable Truth: How Fusion Power Can Save the Planet*,
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shortfall. The inside temperature falls to below zero. Mrs. Johnson has an electric heater, but there is no power. She cannot cook without electricity. After two days, she unfreezes a can of soup by lying next to it in bed. On the third day, she looks at a picture of her grandchildren on her nightstand and wonders if she will ever see them again. Then, on the fourth day, the power goes back on. Yes, she will see them again. Thank goodness for backbone power! This is a dramatization, but loss of backbone power can have deadly consequences. Fortunately, most hospitals have emergency power systems that run on fossil fuels. This is one use of fossil fuels that is defensible.

Renewable energy sources are absolutely necessary for limiting greenhouse gases, but the ones that most people know about – wind, solar, and hydro – are not sufficient or dependable enough to be the primary energy source. Great strides are being made to increase the fractional contribution of these sources, but they can only supplement the primary source. That is because we cannot store energy from intermittent sources or transport that energy from where it is produced to where it is needed. Backbone power has got to be available at all times. This means that reserve generating capacity has to be built to supply power when all else fails. Backbone power keeps people alive and functional in their normal activities. Green energy can save on fuel cost, but not on capital costs, because backbone power plants still have to be built to supply the necessary standby capacity. This will be quantified in the section on wind power. *Only three energy sources fulfill the requirements of backbone power: fossil fuels, fission, and fusion. Of these, only fusion energy has the prospect of being backbone, green, and safe.*

The Energy Deficit

Energy Units

Before we talk about energy, let us be sure we know what it is. If you turn on a 100-W light bulb, it will use up 100 W of energy, right? Not exactly! Watts measure the *rate* at which energy is used, which is called *power*. Energy is something we can store, and power is how fast we use it up. A toaster takes about 1,000 W, or 1 kW, of electricity to run. If we turn it on for an hour, it will consume 1 kWh of *energy*. A 200-W light bulb left on for 10 h would use up 2,000 Wh, or 2 kWh of energy. On a more personal note, suppose you ate a 200-calorie hamburger (a small one). That's energy which you store. Suppose it takes you 2 h of exercise to burn off that energy, then you are using up 100 C/h, which is the average *power* you put out during the workout. What confuses most people is that the well-known electrical unit, the watt, is a unit of power, not energy. You have to multiply by time to get energy.

To compound the confusion, articles about the energy crisis do not use the same units for energy. There are British thermal units (BTUs), terawatt-years, millions of barrels of oil equivalent (MBOE), megatonnes of coal equivalent, and so forth. In this book, we convert all the data to metric units; namely, watts and joules and their multiples. The conversion factors among the most common units are given in Box 2.1.

Box 2.1 Conversion of Energy Units

One of these units	Equals this many of these units: kJ	kWh	BTU	BOE
Kilojoule	1	2.8×10^{-4}	0.95	1.6×10^{-7}
Kilowatt-hour	3,600	1	3,412	5.6×10^{-4}
British thermal unit	1.055	2.9×10^{-4}	1	1.7×10^{-7}
Barrel of oil equivalent	6.1×10^{6}	1,700	5.8×10^{6}	1
Tonne of oil equivalent	4.5×10^{7}	1.2×10^{4}	4.3×10^{7}	7.33

One of these units	Equals this many of these units: TJ	TW-year	MBtu	Quad	MBOE
Terajoule	1	3.2×10^{-8}	948	9.5×10^{-7}	1.6×10^{-4}
Terawatt-year	3.2×10^{7}	1	3.0×10^{10}	30	5,200
Million British thermal units	1.1×10^{-3}	3.3×10^{-11}	1	1.0×10^{-9}	1.7×10^{-7}
Quad	1.1×10^{6}	0.033	1.0×10^{9}	1	172
Million barrels of oil equivalent	6.1×10^{3}	1.9×10^{-4}	5.8×10^{6}	5.8×10^{-3}	1
Million tonnes of oil equivalent	4.5×10^{4}	1.4×10^{-3}	4.3×10^{7}	0.043	7.33

The first table shows the basic units, the most familiar of which is the kilowatt-hour (kWh) used for electrical energy. A joule is the metric unit for energy; but the joule-per-second, a unit of *power* called the watt, is better known. A kilowatt is then 1,000 W or a kilojoule (kJ) per second. Since there are 3,600 s in an hour, a kilowatt-hour is 3,600 kJ. The BTU, used well before the metric system was established, is still widely used and is conveniently close to 1 kJ. A tonne is a metric ton, equal to 1.1 tons. For energies outside the laboratory, industrial people often use barrels of oil equivalent (BOE), which is obviously imprecise, since it depends on the kind of oil and how efficiently it is burned; but it has been defined by the US Internal Revenue Service as 5.8 million kilojoules.

The second table shows the scaled-up units that one has to use to measure energies on a national or global scale. A terajoule (TJ) is a trillion (10^{12}) joules or a billion kilojoules. In scientific notation, the exponent (the superscript above the "10") is simply the number of zeroes after the "1." Here are the prefixes corresponding to the various multiplication factors:

Thousand: 1,000 (10^{3}), kilo-
Million: 1,000,000 (10^{6}), mega-
Billion: 1,000,000,000 (10^{9}), giga-
Trillion: 1,000,000,000,000 (10^{12}), tera-
Quadrillion: 1,000,000,000,000,000 (10^{15}), peta-
Quintillion: 1,000,000,000,000,000,000 (10^{18}), exa-

(continued)

Box 2.1 (continued)

A terawatt-year is 32 million terajoules, since there are that many seconds in a year. A large power plant generates about 1 GW of power, and thus a GW-year of energy per year. A terawatt-year is the annual output of 1,000 power plants. Since 1 BTU is about 1 kJ, a million BTU (MBtu) is about a billion joules or about 1 GJ. This size unit is used for partial energies. A Quad is a quadrillion (10^{15}) BTU or a billion MBtus, a unit appropriate for worldwide production. It is equal to 172 MBOEs, a unit often used in magazine articles as well as technical journals. We shall convert all graphs to Quads and MBtu's here, the saving grace being that they are close to the modern metric units.

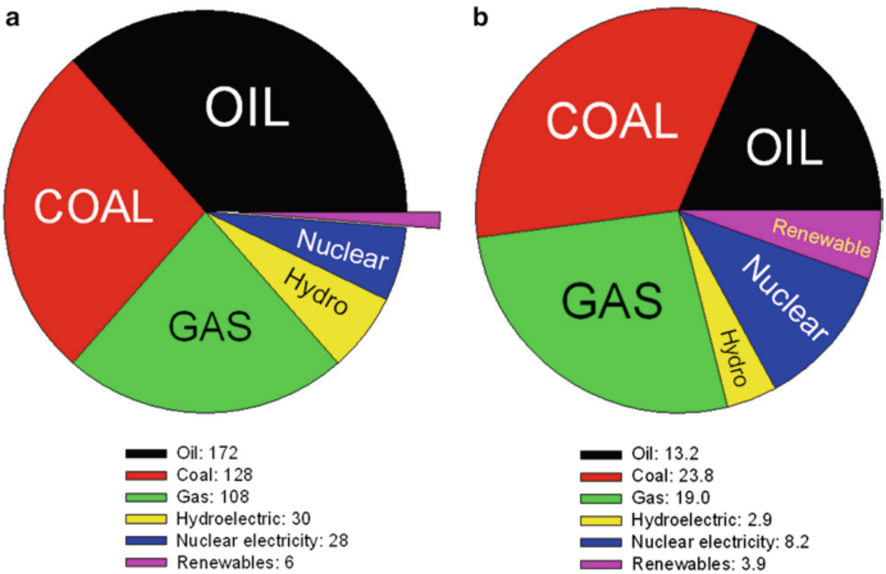


Fig. 2.1 Sources of energy consumed in (**a**) the world[1] and (**b**) the USA[5]. Data are for 2006 and are in units of Quads per year

Energy Consumption

The consumption of energy in the world and in the USA is shown in Fig. 2.1. For the world, the total of 472 Quads is dominated by oil, with all fossil fuels accounting for 79% of the total. For the USA, the total of 71 Quads is dominated by coal, with fossil fuels accounting for 86% of the total. Renewable energy, mainly from wind, solar, and biomass (wood and waste), amounted in 2006 to only 1.3% of the total in the world and 5.5% in the USA.

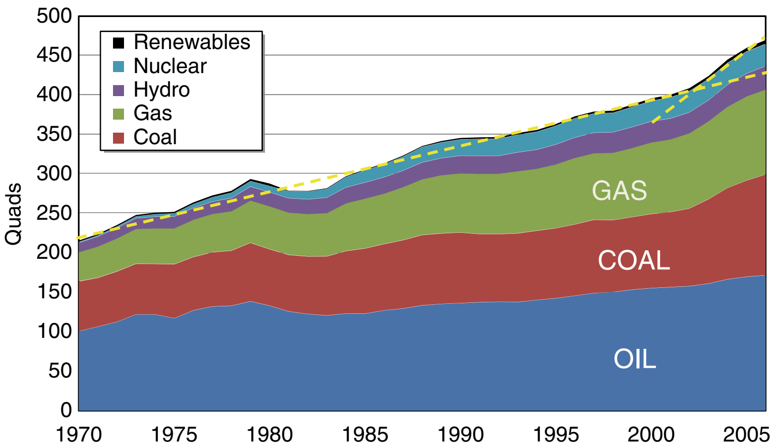
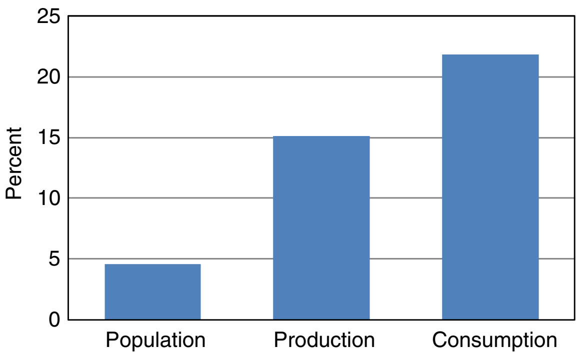


Fig. 2.2 36-Year history of the world's annual consumption of energy from various sources. The *dashed lines* show the average rate of increase from 1970 to 2002 and from 2002 to 2006 (Data from footnotes 1 and 5)

Fig. 2.3 The US share (in percent) of the world's population and energy production and consumption in 2005[1]



The growth of the world's energy consumption over the last 36 years is shown in Fig. 2.2, organized by source. The total dominance of fossil fuels is evident. The contribution of renewable sources is only the thickness of the black line at the top. The dashed lines show that the rate of increase of total annual energy was rather steady from 1970 to 2002 at about six Quads per year. However, the rate seems to have increased since 2002 to about 16 Quads per year.

Figure 2.3 shows the fraction of the world's resources that the USA consumes. We can see at a glance that the USA, with less than 5% of the world's population, consumes 22% of its energy. It is noteworthy that most of this energy, 15% of the total, is produced within the USA, as shown by the middle bar in the graph. The rest is imported. The USA is relatively rich in fossil deposits, and this explains why it has been lagging in the race to develop alternative sources. Countries like France, Germany, and Japan are more dependent on imports and have taken the lead in developing fossil alternatives.

Energy Forecasts

Estimating the energy the world will need in the future is risky business. We have to depend on computer simulations, as we did for climate change. Some of these models are the same ones used in Chap. 1, and they differ widely in the assumptions made in each scenario. Results up to 2030 are shown in Fig. 2.4. The middle bar in each group is the reference scenario, in which policies and laws remain unchanged. The low and high bars in each group are the minimum and maximum predictions across all scenarios. As expected, uncertainty increases with time, and so does the range of predictions. For the case of high economic growth, we see that the present consumption of some 470 Quads will grow to 760 Quads by 2030. By the end of the century, the level will be above 1,200 Quads. The problem is obvious: this doubling and then tripling of energy demand will occur while oil and gas reserves are being completely depleted.

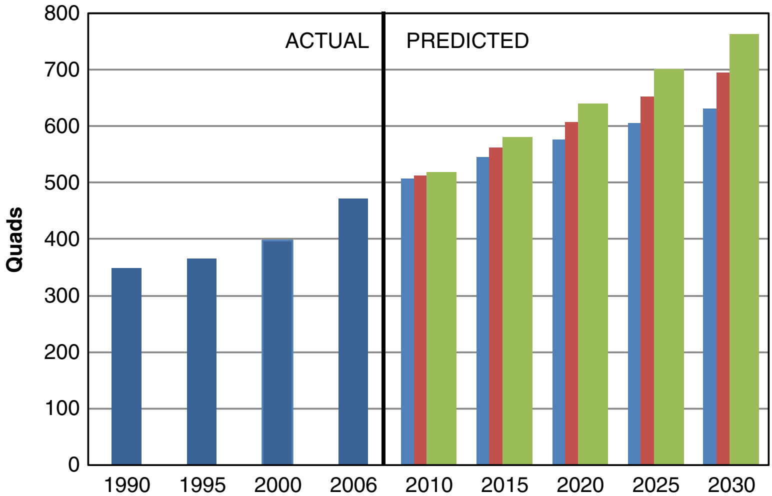


Fig. 2.4 Predictions of the world's annual energy needs up to 2030. The *triple bars* show the minimum, average, and maximum values computed using different scenarios (Data from footnote 1)

What Drives the Increasing Demand?

Population increase is one cause, but not the main one. The projections are shown in Fig. 2.5. In developed countries, the scenarios generally predict a slowing population growth peaking around 2040, followed by a slow decline to the end of the century. The underdeveloped countries in Africa and Latin America are responsible for the continuing increase to 2100. Experts believe that population will stop growing at 10 billion people, the most that the earth can support. After that, we will have to start colonizing the moon and Mars.

It is the productivity of man that drives the need for more and more energy, as shown in Fig. 2.6. One measure of this is the gross domestic product or GDP. This can be evaluated for a single, developed country; but to do this for the whole world requires dealing with different currencies and ways of accounting. For this reason, the GDP for the world is estimated differently by different sources; and the data for the past are not necessarily accurate. Nonetheless, projections for *growth* can be calculated using a consistent system. In Fig. 2.6, we have reduced the GDP data to US dollars of the year 2000. There we see that the GDP is expected to grow exponentially. This is in spite of the fact that the GDP per person in developed countries is expected to decline slightly. It is the industrialization of the rest of the world that drives energy demand.

To illustrate this, Fig. 2.7 shows energy demand in the high economic growth case of Fig. 2.4, broken down between OECD and non-OECD countries. The

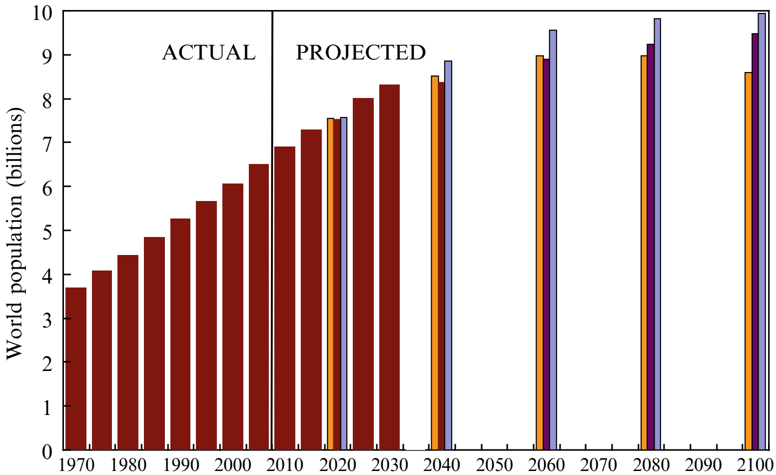


Fig. 2.5 Projections of population increase. The *triple bars* show the predictions of three different scenarios where this information is available (Data from Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, US Climate Change Science Program, Synthesis and Assessment Product 2.1a, 2007 and footnote 1)

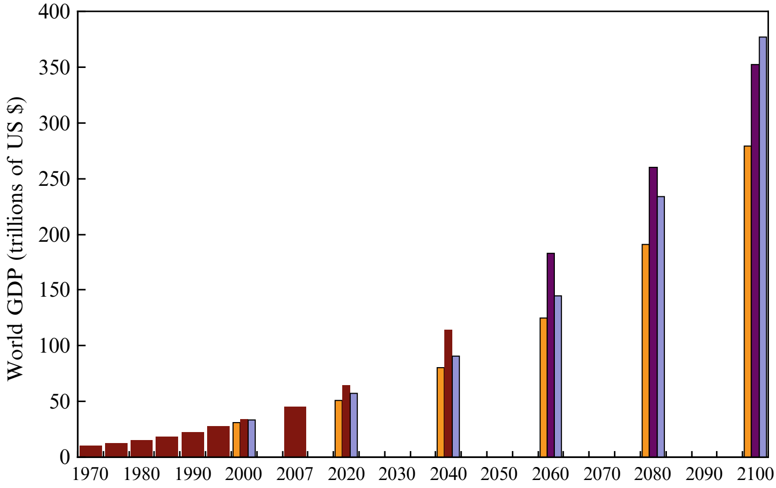


Fig. 2.6 Projections of gross domestic product increase. Units are in trillions of US dollars of year 2000. The *triple bars* show the predictions of three different scenarios from Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations, US Climate Change Science Program, Synthesis and Assessment Product 2.1a, 2007. The 2007 point is from the CIA World Fact Book

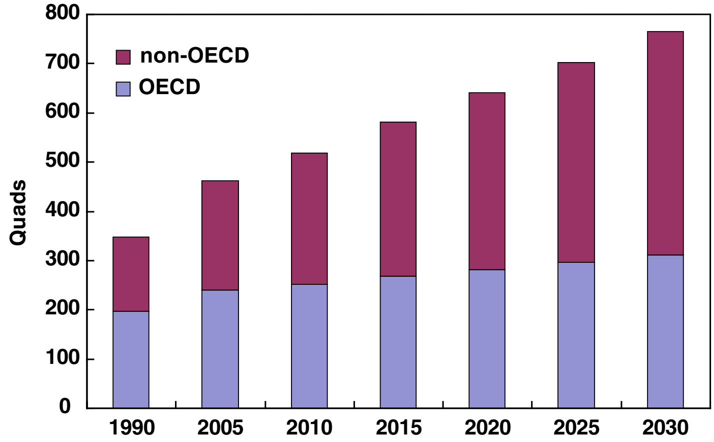


Fig. 2.7 Current and projected energy demand by OECD and non-OECD countries, in Quads (Data from International Energy Outlook 2008, Energy Information Administration, US Department of Energy. See also *World energy, technology, and climate change policy outlook 2030*, Directorate-General for Research (Energy), European Commission, Brussels (2003).)

Organization for Economic Cooperation and Development consists of some 30 industrialized countries mostly those in Europe and North America, plus Japan, South Korea, and Australia. The non-OECD countries include Russia, China, India, Africa, the Middle East, and Central and South America. It is clear that most of the growth is in the non-OECD countries up to the year 2030, and the projections of

GDP in Fig. 2.6 show even greater dominance of the non-OECD countries in the second half of the twenty-first century.

Can we believe these predictions? We may not trust what unseen scientists do with their computers, but this is the best information we have if we are to plan for the future. Doubters and naysayers are usually single persons who act on their intuitions without doing the homework. By contrast, the scenarios shown here are worked out by large groups of experts using massive amounts of data. The ground rules of a scenario are decided at the beginning, and widely differing approaches are taken to cover the spectrum of possible results. For instance, in predicting the path of underdeveloped countries, one scenario assumes that different localities modernize in isolation, following their own customs and ways of life, while another scenario assumes that communication is so good that all countries are connected by the internet and can share methods and economics with the rest of the world. The different regions have GDPs that increase at vastly different rates, but they tend to average out over the world. This leads to the scenario results of Fig. 2.6, which differ greatly by the year 2100 but nonetheless show a definite trend. In the energy projections of Fig. 2.4, these vastly different scenarios still agree within ±10% in the year 2030.

Where Does the Energy go?

Not all energy is the same. Electricity is the form of energy that governs the way we live in modern society; we depend on it in ways that we do not always appreciate. Much of the energy needed by underdeveloped countries will be for building an electricity infrastructure. The next four graphs will show where electricity comes from and where it goes. The readily available data here are for the USA.

Figure 2.8a shows that total energy use in the USA is shared almost equally by the transportation, industrial, residential, and commercial sectors, but they use

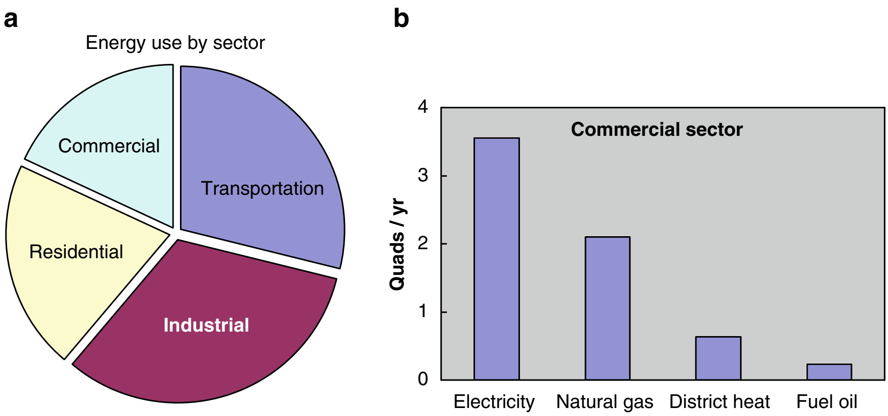


Fig. 2.8 (**a**) Energy use by sector and (**b**) energy sources for the commercial sector. US 2007 (Data from Annual Energy Review 2007, Energy Information Administration, US Department of Energy.)

different sources. Transportation energy comes almost entirely from petroleum (loosely called "oil" here). Industry burns most oil and natural gas ("gas"). In the commercial and residential sectors, electricity and gas are equally important, but electricity is fast overtaking gas, as seen in Fig. 2.8b for the commercial sector. In this sector, lighting and air conditioning in buildings use large amounts of electricity, much of which can be saved by strict conservation practices. In the residential sector, 31% of the electricity is used for space heating, cooling, and ventilation; and 35% for kitchen appliances and hot water. Lighting, electronics, laundry, and other uses take up less than 10% each.[2] Each household in the USA uses 1.2 kW of electricity steadily when averaged over day and night, winter and summer. There being 2.6 persons in each household on average, each person is responsible for about 470 W of electricity consumption.[2] The peak load is, of course, many times that; and power plants have to be built for peak demand.

To make things worse, making electricity is very inefficient. The losses are shown in Fig. 2.9a, and the sources of energy for electricity are shown in Fig. 2.9b. Two-thirds (69%) of the fossil energy used for electricity is lost in production! The main loss is in converting heat into electricity. The raw material, such as coal, has to be prepared to be burned. It then burned to produce steam, and the steam is used to drive a turbine (an electric motor in reverse) to generate electricity. Each of these steps takes energy. The main loss comes from an old thermodynamics principle called Carnot's theorem, which states that the best that any engine can do in converting heat to mechanical energy is to suffer a fractional loss equal to the initial temperature divided by the final temperature. For instance, if the steam is heated to 500°C (932°F) and cooled to 100°C (212°F) to drive the turbine, the absolute temperatures are about 770 and 370 K, with a ratio of about 0.48 or 48%. This is the part that is lost, leaving 0.52 for the part that can be used. So even if all is ideal, the efficiency cannot be more than 52%. Modern heat engines can exceed this figure,

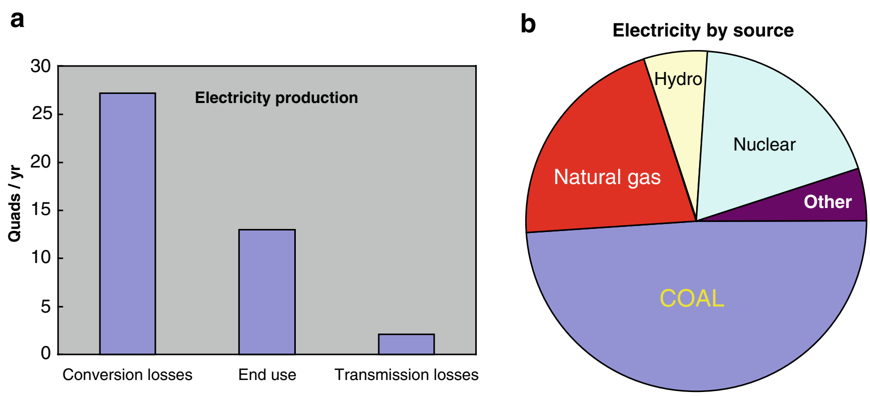


Fig. 2.9 (**a**) Losses in electricity production, expressed in Quads/year rather than a percentage; and (**b**) relative contribution of different sources of electric energy. US data for 2007 and 2003, respectively, from Annual Energy Review 2007, Energy Information Administration, US Department of Energy

but then the turbine is not perfectly efficient either. This conversion loss is shown in Fig. 2.9a. To this we have to add the losses in transmission and distribution, including the heating of the high-voltage cables and the transformers to step the voltage down to wall-plug values. These losses are given by the last column in Fig. 2.9a. What is left for use is the middle column there.

Our thirst for electricity comes at great cost. We are using precious fossil fuels very inefficiently. Systems that produce electricity directly without going through a heat cycle make much more sense. These are hydroelectricity, wind, and photovoltaic solar cells. Solar, unfortunately, has its own physical limits on efficiency, as will be seen later in this chapter. We see in Fig. 2.9b that by far the largest fraction of electricity comes from coal, the dirtiest of all fossil fuels! And we have not yet counted the fossil energy expended in mining, transporting, and refining coal. It is encouraging that the slice labeled "other," which includes wind and solar, appears larger than the splinter seen in our other pie charts. This is because they can produce electricity directly, without going through a heat cycle.

Energy Reserves

Here is the bottom line: how much fossil fuel the world has left, and how long it will last. The data are for 2007, and the heat equivalents have been reduced to Quads.[3] First, let us look at coal, the largest resource, shown in Fig. 2.10. The regions are as follows: Asia Pacific includes China, India, Japan, Korea, Australia, and other nations on the Pacific Rim. Europe and Eurasia include West and East Europe, the Former Soviet Union, Greece, and Turkey. North America is the USA, Canada, and Mexico. South and Central America is self-explanatory, and so is Middle East. Proven reserves are known deposits that can be mined using existing techniques.

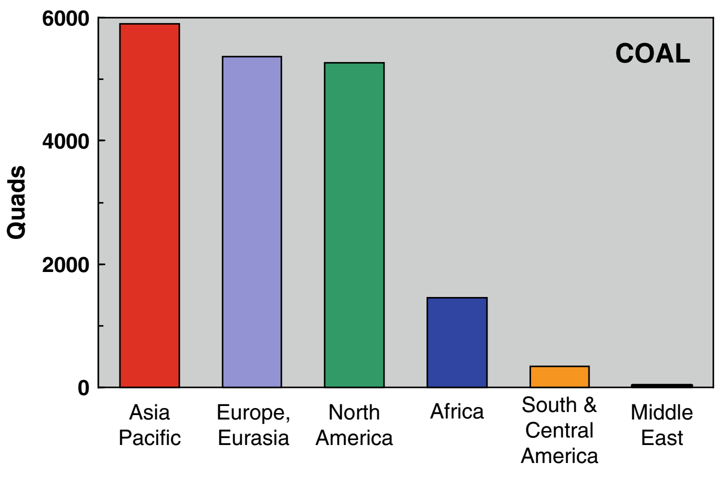


Fig. 2.10 Proven coal reserves by region (Data from BP Statistical Review of World Energy 2008.)

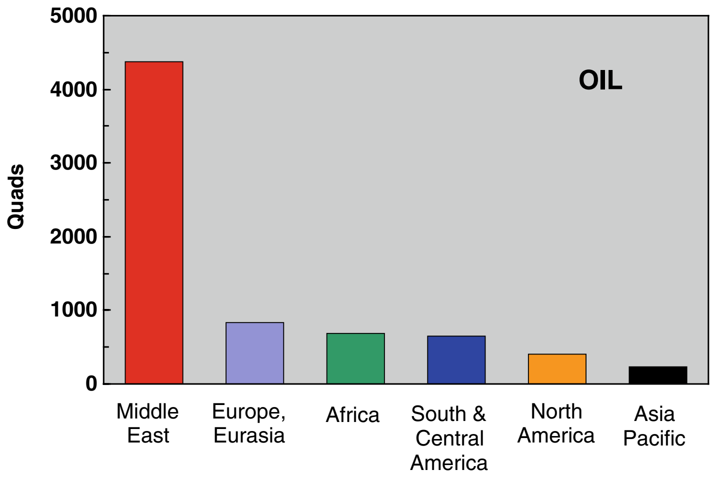


Fig. 2.11 Proven oil reserves by region (Data from BP Statistical Review of World Energy 2008.)

We see that coal deposits are concentrated in the first three regions and are practically nonexistent in the Middle East.

Petroleum, of course, is a different story. Figure 2.11 shows what we already know: most of the world's oil is in the Middle East. In addition to normal oil, there are reportedly large amounts of oil trapped in oil sands and shale oil in Canada. However, this oil is extremely hard to extract, and known methods are energy intensive. This oil is not included here because it would take a new technology to get a large net energy gain.

Natural gas reserves are shown in Fig. 2.12. The Middle East leads here also, but note the difference in scales. The amount of energy in gas is small compared with coal and oil.

The dominance of coal is more clearly seen when we put these reserves on the same scale, as done in Fig. 2.13. For oil, we see from the red columns that we will still be dependent on the Middle East for our main transportation fuel.

Now we come to the crux of the problem: how long will fossil fuels last? This is estimated by the R/P ratio, the ratio of Reserves to Production. Hubbert's Peak, mentioned in the Prologue, has been estimated numerous times, but more exact information is now available in the R/P ratio, shown in Fig. 2.14. If we take the fossil energy available in known deposits in each region and divide by the annual production of energy in that region, we can get the number of years the supply will last *if there is no trade*. Clearly, some regions will be more self-supporting energywise than others. In the real world, we import and export fuels; and the number of years the world's fossil reserves will last is shown at the right of the figure. Oil will be depleted in 42 years, natural gas in 60 years, and coal in 133 years. Note that the consumption rate has been *assumed to be steady at the 2007 level!* With the predicted increase in consumption shown in Fig. 2.4, these reserves will be gone in a much shorter time.

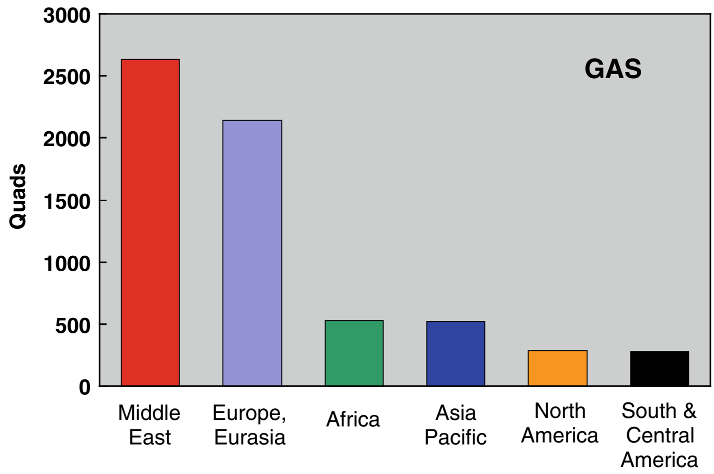


Fig. 2.12 Proven natural gas reserves by region (Data from BP Statistical Review of World Energy 2008.)

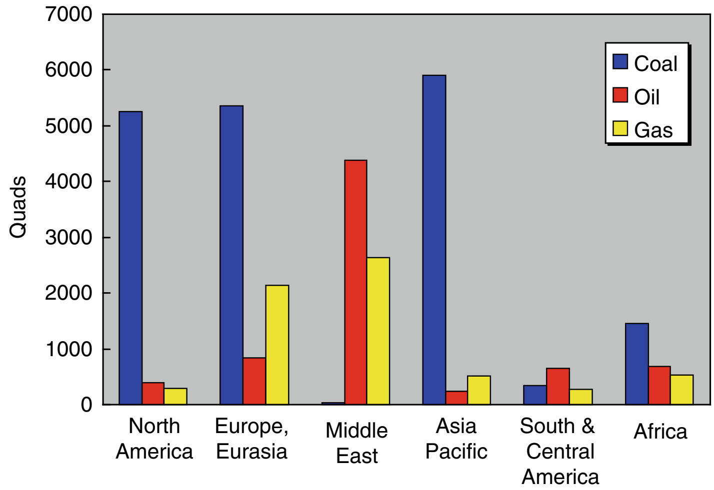


Fig. 2.13 Summary of the world's proven fossil reserves (Data from BP Statistical Review of World Energy 2008.)

Let us examine the case of oil, which is critical for gasoline and all our travels. In the Prologue, we mentioned Hubbert's peak, a prediction by M. King Hubbert in 1956 about the eventual decline of production as we run out of fossil fuels. The shape of the peak is usually shown as a smooth, symmetric curve like that in Fig. 2.15. The dots there are yearly data on oil production in the USA since 1900, expressed in Quads per year of equivalent thermal energy. We see that indeed the data lie on a Hubbert-type curve, and the peak was reached in 1973, the year of the oil crisis.

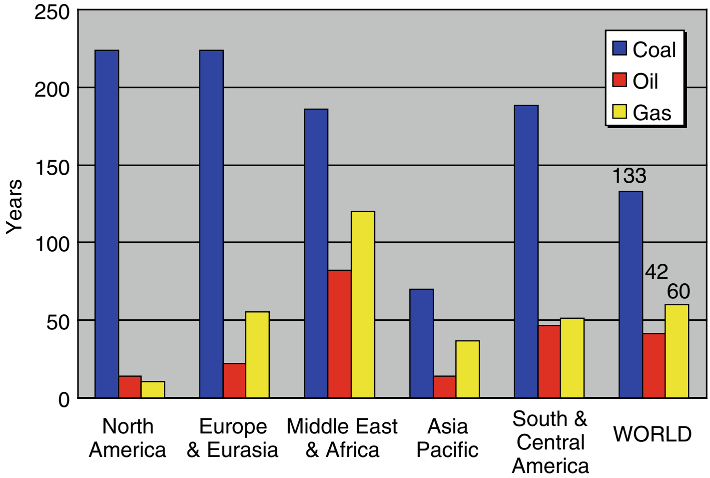


Fig. 2.14 Reserves-to-Production ratio for different regions and for the world (Data from BP Statistical Review of World Energy 2008.)

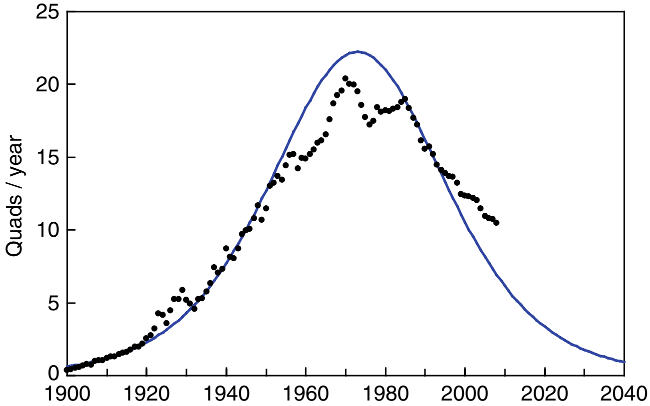


Fig. 2.15 Production of oil in the USA from 1900 to 2008 (*dots*), fitted to a Hubbert-type curve (*line*). The area under the curve is the total amount of oil in conventional deposits (Data from Energy Information Administration website)

US oil production has been declining since then, but clearly this is not true for the whole world. Figure 2.2 showed that use of all fossil fuels, including oil, is still increasing. What the USA lacks, it is importing from the Middle East. We are not changing our habits in airplane and car travel, or in the transport of food and merchandise in trucks. This means that the consumption curve will not be symmetric. It will keep going up and then crash rapidly when oil becomes more and more difficult to find.

When will this come? Figure 2.4 showed predictions of the world's fossil fuel consumption up to 2030. We can get specific predictions for oil for that period from the Energy Information Administration's Reference Case.[1] Using the average rate of increase of 1.2% per year, we can predict the annual consumption beyond 2030. Then, knowing the total amount of oil reserves in conventional deposits in 2007 (7,180 Quads) from footnote 3, we can calculate how those reserves decrease year by year. This is shown in Fig. 2.16. *The oil reserves in the world will be depleted by 2040*. Though this seems to agree with Fig. 2.15, it is different. First, this is for the whole world, including the Middle East, not just the USA. Second, the drop will be much sharper, as shown by the dotted line, since the consumption rate keeps going up until the price of oil becomes prohibitive. It will become imperative to use alternative fuels, so complete depletion of reserves can be avoided. Oil consumption (the same as production when the whole world is involved) will decrease much faster than it rose, giving an asymmetric Hubbert curve. There are unconventional sources which can be tapped at great cost, but this would extend the curve only slightly. The point here is that the *world's* oil will soon be depleted. The world cannot import oil from elsewhere the way the USA can.

The need for petroleum can be mitigated several ways. Cars can be made much more efficient if they are, for instance, made of carbon fiber instead of heavy steel. Current gasoline engines are terribly inefficient. Only 1% of the energy is used to move the driver, and only 10% to move the car; the other 90% is lost in heat.[4] Gas–electric hybrids are already marketed and can double gas mileage. Electric plug-in vehicles use no gas, shifting the burden to the more abundant fuel, coal, which

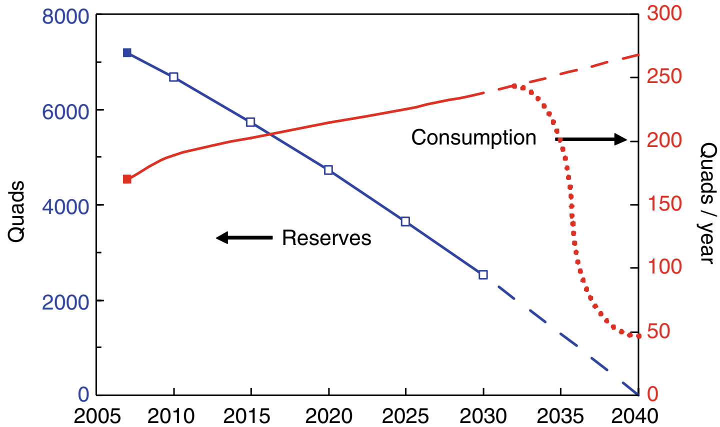


Fig. 2.16 Predictions of world oil reserves (*blue line*, *left scale*) and annual consumption (*red line*, *right scale*). The 2007 points (*solid squares*) are actual data. The *hollow squares* are from computer simulations; the *dashed lines* are extrapolations; and the *dotted line* is a conjecture (Data from BP Statistical Review of World Energy 2008 and International Energy Outlook 2008, Energy Information Administration, US Department of Energy. See also *World energy, technology, and climate change policy outlook 2030*, Directorate-General for Research (Energy), European Commission, Brussels (2003).)

can be burned more efficiently at high temperature at central power plants. Alternate fuels such as hydrogen and ethanol have their own problems, which will be discussed in Chap. 3. The buying public's preference for horsepower and speed has to change to one for fuel efficiency. It will take many decades to change the manufacturing infrastructure from one making steel parts and gas engines to another making carbon parts and efficient new types of engines. Changing the infrastructure of fuel distribution (gas stations and pipelines) will also require decades. Thus, the oil problem is already upon us.

We have stressed oil as the most imminent problem, but all fossil fuels will soon have to be replaced. It has been said that there is no shortage of coal, which may be true for North America and Europe, but not for the entire world. China is building a new coal plant every week, thus depleting its reserves rapidly. In Fig. 2.14, the Asia Pacific region already has the lowest amount of reserves compared with its consumption rate. Eliminating greenhouse gases from all coal plants will be very costly, if at all possible. As for oil, it does not make sense to burn up this precious resource when it should be saved for special applications, such as making plastics. By the time, oil and gas run out by mid-century, their entire energy slices in Fig. 2.2 will have to be filled by nuclear, fusion, and renewable energy. Renewables like wind, solar, and biofuels would have to expand a 100-fold to make up the difference. Nuclear energy can do it by expanding 17 times, but it has environmental problems. These sources are discussed in the next chapter. They would be needed, together with continued use of coal, to fill the energy gap in the first half of this century. *If fusion can be online by mid-century, it will help. It will definitely be needed for the second half of the century. By 2100, with even coal and uranium running out, fusion should become the main source of backbone power*. How fusion works and its difficult development will concern us in Part II.

Coal and Carbon Management

Coal is the major problem. It supplies 27% of the world's energy and 40% of its electricity. In the USA, coal supplies 23% of all energy and a whopping 49% of electrical energy.[5] Coal is also the worst CO_2 emitter. In 2007, CO_2 emissions from coal burning amounted to 2.65 billion tons in China and 2.20 billion tons in the USA.[6] No other nation was responsible for more than 0.54 billion tons. No wonder, since China and the USA produced 41.1 and 18.8% of the world's energy from coal because of their large deposits.[3] It is easy to see why coal is so dominant: it is cheaper than oil or gas; there is a large supply of it; and it is easy to transport by rail. The mines are not remote; no pipelines need to be built; and there is no need for tankers which occasionally crash and foul our beaches.

Coal is bad news also because it causes deaths in mining accidents, it destroys the environment when whole mountains are dug up, and it emits many pollutants such as sulfur. We all remember stories of families waiting in vain for news about their loved ones trapped miles deep in the earth with no hope of rescue. In the USA alone, 100 million tons of coal ash and sludge are stored in 200 landfills annually, and these contain dangerous contaminants such as arsenic, lead, selenium, boron, cadmium, and cobalt.[7] The problems are exacerbated by the rapid development of China, where coal plants are being built at the rate of one large one in a week, while the USA has stopped building them as of 2007. Let us concentrate on this biggest problem: the unstoppable industrialization of China and India. In China, 74% of energy comes from coal, and this will increase to 90% with continued growth, though efforts to develop renewables may hold the line at 70%.[8] China has about 30,000 coal mines, 24,000 of which are small ones which use antiquated equipment and are not regulated for safety. In 2006, 4,746 miners died in China, versus only 47 in the USA; both numbers are down from those in earlier years. Chinese coal generates every year 395 billion cubic meters of methane, SO_2, and black soot, all of which have larger warming potential than CO_2. Furthermore, the methane is what causes explosions in mines, and the SO_2 causes acid rain. Of the million people in China suffering from black lung disease, 60% are miners. This disease increases the coal mining death total by 50%.[8] It is not likely that other energy sources can replace coal any time soon, but we can try to mitigate its effect on global warming.

Cap and Trade

The coal industry will not do anything that lowers its profits without government intervention. What is being done in most developed countries is to legislate a decrease in carbon emissions by a certain deadline. The Cap and Trade system allows large utilities to meet these standards without a sudden capital expenditure. However, Cap and Trade does not directly lower total CO_2 emissions. It works as follows. An emissions cap is legislated for each industry, and this cap is divided into credits, in terms of tons of CO_2, that that sector is allowed to emit. Credits are then auctioned off. Heavy emitters, such as a large utility, may find it less expensive to buy credits than to build equipment to reduce emissions, while light emitters, such as a modern, efficient plant, can sell the credits that they do not need. Both utilities would gain financially. To make this work, the government has to establish a fraud-proof monitoring system and assess severe penalties for noncompliance.

Unfortunately, Cap and Trade does not actually decrease carbon emissions because, in the example above, both utilities would emit the same amount of CO_2 that they would without trading credits. It actually allows the large utility to delay investing in the equipment for capturing CO_2, when it should be forced to do it as soon as possible. New power plants using solar or wind energy can sell their credits to coal plants, but these producers of green power are being built *anyway* because they are profitable, not because of Cap and Trade. Cap and Trade does not force industries to lower their emissions if they are already taking steps to do this because of societal concerns or because it is profitable publicity-wise. Only *additional* low-carbon plants should be counted, not those that already exist or are planned.

Loopholes in the scheme allow accounting tricks to get around doing anything constructive. The only advantage of Cap and Trade is to make large polluters aware of what is coming and begin to worry about it.

Carbon Sequestration

To continue using coal, we have to capture the emitted CO_2 and bury it. This is called carbon capture and storage (CCS), but we will continue to avoid acronyms when possible. There are three steps: first, CO_2 has to be separated from the flue gas out of a coal burner; second, the CO_2 has to be transported to a burial site; and third, it has to be injected into a geological formation that can hold it forever. The last part is of course highly debatable; but it is the first part, capture, that is the most expensive. There are three basic ways to do this.[9] In the first method, the flue gas is mixed with a liquid solvent called MEA into which the CO_2 dissolves. The MEA's chemical name is not always spelled the same way, but it is a corrosive liquid found in household products such as paint strippers and all-purpose cleaners. When the MEA is heated to 150°C, pure CO_2 is released, and the MEA is cleaned up with steam to be reused. This method can be retrofitted to existing plants, but there is a huge penalty. The heating and steam production takes up to 30% of all the energy produced by the power plant! The cost of this step can be as much as four times higher than that of the other two steps. At the moment, other absorbers are being tried to lower this cost.[10]

In the second method, the flue gas mixture is controlled by burning the coal in a specific way. When it is burned in air, which is 80% nitrogen and 20% oxygen, there is a lot of nitrogen in the mix, and N_2O is a greenhouse gas. A better way is to remove the nitrogen from air at the outset and burn the coal in pure oxygen. What comes out is water and pure CO_2, ready to be sequestered. However, separating the nitrogen from the air to get pure oxygen requires 28% of the power plant's energy, still a steep penalty. This method is being tested by Vattenfall, Sweden's energy company, in the town Schwarze Pumpe in Germany. The experiment is fairly large – 30 MW – but not of electric utility size. A novel feature was added to this "oxyfuel" process: the flue gas is recirculated into the burner with the oxygen. This keeps the temperature low enough to prevent melting the boiler walls, as would happen with pure oxygen. In effect, the CO_2 in the flue gas replaces the nitrogen in air, diluting the oxygen without using nitrogen.

The third method is coal gasification: the coal is heated to a high temperature with steam and oxygen, turning the coal into a gas, called syngas, which is a mixture of carbon monoxide (CO) and hydrogen (H_2), plus some nasty contaminants. After the syngas is purified, it is the fuel for generating electricity in an "integrated gasification combined cycle," or IGCC, an acronym that seems unavoidable in this case. Coal gasification has been tested in fairly large power plants, but the IGCC sounds like a Rube Goldberg type contraption that has yet to be verified on a large scale. An air separation unit to get pure oxygen is still required both for syngas generation and for burning the syngas later. After the pollutants are taken out, the gas goes into a chamber where the CO combines with steam (H_2O) to form CO_2 and H_2. Pure hydrogen is separated out through a membrane, giving carbon-free fuel. The rest of the gas, containing CO_2, CO, and H_2, is burned with oxygen in successive turbines, a gas turbine and a steam turbine, to generate electricity. The pure hydrogen separated by the membrane can be sold or burned to generate more electricity cleanly. The IGCC can be 45% efficient, compared with 35% in ordinary coal plants limited by the Carnot theorem that we described earlier. Meanwhile, the CO_2 generation is lower, and it comes out in pure form to be stored. This separation system adds only 25% to the cost of electricity. An even more efficient method called chemical looping is under development.[9] New chemical structures for capturing CO_2 are described in Chap. 3 under Hydrogen Cars.

In 2003, the FutureGen Alliance had proposed a plan to test IGCC on a large scale by building a $1 billion plant in Illinois, finishing in 2013. That project was canceled by President G.W. Bush in 2008 because the projected cost had almost doubled. Unbelievably, this figure was an accounting error; the actual increase was to only $1.5 billion. Under President Obama, Energy Secretary Steve Chu has pledged $1.1 billion of economic stimulus money to restart the project, with the other funds to be raised by FutureGen. There is $2.4 billion of stimulus money slated for CCS research. This is to be compared with $3 billion spent by the Department of Energy for this purpose since 2001.

Now that we have separated out the CO_2, the problem is where to put it. There are three main places: old wells, underground, and undersea. The oil and gas that we mine have been trapped in the earth for millennia, so it is possible that porous rock or underground caverns can hold liquids and gases stably. To carry CO_2 to these sites, the gas has to be highly compressed to a small volume and transported by truck or rail. This step entails a certain amount of danger, should there be an accident causing the container to explode and release tons of CO_2 into the atmosphere. The gas is then injected under pressure into depleted oil or gas wells, where it could stay for millennia if it were not for the leaks made in drilling the wells in the first place. These old wells have to be sealed tightly. The trouble is that carbon dioxide and water combine to form carbonic acid, and the seal has to withstand this acid attack. This storage solution is well tested because it is used to store excess gas and oil mined in the summer for use in the winter. The difference here is that the storage has to be stable essentially forever. The possibility of leaks has to be carefully monitored. Injection of CO_2 into oil wells is actually beneficial, for it helps to push the oil up. Toward the end of life for an oil well, the oil gets quite thick; and gas, which might as well be CO_2, is injected to lower the viscosity. This is what happening in those nodding pumps seen along the California coast.

There are many large subterranean formations that can hold carbon dioxide. These are porous sandstone deposits covered with a cap of hard, impervious rock. For instance, such a depository has been found below a little town called Thornton somewhere south of California's capital of Sacramento. It is estimated that it can hold billions of tons of CO_2 in its pores, enough to store away hundreds of years of California's emissions.[11] Of course, no one knows whether it will leak.

Fig. 2.17 The Sleipner Platform in the North Sea (http://images.google.com)

There are plans to drill into this formation and test it, to the dismay of local residents. The reaction, NUMBY (Not Under My Back Yard!), is a switch from NIMBY (Not In My Back Yard!), an epithet used against wind and solar power.

Large geologic formations under the sea have also been found for CO_2 storage. These are layers of porous sandstone called saline aquifers lying deep below the seabed and capped by impermeable slate. Storage in these aquifers is the only sequestration method that has been tested on a large scale, and this is a story in itself.[9, 11–13] The Sleipner Platform, shown in Fig. 2.17, is a huge oil drilling and carbon sequestration plant located in the middle of the North Sea, halfway between Norway and England. It was built in 1996 by Statoil, Norway's largest petroleum company to produce oil while testing sequestration. Built to withstand the frigid conditions and storms with 130-mile winds and 70-foot waves, it houses a crew of 240 whose jobs are considered the most dangerous in the world. Below Sleipner lies not only a rich field of natural gas but also a saline aquifer called the Utsira Formation lying a kilometer below the seabed (Fig. 2.18). The aquifer is very large: 500×50 km in area and 200 m thick. It can hold 100 times Europe's annual CO_2 emissions.

There was a special reason to build sequestration into the plant *ab initio*. The gas from the Sleipner field contains about 9% CO_2, too high to burn properly unless reduced to 2.5%. The gas has to be scrubbed using the MEA solvent described above, thus releasing a million tons of CO_2 a year that has to be stored. The way the CO_2 is injected involves a little physics. It is compressed to 80 atmospheres because at this pressure it turns into a liquid about 70% as dense as water. So it is stored as a liquid. When it is mixed with the salt water in the aquifer, it tends to rise, since it is less dense. One worries how fast it moves and whether the 200-m thick layer of shale above the storage volume can spring a leak. Such leaks can arise from drilling through the cap to inject the gas, and these holes have to be carefully sealed with acid-proof material. Statoil has spent millions of dollars to develop a way to measure the spreading and leaking of the CO_2 using sound waves. Since the system has 25-m resolution and the area is measured in kilometers, the amount of data is many megabytes. These data clearly show that the CO_2 is spreading sideways as well as upwards, and that there are no leaks so far. In the best scenario, the CO_2 will eventually dissolve into the brine (in 1,000 years or so) and thus become a liquid heavier than water. This then moves safely downwards, and on a geologic timescale will turn into a mineral, thus locking the carbon away permanently. All fossil fuels will be but a distant memory by that time.

The Utsira formation is unusual in that it is located at the same place as the gas deposit, so that no transportation of the CO_2 is necessary; but it is not unique as a large burial site. It is estimated that the USA has subterranean reservoirs capable of storing 4 trillion tonnes of CO_2, enough to take care of its emissions until coal runs out. Statoil would not have built the Sleipner plant if it did not have to pay an annual $53M carbon tax imposed by the Norwegian government. Global warming cannot be halted without strong legislation by enlightened political leaders. The cost of separating the CO_2 and burying it is estimated to be about $25–$50 per tonne. Though this may come down as new techniques are developed, it is still a huge expense. Three tonnes of CO_2 is produced for each tonne of coal burned, and a fairly large (1 GW) coal plant gives off 6 million tonnes of carbon dioxide per year. The cost of up to $300M would be passed on to the consumer. That is not even the main problem. It is simply not possible to make a fundamental change in all coal plants or to build enough new-technology plants in a short time. Up to now, except for Sleipner, only small, scattered projects for cleaning up coal have been funded,

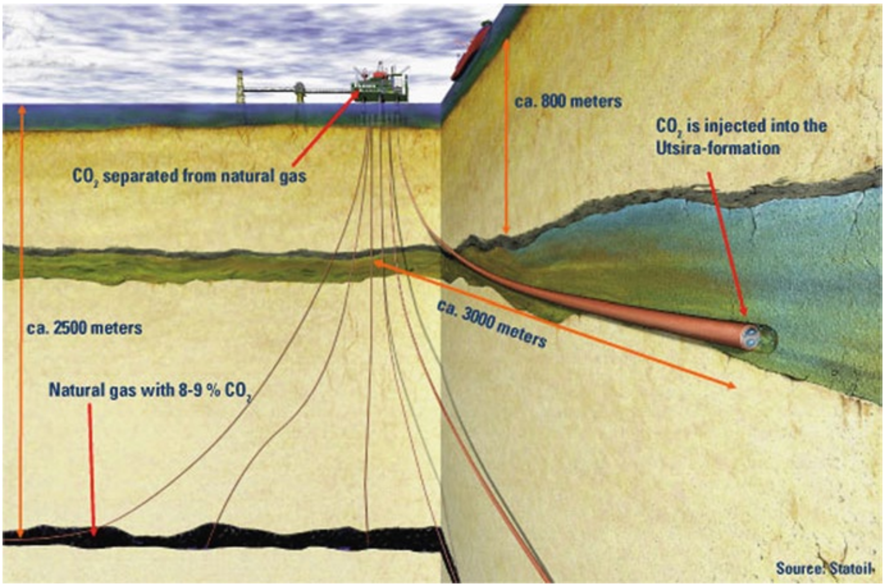


Fig. 2.18 Diagram of the gas field and saline aquifer below Sleipner (http://images.google.com)

with no integrated plan for replacing all dirty coal power with clean coal power. This is in stark contrast to the ITER project for developing fusion power; there, even the political problems of a large international collaboration have been tackled and solved. It may take two or three decades to clean up all coal power, and this is no shorter than the time needed to commercialize carbon-free renewable sources.

Oil and Gas Pipedreams

We discussed the shortage of oil earlier in this chapter but gave short shrift to natural gas, which supplies as much energy as oil, as seen in Fig. 2.1. That is because gas and oil mostly occur in the same places, are mined the same way, and are similarly depleted. We also ignored the minor overlap between oil and gas: oil can be converted to propane and butane gases, which we use for camping and power in remote houses; and gas can be liquefied at low temperatures for more convenient transport as LNG (liquefied natural gas). In this section, we will again consider these fuels together as we consider the various proposals for extending their supplies.

The price of oil can jump wildly, as it did in 2008–2009 from higher than $140 to less than $40 per barrel, and it can jump back. The price of gasoline follows, and this has a great effect on the economy as people travel less and buy fewer large cars. The gas crisis of 1973 even triggered legislation setting the speed limit in the USA at 55 miles per hour. These rapid changes are not our concern here; we are worried about the end of oil and gas altogether. In 2007, BP (British Petroleum) reported that proven reserves are 15% higher than previously thought, so that oil will last another 40 years,[14] 30 more than predicted in Fig. 2.16. There was widespread doubt, however, about this result from a normally reliable source. For instance, the IEA (International Energy Agency) assessed the top 400 oil fields and found them old and in bad condition.[15] They did not see how the present consumption of 87 million barrels per day can exceed 100 million, much less than the 116 million predicted by 2030. Similarly, the six oil fields that produce 90% of Saudi oil were found to be greatly depleted.[16] In the USA, the crunch is already felt as the Alaskan pipeline, built in the 1970s to carry most of our domestic oil and gas, is carrying only one-third as much these days because the wells at Prudhoe Bay are being depleted at the rate of 16% per year. Figure 2.19 shows that discoveries of new oil fields have been declining since 1964.[17]

Russia exports more oil and gas than any other country. It produces 11.8% of the world's oil, compared with 9.9% for Saudi Arabia and 12.4% for Iran, United Arab Emirates, Kuwait, and Iraq combined.[15] Its state utility, Gazprom, is so powerful that it held the Ukraine and other parts of Europe at its mercy by shutting off gas deliveries through its pipeline. The politics of gas and oil are changing. The former holders of power, ExxonMobil, Chevron, BP, and Royal Dutch Shell are being replaced by the new "Seven Sisters": Aramco (Saudi Arabia), Gazprom (Russia), CNPC (China), NIOC (Iran), PDVSA (Venezuela), Petrobas (Brazil), and Petronas

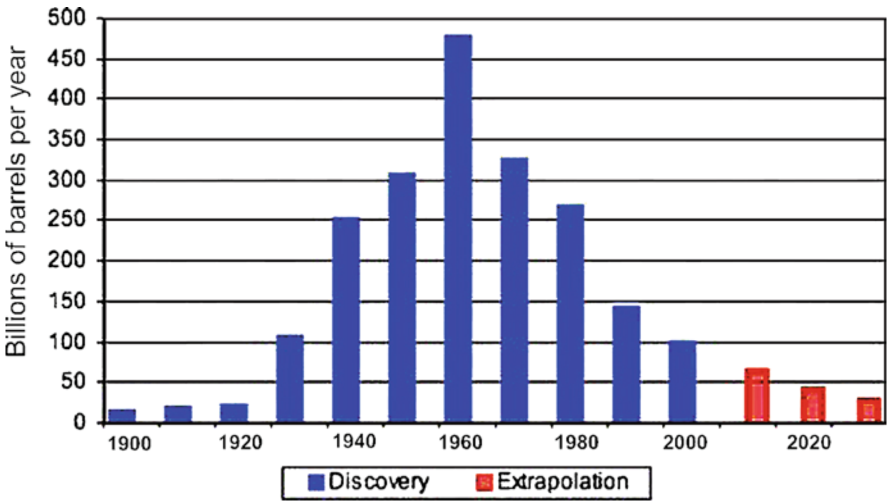


Fig. 2.19 Rate of oil discoveries since 1900 (http://www.theoildrum.com)

(Malaysia).[18] The IEA predicts that 90% of new oil and gas discoveries will come from developing nations. We will next show the different ways in which the industry is trying to explore beyond "proven" reserves.

Deep Drilling

There are new oil fields to be found if one is willing to drill deep enough. In addition to the Caribbean, deeply lying deposits are believed to exist in the North Sea, the Nile River Delta, the coast of Brazil, and West Africa.[19] To see how hard this is, consider Chevron's Jack 2 well, 175 miles offshore in the Gulf of Mexico. The drill goes 1 mile in water down to the bottom, then four more miles down into the ground. To find such large deposits, modern supercomputers are used to analyze seismic signals in three dimensions, requiring the processing of huge amounts of data. A new generation of drilling rigs had to be built to go twice as deep as ever before. These platforms, almost as large and as dangerous as that at Sleipner, cost half a million dollars a day to rent, but they could still be profitable if oil prices stay above $45 a barrel. This large deposit could yield 15 billion barrels, just a drop in the bucket compared with the world's proven reserves of 1,200 billion barrels. New deposits have been found that can be accessed only by *horizontal* drilling.[20] From a central platform, pipelines are drilled down and then horizontally out to deep-lying deposits kilometers away. The oil collected from these wells is then pumped to the mainland in a large pipeline. Figure 2.20a shows what a normal-size drilling rig looks like when the weather is nice. These are ships that go wherever they are needed. Storms and uncontrolled fires make oil drilling a dangerous occupation. An oil platform under less ideal circumstances is shown in Fig. 2.20b.

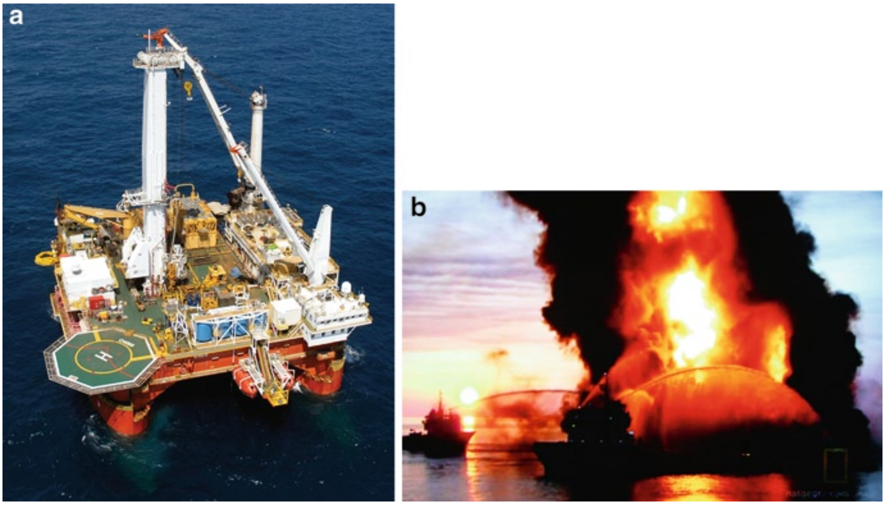


Fig. 2.20 (**a**) A drilling vessel in the Gulf of Mexico (http://images.google.com); (**b**) The Deepwater Horizon, 2010 (National Geographic Channel, July 2010)

These words, written previously, were brought to a focus when the Deepwater Horizon platform in the Gulf of Mexico exploded on April 20, 2010, killing 11 workers. The huge rig burned for days, and the oil leaking into the Gulf was uncontrolled, contaminating thousands of square miles and disrupting the fishing and shellfish industries in Louisiana. The damage to aquatic and avian wildlife is yet to be determined. Before the leak was capped in August, 4.9 million barrels of oil had been released, exceeding the 3.3 million barrels in the Ixtoc 1 blowout off the Yucatan peninsula in 1979. These numbers overwhelm the 257,000 bbls from the 1989 Exxon Valdez tanker spill in Alaska, whose effects are still felt 30 years later. Energy giant BP, owner of the Deepwater Horizon, suffered severe economic losses. The accident triggered legislation to regulate and restrict deepwater drilling. Aside from ecological concerns, it is becoming apparent that it would be cheaper to develop a substitute for oil than to ferret out the last of the earth's deposits.

Arctic Drilling

There is more oil and gas to be found if you are willing to endure conditions in freezing, inhospitable places. Russia owns a lot of property where no one wants to go. North of Japan lies Sakhalin Island, where they used to send prisoners. The deposits there contain 14 billion barrels of oil and 2.7 trillion cubic meters of gas.[21] Shell and Royal Dutch want to build an 850 km (500 mile) long pipeline to carry LNG to the USA. This is still being contested by Russia. The third largest gas field in the world is at Shtokman, in the Barents Sea near Murmansk, the largest city north of the Arctic Circle. That reserve contains 3.2 trillion cubic meters of gas, compared with 177 trillion in proven reserves. Western companies are bidding to get a part of this. But the cold conditions require the latest equipment and hard-learned techniques. There are icebergs, and shore is 550 km (340 miles) away. A pipeline on the bottom could be scraped by icebergs. Worse yet, antifreeze (glycol) has to be added to prevent the gas from reacting with the water that comes with it to form gas hydrates (more on this later), which can clog up the pipe. The water and glycol have to be separated out later. These arctic mining techniques are being tested in the Snohvit gas field in Norway. It may take $3 trillion to exploit these reserves.[22] It is clear that Russia can afford to do this only with foreign investment.

The Arctic north of Canada contains oil and gas fields made more accessible by the shrinking ice cap and the opening of the Northwest Passage. The US Geological Survey estimated that between 25% (some say 10%) of the world's "undiscovered oil reserves" could lie in the Arctic.[23] This is, of course, an oxymoron. How would you know how much is undiscovered? One deposit was estimated to contain 31 billion BOE in gas, enough to supply the US for four years. The problem here is a political one: no one knows who owns these deposits. North of Canada is also north of Russia, and the Russians planted a Russian flag at the North Pole. Stay tuned.

Shale Oil

Far below sagebrush country where mule deer and sage-grouse roam in Colorado, Utah, and Wyoming, there lie layers of organic marlstone bearing oil. The USA is reported to have two of the world's 2.6 trillion barrels of shale oil locked in the rock there. Of this, 800 billion barrels are deemed recoverable, 2/3 as oil and 1/3 as gas. By comparison, the proven oil and gas reserves of the Middle East total 1.2 trillion BOE. But to get it out, one has to essentially boil rock. Rather than digging up 200 million tons of rock per year to get a million barrels of oil a day, it is less destructive to get the oil out *in situ*, by drilling rather than digging. In western Colorado, Shell Oil has drilled 1,000-foot deep holes to test the feasibility of this process, which works as follows. Three holes a few feet apart are drilled into the shale. In two of them, electric heaters, like toaster wire, are inserted in pipes to heat the rock to some 700°F (370°C). It takes months or years for the rock to reach this temperature, and it has to be kept there for the life of the well, say 10 years. Fortunately, earth is a good insulator. The gas and oil are boiled out of the rock and can then be pumped out conventionally in the third pipe and sent in a pipeline to a processing plant. Mentioning electricity used for heat should raise your hackles because electricity is much more efficient for mechanical work than for heating. That is why your microwave or toaster runs on 1,000 W while a large window fan uses only 100 W. *In situ* mining uses electricity generated by a conventional power plant that loses 69% of the fossil fuel energy that it consumes, as can be seen above in Fig. 2.9a.

Will mining shale oil produce net energy? It is marginal. Let us do a back-of-the-envelope calculation to see if shale mining can be in the right ballpark. One ton (2,000 lbs) of shale will yield 25 gallons of oil.[24] It is easier to use metric units: 1 ton is about 0.91 metric tons (tonnes). At 42 gallons per barrel, we get 0.65 bbls of oil per tonne of shale. If we were to heat water, that would take 1 C/g/°C, so 1 tonne (a million grams) would take a million calories per degree centigrade. One calorie is about 4 J, so a million calories is 4,000 kJ. It is easier to heat rock, however. The specific heat of rock is only about 0.2, so now we only need 800 kJ per tonne per degree centigrade. We have to heat it by 700°F, which is about 380°C. To heat one tonne of rock by 700°C then requires 800×380 or about 300,000 kJ. From Box 2.1, we see that 1 kJ equals 1.6×10^{-7} BOE, so 3×10^{5} kJ equals about 0.05 BOE. But we get only 0.65 bbls from 1 tonne of rock, so 1 bbl of shale oil requires 0.08 BOE of electrical energy for heating alone. If the electrical plant is 30% efficient, 1 bbl of shale oil needs 0.25 barrels of *real* oil for heating. To this we have to add the energy to run the refining plant. Using microwaves to heat, as proposed by Raytheon,[25] would be even less efficient.

In addition to all this, it is planned to build a "freeze wall" to keep oily liquids from seeping into the groundwater. This would be a wall of existing rock and water 1,800 feet deep and 20 feet thick surrounding the drill sites. By drilling more pipes, a cold ammonia solution is circulated to keep the wall at freezing temperature. Since refrigeration is even more inefficient than heating, this could double the electrical cost, and we would get only two barrels of shale oil for each barrel of oil equivalent in, say, coal used to generate the electricity. There would be an advantage in that oil is a liquid and much more valuable than coal for transportation. Destruction of the environment is a high price to pay for this marginal fossil resource.

Estonia provides an example of what happens if shale is strip-mined.[26] There, shale oil provides 70–90% of the electricity. Shale is crushed to 6–10 mm size (about 0.5 in.) and burned in boilers topped by 250-m high chimneys. The ash and pollutants are blown up the chimneys, and the large particles of shale are re-burned when they fall back down. CO_2 emission is 10 million tonnes a year. Only after new boiler technology from Foster-Wheeler of the USA was adopted did the SO_2 and N_2O emission fall below acceptable levels. Solid slag is piled up 100 m high. Five million tonnes of ash are produced annually. This is pumped with waste water into a huge lake formed by a surrounding levee 30 m high. This blue-green lake looks nice but is a toxic stew containing potassium, zinc, sulfates, and hydroxides.[26]

Tar Sands

If you thought shale oil was bad news, you should see what tar sands are like. At least shale is in one solid piece. Tar sands are a mixture of oil, sand, water, and worse yet, clay, made of very fine particles. To get the oil out is harder than cleaning up an oil spill on a beach. The huge deposits of tar sands, or sand oil, in western Canada are often in the news as examples of untapped energy reserves, estimated to be around 1.7–2.5 trillion barrels of crude oil.[27,28] In the northwest corner of the province of Alberta, the Athabasca River starts from Athabasca Lake and meanders all the way to Jasper National Park. At the northern end, near Fort McKay, is the largest of three oil sand deposits in Canada. Alberta's sands yield a million barrels a day and have a proven, economically recoverable reserve of 173 billion barrels, perhaps extendable to 315 billion, compared to 264 billion in Saudi Arabia.[27] The USA gets 10% of its imported oil from these sands. That's the good news. The bad news is that it takes a lot of energy to get the oil out, and there is a huge environmental impact in doing so. For deep deposits, the *in situ* method described above for shale can be used, with wells drilled down to the tar sand layer and then horizontally along the deposit. Steam is injected in one well to melt the tar, which drips down into a lower well and is then pumped up to the surface. Open-pit mining uses less energy but still requires heat. For each barrel of oil produced, *in situ* mining of tar sands emits 388 lbs of CO_2 and open-pit mining 364 lbs, compared with 128 lbs in conventional oil mining.[27] Eighty percent of the deposits lie deep enough to require energy-intensive *in situ* mining.

Here is how it works. Tar sands contain oil in the form of bitumen, which is as thick as molasses in the summer and as hard as a hockey puck in the winter. Roughly speaking, the sands consist of 10% bitumen, 5% water, 20% clay, and 65% sand.[28] To get at them, the forest has to be cut down first; then, to dig down to the sands, 100 feet of earth has to be removed: 4 tons of earth for each barrel of oil. Huge shovels then scoop the sands into monstrous trucks three stories high, carrying 400 tons at a time. The ore is dumped into crushers and then into tanks where warm water at up to 80°C (175°F) is added to form a slurry. The slurry is pumped in a pipeline up to 5 km (3 mi.) long to a separation tank. The pipeline serves an important function. The lumps rub against its walls during the transport in such a way that the bitumen is separated from the sand and becomes attached to air bubbles. The air and bitumen form a froth which rises to the top and can be separated out, while the sand and clay fall to the bottom. Some of the bitumen is still in the mix, which can be recirculated to get more bitumen out in a secondary froth. It takes time for the air bubbles carrying the bitumen to rise to the top, because they collide with the heavy stuff going in the opposite direction. A faster way is to put the mixture between two parallel plates which are inclined at an angle to vertical. The bubbles then rise along the top of the gap while the water and sand fall at the bottom plate, and they do not have to collide. Really high tech. The air in the froth is then boiled off, leaving an emulsion of water (30%), bitumen, and clay. An emulsion is a mixture of immiscible fluids, such as vinegar and oil in salad dressing. If the water droplets in this emulsion would coalesce, the water would sink to the bottom and the oil to the top, as in salad dressing left standing around. In a draconian twist, the water droplets are coated with a fine layer of particles from the clay, which keeps the droplets from coalescing. Solvents have then to be added to get the water out. The bitumen ends up with 2% water and 0.8% clay. The chemicals in these contaminants will corrode the pipelines later on, so the oil next goes to an upgrading plant, where it is heated to 480°C (900°F) and compressed to 100 atmospheres. The energy cost of this would be excessive if the heat were not recovered for the initial heating of the oil sands.

There are other energy costs not mentioned above. The shovels that do the digging have steel teeth each made of a ton of steel and wear out in a day or two. The energy used to mine and refine that steel is usually ignored. The trucks use 50 gallons of diesel per hour, and their huge tires last only six months. The sands have to be near a river, because lots of water is needed for washing, 200,000 tons of which has to be heated every day at Athabasca. What happens to the sand and clay that were removed in the first step? They go into tailing ponds, which are the worst news yet. The tailings are a thick sludge consisting of the waste water and 30% sand and other solids from which the bitumen had been stripped. It also contains toxic chemicals. One pond can cover four square miles (10 km^2), and there are 50 square miles (130 km^2) of these ponds in Canada, about a third of the area despoiled by tar mining. A sand dike 300 feet (100 m) high around each pond contains the tailings, but some suspect that the toxic chemicals have leached into rivers and lakes. Fish have been found with unusual red spots on their skins. Once 500 ducks landed on the oily brew and died. Self-operated, flapping mechanical falcons have been installed as scarecrows, insufficient for the purpose. It takes 1–2 years for the clear water to rise to the top, from where it can be reclaimed to supply half the water for mining. What is left at the bottom, however, is still liquid and is difficult to solidify to restore the forest land. So far no tailings pond has been reclaimed.

The mines operate day and night, winter and summer, to supply the demand for oil. The large reserves are there, but the price is steep. The cost of mining is many times the cost for conventional oil, and this does not include the cost of carbon capture and sequestration, which has not started. Tar mining emits CO_2, and more CO_2 is emitted when the oil is converted to gasoline and burned in cars. The environmental impact alone makes this a poor choice for stretching our oil supply. Perhaps the most poignant argument is that the energy used in tar mining is mostly natural gas, the cleanest burning fossil fuel. This is wasted to produce a low-grade oil because liquid fuels are so valuable for transportation.

Oil from Algae

We know that photosynthesis in trees uses sunlight to convert CO_2 into oxygen. Could it also produce oil? It turns out that fast-growing algae, considered scum that chokes up ponds, can contain both biodiesel oil and carbohydrates that can be fermented into ethanol. Funded by venture capitalists, hundreds of startup companies are scrambling to develop a process that can be commercialized to compete with fossil oil. The Center for Algae Biotechnology was founded in 2008 in San Diego, CA, and 200 companies have been set up in that area. In the Imperial Valley to the east, there are 400 acres (81 hectares) of algae farms.[29] Algae, half of whose weight is in oil, are expected to produce 10,000 gallons of oil per acre per year, compared with 650 gallons from oil-palm trees.[29] Growing algae needs carbon dioxide, which can be from the exhaust of coal-burning plants, and light, but not necessarily sunlight. This is because most of the sunlight is of the wrong frequency (color). Algae can be grown in acres of tanks lined with plastic sheets and given the right amount of CO_2 and water at the right temperature. Under the best conditions, algae of the right species can double their weight in 1 day.

Small-scale experiments at OriginOil, Inc.[30] have shown an efficient way to grow algae, harvest it, and extract the oil. Efficient LED lamps of the right frequency are used instead of sunlight to grow the algae, and CO_2 is fizzed in. After harvesting, the cell walls of the algae have to be broken up to release the oil. CO_2 is first added to change the pH. Then pulsed microwaves are applied whose frequency, intensity, and pulse rate are feedback-controlled. The mix is then moved to a settling tank, where gravity causes the oil to rise to the top, the biomass to the bottom, and water in between. The biomass can be used for feedstock. The separation occurs in a single step with no further input of energy. Whether oil from algae will be worth it is not yet known, since the process is still in the research stage.

Gas Hydrates

Gas hydrates are solids like ordinary ice, but they exist only under high pressure, typically below hundreds of meters of ocean. They contain methane bubbles trapped by H_2O molecules and will burn if ignited in air. The methane is believed to have been created by bacterial action ages ago. Gas hydrates are found on continental shelves and under the tundra in the Arctic. Figure 2.21 shows why. The dotted vertical line shows the freezing point of water; it is around 0°C and does not change much with pressure. Water is liquid on the right of the line and is ice on the left side. Gas hydrates, however, can exist only at great depths, where the pressure is high; and the depth is greater if the temperature is higher. The possible temperature-depth combinations for gas hydrates are shown by the yellow part of the diagram. In the ocean at temperatures above freezing, gas hydrates lie below 500 m of seawater. In the Arctic, they are closer to the surface because the temperature is lower.

The US Geological Survey (USGS) has led the exploration of gas hydrates under coastal waters such as the Carolina Trough, in the North Slope of Alaska, in the Gulf of Mexico, and even in the Bay of Bengal in India and the Andaman Sea of Thailand. Drilling projects in the Gulf of Mexico were carried out in 2005 and 2009 to obtain cores of the layers where hydrates are found. Detailed data have been obtained not only on the concentration of gas hydrates but also on the nature and stability of the sand layers through which the drill goes. It has been estimated that the amount of fossil energy in these hydrates can exceed the energy in all other fossil fuels on earth, but this is highly speculative. One estimate is between 100,000 and 300 trillion cubic feet of gas in hydrates, which translates to the same number of Quads, since 1 trillion cu. feet contains approximately 1 Quad of energy. This compares to the world's proven conventional gas reserves of 6,385 Quads given in Fig. 2.12. The highest estimate is 47,000 times this number and should be taken with a grain of salt. More accurate information became available more recently.[31]

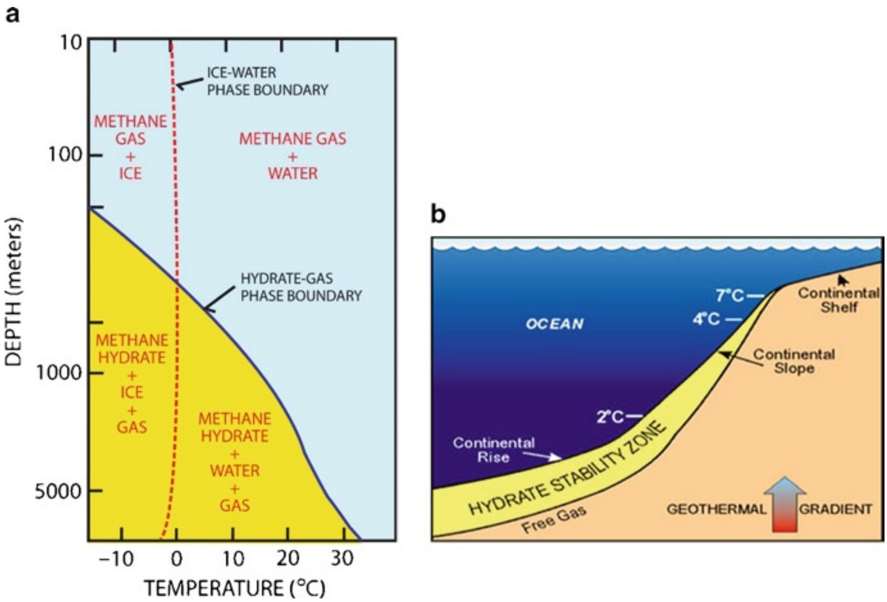


Fig. 2.21 (**a**) The depths in the ocean where gas hydrates can be found (*yellow region*), depending on the temperature (USGS website http://energy.usgs.gov/other/gashydrates); (**b**) relation of this region to the continental shelf (W.F. Brinkman, US Department of Energy, *FY 2011 Budget Request to Congress for DOE's Office of Science*)

We are clearly still in the exploration state on this resource. There is no proposed method to mine gas hydrates safely and distribute the methane. The problem is that methane is a greenhouse gas ten times as powerful as CO_2, and it is released as soon as the hydrates are relieved from the pressure they are under. Leakage of a small fraction of this gas into the atmosphere would be catastrophic. Methane can also be released from sand layers that the drills have to go through. Although methane is a clean-burning gas and emits less CO_2 than other fuels, it is still a fossil fuel, so CO_2 is emitted when it is burned. Even if it's true that the gas reserves in hydrates are huge, it is dangerous to exploit this source when completely carbon-free energy sources can be developed. These are the subject of the next chapter.

To conclude this chapter philosophically, we refer back to Fig. 2.2 in the Prologue. There we saw that the use of fossil fuel occupies only a thin slice of human history. For millions of years, solar energy was stored in trees which decayed and were stored deep underground as carbon compounds. This fortuitous treasure was discovered by man and is being recklessly consumed to advance our civilization without regard for the future. Mother Nature's endowment, however, was not meant to be wasted. The endowment was sufficient for humans to develop enough intelligence to find an unlimited resource: fusion energy. First, she showed us the enormous power available by leading us to develop the hydrogen bomb. She is now gently leading us to the next step. In Chap. 7, we will see evidence of her helping hand.

There have been totally unexpected bonuses in our attempts to control the reaction. It is a way to continue the benefits of the one-shot legacy of fossil fuels without destroying all the species of birds, fish, and animals that she has created.

Notes

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