Chapter 6
Fossil fuels

Fossil fuels, in the form of coal, oil, and natural gas, have been the principal energy sources powering US and global economic development over the past century. Today they supply more than 80% of all the energy consumed in industrially developed nations. They are hydrocarbons, compounds containing only carbon and hydrogen, and range from volatile materials such as natural gas (largely methane, CH_4) with low carbon to hydrogen ratios, to almost pure carbon materials such as anthracite coal. When a fossil fuel is burned (oxidized to CO_2 and H_2O) large amounts of energy are released, which can be used for heating and to produce electricity. When petroleum is refined (i.e., processed into gasoline or diesel fuel) it can be used as a liquid fuel for transportation. Natural gas, when compressed, can also be used as a transportation fuel. Over the past few decades the burning of fossil fuels was responsible for more than 70% of human-caused greenhouse gas emissions.

The idea that fossil fuels were formed from the fossilized remains of dead organisms and plants, via exposure to high

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temperatures and pressure deep in the Earth over millions of years, was first mentioned in the 16th century. Today, it is understood that petroleum and natural gas are the products of anaerobic (low oxygen) decomposition of dead organisms such as aquatic phytoplankton and zooplankton. Coal and natural gas are understood to be decomposition products of terrestrial plants. While these processes are still underway, fossil fuels are considered to be non-renewable resources because they take tens to hundreds of millions of years to form, while they are being consumed at high rates today.

6.1 COAL

Coal is used primarily to heat water to produce steam to generate electricity. China is the world's leading coal producer (45%), followed by the US at 11%. Just over one third of global electricity is currently generated by burning coal. While the world has large reserves of coal, its downside is that coal combustion produces a wide range of air pollutants that are harmful to human health and the environment. These include sulphur dioxide (SO_2) which is responsible for acid rain; nitrogen oxides (NO_x), a family of oxides that contribute to the formation of smog, acid rain, and ozone; mercury (Hg), a cumulative poison when taken into the body; and radioactivity from elements like uranium and thorium that are often found in coal deposits. As discussed in Chapter 4, coal combustion is also a major source of the greenhouse gas CO_2.

The term 'clean coal' was introduced in 2008 by coal industry groups at a time when the US Congress was considering legislation to limit CO_2 emissions. While deliberately vague, it is usually interpreted to mean coal-fired power plants that capture and sequester the CO_2 emitted from smokestacks. This process has been given the name Carbon Capture and Sequestration (CCS). It is a complex and contentious approach to reducing CO_2 emissions from industries such as power generation and cement production, which is discussed in more detail below.

6.1.1 Carbon capture and sequestration

Wikipedia defines CCS as 'the process of capturing waste carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, transporting it to a storage site, and depositing it where it will not enter the atmosphere, normally an underground geological formation.'

Considerable literature exists on CCS, exhibiting a wide range of opinion on its viability as a technology to reduce CO_2 emissions. The principal argument for CCS is that the world today is fueled largely by coal, oil and natural gas and that this situation is not likely to change any time soon. In fact, as many developing nations industrialize and they emerge from poverty, the demand for energy increases steadily and it is argued that only fossil fuels can meet that demand in coming decades. It is also argued that, while solar, wind and other renewable energy technologies can eventually replace electricity from coal and natural gas power plants, this will not occur quickly and people will need fossil energy during the long transition. In addition, some industries like steel and cement are not so easily 'fixed' and will continue to use fossil fuels in increasing amounts as global industrialization grows.

These points raised in support of CCS are countered by the following arguments:

- CCS is expensive, whether added to an existing power plant or industrial carbon dioxide source, or included in newly constructed facilities. The energy penalty for operating CCS is also high, requiring a fair amount of parasitic energy that reduces efficiency and revenues.
- When operating, CCS systems require large amounts of water.

- Captured CO_2 must be liquified and stored for indefinite periods of time in such a way as to avoid leakage and sudden large releases ('burps') that can be toxic. This requires identification and development of storage sites (depleted oil and gas wells, coal mines, underground aquifers) and infrastructure to transport liquid CO_2, which adds additional costs and raises questions of liability if something goes wrong and stored CO_2 is accidentally released.
- The time required for development, demonstration and large-scale deployment of CCS technology that can have a meaningful impact on global warming is too long compared with other options.

Proponents of CCS (see http://www.globalccsinstitute.com) argue that CCS costs can be brought down significantly with a sufficient number of demonstration projects and the economies of scale associated with large-scale deployment. Nevertheless, at the 2013 Doha Clean Energy Forum even one of its supporters admitted that to make an impact a global CCS system will cost an estimated $3.6 trillion. One immediate reaction at the meeting was that for $3.6 trillion we can deliver an awful lot of non-CO_2 emitting renewable energy that will replace coal, oil, and natural gas used in power generation and transportation. Nevertheless, there is the argument that the CO_2 emissions from some industries will still be there in large and growing amounts even with large-scale deployment of renewables and CCS may be the only way to limit these emissions.

These are strong arguments for some attention to CCS R&D and demonstration. Nevertheless, CCS demonstrations are expensive, and the money for them would have to come from somewhere. Government funding is at best problematic in current budget situations. Other funding possibilities are the fossil fuel industries themselves. Countries with large reserves of fossil fuels will also see value in CCS allowing extended use of secure domestic energy reserves.

In a world committed to reducing carbon emissions CCS offers a helping hand but not a definitive one. It may offer a partial answer for the rest of the 21st century, but governments are unlikely to provide the needed funds for large-scale deployment. A major question is whether the private fossil fuel sector is willing to step up to protect its vested interests.

6.1.2 A conundrum

The mining and use of coal presents a difficult-to-resolve conundrum, especially for countries like China, Australia, and the US with large amounts of this fossil fuel. Coal reserves provide a relatively low-cost energy resource, but its combustion produces large amounts of $CO_{2,}$ a greenhouse gas. The conundrum is a clear example of a conflict of values – the need to provide energy services to people around the world, in particular people in developing countries whose per capita consumption of electricity is well below that of developed countries, and the need to address climate change with its many adverse consequences. No easy answer exists to satisfy those on both sides of this conflict.

Joby Warick, in a well researched piece in the 16 October 2015 edition of *The New York Times* examined this question from the US perspective. Several statements caught my attention: 'Just a dozen nearby mines, scattered across a valley known as the Powder River Basin (Wyoming), contain enough coal to meet the country's electricity needs for decades. But burning all of it would release more than 450 billion tons of carbon dioxide into the atmosphere – more than all greenhouse-gas emissions from all sources since 2000.' and 'The Obama Administration is seeking to curb the United States' appetite for the basin's coal, which scientists say must remain mostly in the ground to prevent a disastrous warming of the planet. Yet each year, nearly half a billion tons of this US-owned fuel are hauled from the region's vast strip mines and millions of tons are shipped overseas for other countries to burn.'

Given the legitimate needs on both sides of this conflict I can see only one path to follow to bring the benefits of electricity to as many people as possible while minimizing the risks associated with burning coal. This is to promote the use of energy efficiency technologies wherever feasible, to reduce the demand for coal-based electricity, and to expedite the development and deployment of renewable electric technologies such as solar and wind, and perhaps nuclear, as substitutes for coal. This is already happening to some extent as the world slowly begins to come to grips with the climate change problem, but the pace needs to and can be accelerated.

The ability of renewables to meet most of the world's electricity needs has been documented in several recent studies, for example, the June 2012 NREL report entitled 'Renewable Electricity Futures Study'. What is now needed is a commitment on the part of national governments and international institutions to make it happen as quickly as possible. It is a matter not of technology but of political will and financial resources. Admittedly, such a switch from coal and other fossil fuels that also produce CO_2 when burned, to a renewables-based energy economy, will take time, planning, and money. However, when the full costs of using fossil fuels are taken into consideration, including not just market costs but also health and climate-change-related costs (such as coastline flooding due to rising seas, changes in precipitation patterns that adversely impact water availability and agricultural production, etc.), and international tensions due to competition for fossil fuel resources, then renewables become a much more attractive and even less expensive long-term option. Renewable resources are also insensitive to cost increases once initial capital investments are made, unlike fossil fuels that rely on a depletable resource that produces uncertain and often volatile costs. Renewable energy technologies are discussed in Chapter 8.

Note: Nuclear power advocates will make some of the same arguments since the process of releasing energy via nuclear fission does not produce greenhouse gases, but nuclear technology faces four serious problems: high cost, safety, the need for long-term radioactive waste storage, and proliferation of weapons capability. If these problems can be successfully addressed, then nuclear-powered electricity can be a viable option for the future. Nuclear power also offers the tantalizing option of nuclear fusion, a relatively safer and cleaner nuclear technology with enormous resource potential, but the problem of achieving controlled nuclear fusion on Earth – it is the process that powers our Sun – is proving to be the most difficult technological challenge the world has faced to date. It can legitimately be labeled 'the technology that is always a few years away.' Discussion of the promise and problems of both nuclear fission and fusion power can be found in Chapter 7.

In addressing the conundrum the choice is ours – we can continue to use our coal resources without limit or we can move more quickly to a clean energy society that provides needed energy services and minimizes global warming and climate change effects. Most people today would vote for the latter.

In addition, it is important to recognize an important reality of our evolving energy system: as renewable energy begins to displace energy from fossil fuels some people will be adversely impacted as this transition unfolds. We must take these impacts into account as we move forward to a clean energy future. Dr Maria Zuber, Chair of the US National Science Board and Vice President for Research at MIT, has written eloquently on this topic (36):

> 'As a daughter of coal country, I know the suffering of people whose fates are tied to the price of a ton of coal. But as a scientist, I know that we cannot repeal the laws of physics. When coal burns, it emits more carbon dioxide than any other fossil fuel. And if we keep emitting this

gas into the atmosphere, Earth will continue to heat up, imposing devastating risks on current and future generations. There is no escaping these facts, just as there is no escaping gravity if you step off a ledge.

The move to clean energy is imperative. In the long run, that transition will create more jobs than it destroys. But that is no comfort to families whose livelihoods and communities have collapsed along with the demand for coal. We owe something to the people who do the kind of dangerous and difficult work my grandfathers did so that we can power our modern economy.'

6.2 PETROLEUM

Petroleum (crude oil) is today the world's primary fuel source for transportation (90%), and is likely to remain so for at least a few decades into the future. It is most often extracted from deep geologic reservoirs underground or below the ocean seabed. It can also be found in shale deposits and tar sands, and both of these 'non-conventional' petroleum sources are now being exploited commercially. Once extracted, it is processed in oil refineries into gasoline, diesel fuel, heating oil, liquefied petroleum gas, and other non-fuel products such as pesticides, fertilizers, pharmaceuticals, plastics, and heavy residues for use in asphalt.

6.2.1 Oil spills

Oil use in transportation creates major environmental problems. Its combustion creates CO_2 and NO_x, as well as particulate matter (a complex mixture of extremely small particles and liquid droplets) that can lead to serious respiratory problems when inhaled. A major concern is that because of its wide use in billions of cars, trucks, and other vehicles, each of which acts as an individual point source of pollution, control of this pollution is quite difficult. Oil, either in extracted or refined form, also has to be transported by ship, pipeline, or truck to its final point of use, and spills are an ever-present danger. While there are many oil spills each year, at least two have attracted international attention, the *Exxon Valdez* spill into Alaska's Prince William Sound in 1989 and the *Deepwater Horizon* oil spill into the Gulf of Mexico in 2010.

In the former case 11 million gallons of crude oil were released into Prince William Sound, with dire impacts on hundreds of thousands of birds, other water creatures, and local fishing and other businesses. Some of those impacts remain to this day.

Two decades later the Macondo Well beneath BP's *Deepwater Horizon* drilling rig blew out, causing a massive fire, the loss of 11 lives, and the release into the Gulf of Mexico of 170 million gallons of crude oil. This oil coated beaches for hundreds of miles in several states around the Gulf, did terrible damage to wildlife and water- and tourist-dependent industries; again, oil from the spill continues to wash ashore today. Much research is underway to understand the effects on the food chain of this very large spill, which took months to bring under control.

Despite this history, large and damaging oil spills still remain a serious threat. Frances Beinecke, former president of the Natural Resources Defense Council, who served on the Commission investigating the *Deepwater Horizon* accident, has written (37): 'Many lessons from the *Exxon Valdez* spill had not been applied, and the country was once again struggling with an industry ill-prepared to respond.' There is also great concern that, with global warming leading to less ice cover in arctic regions, drilling for new oil resources may take place in areas much more vulnerable to the lasting effects of large oil spills.

Oil transport by pipeline or rail is also a major concern. The first was illuminated by the battle over approval of the Keystone XL Pipeline that would cross the international border between the US and Canada. Approval was denied by the Obama Administration, then granted by the Trump Administration, but the project is still on hold due to economic considerations. The second concern gained visibility as a result of a massive fire in Quebec, caused by the derailment of a train carrying crude oil from Canada to the US. Both are discussed below.

Quoting from Wikipedia: 'The Keystone Pipeline System is a pipeline system to transport oil sands bitumen from Canada and the northern United States primarily to refineries on the Gulf Coast of Texas. The products to be shipped include synthetic crude oil (syncrude) and dilbit (diluted bitumen) from the Western Canadian Sedimentary Basin in Alberta, Canada, and Bakken synthetic crude oil and light crude oil produced from the Williston Basin (Bakken) region in Montana and North Dakota. Two phases of the project are in operation; a third, from Oklahoma to the Texas Gulf coast, is under construction, and the fourth is awaiting US government approval as of mid-March 2013. Upon completion, the Keystone Pipeline System would consist of the completed 2151-mile (3462 km) Keystone Pipeline (Phases I and II) and the proposed 1661-mile (2673 km) Keystone Gulf Coast Expansion Project (Phases III and IV). The controversial fourth phase, the Keystone XL Pipeline Project, would begin at the oil distribution hub in Hardisty, Alberta and extend 1179 miles (1897 km), to Steele City, Nebraska.'

Those opposed to the pipeline cite the contribution to CO_2 emissions from the mining of tar sands in Canada, the possibility and consequences of pipeline leaks associated with heated and highly pressurized bitumen, the initial (now modified) proposed path of the pipeline through areas above the Ogallala Aquifer (a major source of freshwater), and the potential delay in investments in renewable energy technologies due to the continued availability of oil resources.

The proponents of the pipeline argue that Canada will mine the tar sands and produce the bitumen and its associated CO_2 emissions regardless of what the US decides (an alternative pipeline path would be to Canada's west coast for sales to Asia), Canadian tar sands oil is already reaching the US by train and new quantities could be shipped by rail as well, that obtaining oil from Canada is preferable to obtaining oil from the Persian Gulf and other countries and is in the US national security and economic interest, and that pipeline construction today is under better regulation and is safer than ever before.

In his global climate change speech at Georgetown University on 25 June 2013 President Obama, prior to his denial of the Keystone XL Pipeline project, seemed to hint that he would approve the pipeline, arguing that ‘Allowing the Keystone pipeline to be built requires a finding that doing so would be in our nation’s interest. And our national interest will be served only if this project does not significantly exacerbate the problem of carbon pollution. The net effects of the pipeline’s impact on our climate will be absolutely critical to determining whether this project is allowed to go forward.’

The use of the words ‘significantly exacerbate’ seemed significant in that it will be hard to argue that the carbon emissions from mining the Alberta tar sands will add significantly to current global CO_2 emissions. Add they will, and add to oil availability they will as well, but by themselves and in terms of impact on global climate change, not significantly.

Thus, if one assumed that the pipeline would be carefully regulated (and with strict enforcement of those regulations), that the Canadian tar sands will be mined regardless, that the new pipeline path is less risky for the Ogallala, and that the pipeline will reduce US needs for other oil imports, approval of the pipeline was a safe bet to make. This would recognize that current US need for liquid petroleum fuels to support transportation is significant and will continue for a while.

What changed, and led to the decision in 2015 by the Obama Administration to deny the project’s construction permit, was probably several-fold: the market price of oil (which had dropped to approximately half of what it was in 2013), President Obama’s apparent decision to make leadership on global climate change issues an important part of his legacy, and the fact that Canada had a new federal government that was more environmentally oriented than the previous Conservative government. To some, this decision was justified on the basis that if the US won't take even small symbolic steps to reduce carbon emissions and global warming, why should other nations striving to improve their economies undertake such efforts. Others continue to believe that 'The Keystone XL fight hardly matters in the grand scheme of the global climate. Perceptions of US climate leadership depend on Environmental Protection Agency rules to reduce emissions from US power plants and cars, not on a domestic political psychodrama (38).'

6.2.2 Peak oil

Another topic that has come up consistently in recent decades is the notion of Peak Oil: is the world running out of its crude oil resources? The reality seems to be that this is not true on any near-term timescale. Fossil fuels are finite and we are using them much faster than nature can replace them, but much remains to be found and utilized if people wish. This is even more true today with the anticipation of new discoveries in ice-free arctic regions.

An important participant in this discussion was M. King Hubbert, who, at a meeting of the American Petroleum Institute in San Antonio, Texas, in 1956 proposed his theory on oil well production and depletion and published the 'Hubbert Curve' (see Figure 6.1).

It depicts a world oil production distribution, showing historical data and future production, with a peak of 12.5 billion barrels per year about the year 2000. It is valid for some assumptions but ignores other realities that make his conclusions invalid for long-term planning. Before discussing this in some detail, it is important to understand what is meant by Peak Oil.

Hubbert's Peak Theory is based on the fact that the utilization of a finite resource must go through an initial start-up, reach a peak level of production, and eventually tail off as the resource

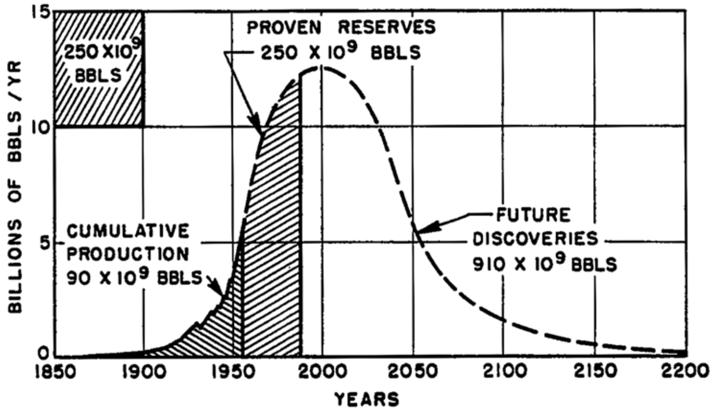

Figure 6.1 The Hubbert Curve (*Source:* 'Nuclear Eenergy and the Fossil Fuels', M.K. Hubbert, March 1956).

is depleted. This is common sense, applicable to all non-renewable resources, and not disputable. What is disputable is the shape of the production/depletion curve and the assumptions that went into identifying the resource to be utilized and eventually depleted. Much of the public discussion that has ensued about the application of Hubbert's Peak Oil theory to petroleum extraction has revolved about these two facets of his theory.

It is important to clarify that Peak Oil is the point in time when oil extraction reaches its maximum rate but is not synonymous with oil depletion. Following a peak in extraction rate about half of the resource is still available for extraction, and the production rate decreases steadily thereafter. Much discussion has focused on the shape of the declining curve after Peak Oil is reached (plateau? sharp decline? slow decline?) and the implications for the US and world economies that are dependent on oil supplies.

Hubbert's theory received great visibility when he correctly predicted, in his 1956 paper, that US domestic oil production would peak between 1965 and 1971. He used the terms 'peak production rate' and 'peak in the rate of discoveries'; the term Peak Oil was introduced in 2002 by Colin Campbell and Kjell Aleklett when they formed ASPO, the Association for the Study of Peak Oil & Gas. ASPO ceased operations in 2017.

Where the application of Hubbert's theory falls short is in the assumptions on which his theory is based. He did not anticipate, nor did others, the rapid emergence of unconventional oil and the substitutions for oil (alternative fuels, electrification of transportation) that have been or are being developed. He did mention these possibilities in the 1956 paper and did his best with the information available at the time.

What has changed is that oil production no longer depends only on 'conventional' oil supplies but increasingly on 'unconventional' resources that are an increasing part of total oil supply. A few definitions, courtesy of Wikipedia, will help:

> 'Conventional oil is oil that is generally easy to recover, in contrast to oil sands, oil shale, heavy crude oil, deep-water oil, polar oil and gas condensate. Conventional oil reserves are extracted using their inherent pressure, pumps, flooding or injection of water or gas. Approximately 95% of all oil production comes from conventional oil reserves.
>
> Unconventional oil is oil that is technically more difficult to extract and more expensive to recover. The term unconventional refers not only to the geological formation and characteristics of the deposits but also to the technical realization of ecologically acceptable and economical usage.'

Given these definitions, it is reasonable to agree that the age of cheap oil, which we enjoyed for a good part of the 20th century, is over. As reported by the former BP geologist Dr Richard Miller in a speech (39) at University College London in 2013: '… official data from the International Energy Agency, the US Energy Information Administration, the International Monetary Fund, and other sources, showed that conventional oil had most likely peaked around 2008.' He further pointed out that ‘peaking is the result of declining production rates, not declining reserves’, that many oil producing countries are already post-peak, and that conventional oil production has been flat since about the middle of the past decade. There has been growth in liquid supply since then, largely due to natural gas liquids and oil derived from oil sands. Reserves have also been growing due to new discoveries, improved oil field extraction technology, and increasing reliance on unconventional resources such as shale oil. In fact, production of shale oil has allowed the US to become the world’s top oil producer.

The debate about Peak Oil has been underway for quite a few decades, and, despite ASPO’s closing, Peak Oil still has its adherents (40). It seems clear that the Peak Oil concept is not valid if you take into account the full liquid fuels situation. In 2009, Dr. Christoph Rühl, chief economist of BP, argued as follows against the Peak Oil hypothesis: ‘Physical Peak Oil, which I have no reason to accept as a valid statement either on theoretical, scientific or ideological grounds, would be insensitive to prices … In fact the whole hypothesis of Peak Oil – which is that there is a certain amount of oil in the ground, consumed at a certain rate, and then it’s finished – does not react to anything … Therefore there will never be a moment when the world runs out of oil because there will always be a price at which the last drop of oil can clear the market. And you can turn anything into oil into if you are willing to pay the financial and environmental price … Global Warming is likely to be more of a natural limit than all these Peak Oil theories combined … Peak Oil has been predicted for 150 years. It has never happened, and it will stay this way.’

According to Rühl, the main limitations for oil availability are ‘above ground’ and are to be found in the availability of staff, expertise, technology, investment security, money, and, last but not least, in global warming. Rühl’s views are shared by Daniel Yergin of Cambridge Energy Research Associates, who added that oil's recent high-price phase might not add to complete exhaustion of resources, but the timely and smooth setup of alternatives.

A further perspective was provided by George Monbiot, writing in *The Guardian* on 2 July 2012: 'We were wrong on Peak Oil. There's enough to fry us all … Some of us made vague predictions, others were more specific. In all cases we were wrong. In 1975 MK Hubbert, a geoscientist working for Shell, who had correctly predicted the decline in US oil production, suggested that global supplies could peak in 1995. In 1997 the petroleum geologist Colin Campbell estimated that it would happen before 2010. In 2003 the geophysicist Kenneth Deffeyes said he was "99% confident" that Peak Oil would occur in 2004. In 2004, the Texas tycoon T Boone Pickens predicted that "never again will we pump more than 82 m barrels" per day of liquid fuels. (Average daily supply in May 2012 was 91 m.) In 2005 the investment banker Matthew Simmons maintained that "Saudi Arabia … cannot materially grow its oil production" (since then its output has risen from 9 M barrels per day to 10 M, and it has another 1.5 M in spare capacity). … Peak oil hasn't happened, and it's unlikely to happen for a very long time.'

6.3 NATURAL GAS

Natural gas (primarily CH_4, but also containing small amounts of other gases, including helium), once burned off as a non-useful byproduct of petroleum production, is an abundant resource in many countries. New discoveries and extraction methods have led to a dramatic increase in its production from shale deposits by fracking, especially in the US, making the US the world's leading producer of natural gas. Considerable research is also going into extraction of natural gas from methane hydrates (both fracking and methane hydrates are discussed below). CH_4 is also released by the decomposition of animal wastes from livestock production and municipal waste in landfills.

Natural gas burns more cleanly than coal or oil – less NO_x and particulate emissions, and minimal SO_2 emissions – and it releases, per unit of energy produced by its combustion, 43% less CO_2 than coal and 30% less CO_2 than oil. As a greenhouse gas in its own right, CH_4 is about 20 times more powerful than CO_2 as a driver of global warming, As a result, leakage of CH_4 from the infrastructure surrounding natural gas production and use is a serious concern. (*Note*: CH_4's half-life in the atmosphere is much less than that of CO_2.)

It is most commonly used to produce electricity and heat for industrial processes and buildings. A small amount of compressed natural gas is used for transportation – for example, in bus fleets. It also serves as a feedstock for the production of fertilizers, paints, and plastics. It is usually transported by pipeline, but increasingly it is being transported internationally in ships as cooled and liquefied natural gas (LNG).

6.3.1 Methane hydrates

For those who follow energy issues closely, a persistent question has been: are methane hydrates a realistically large potential energy resource? The answer is yes.

Several decades ago the information available to answer that question was not available. Today the literature on methane hydrates (also known as methane clathrates, methane ice, and fire ice) is extensive and growing.

What are clathrates and hydrates? Clathrate is a general term that describes solids in which gases are trapped within any kind of chemical cage, while hydrate is the specific term used when that cage is made of water molecules. In methane hydrates the trapped gas is CH_4. CO_2 and other gas hydrates are also possible and are speculated to exist on Mars, other planets and their moons. On our home planet most of the hydrates are filled with CH_4, and they are abundant.

Methane hydrates form as a solid similar to ice under the right conditions of CH_4 and water availability, temperature (low) and pressure (high). They are fragile, easily destabilized (i.e., returned to separated water and CH_4) by pressure and/or temperature changes, and are found most often within, and occasionally on top of, sediments on ocean floors. They are called ‘fire ice’ because they can be lit by a match.

The most common type of methane hydrate (>99%) has a density of 0.9 g cm^{-1} or just slightly less than that of water, so it can float. One litre of the fully saturated solid would yield 120 grams of CH_4 or 169 litres of gas at standard temperature and pressure. It forms in the presence of water and methane under conditions found in the oceans, deep lakes, and under ice caps that fall within a gas hydrate stability zone.

The seafloors of most of the world’s oceans fall within the hydrate stability zone. Methane hydrates are also found in Arctic permafrost and continental deposits in sandstone and limestone in Alaska and Siberia. These deposits may cover even larger reservoirs of CH_4 at greater depths.

There are two sources for this methane: thermogenic methane that is formed deep in the earth by the same thermal/high-pressure processes that convert organic matter to coal, oil and gas, and which leaks upward toward the ocean floor where it forms hydrates when it comes in contact with highly pressurized cold (0–2°C) water; and methane generated by microbes degrading organic matter (plankton) in low-oxygen environments in sediments. This latter process is the dominant source of CH_4 for methane hydrates.

Methane hydrates are important because of estimates that such hydrates contain more carbon (and therefore more potential fuel) than all other fossil fuels combined. The EIA reports that these hydrates could hold as much as 10,000–100,000 trillion cubic feet (Tcf) of CH_4. To put these numbers into perspective, total global consumption of natural gas is currently about 130 Tcf. With methane hydrates we are talking about a very large potential energy resource. It is also widely distributed globally, and has the potential to be an indigenous resource for many countries. It is also straightforward to separate the CH_4 from its hydrate cage by heating it up or reducing its pressure. Both techniques have been demonstrated and are currently being explored actively in public and private research programs in many countries. The production problems arise when one tries to convert this resource into a marketable commodity at a reasonable cost.

The presence of most of the hydrates on the deep sea floor and in sediments just beneath it means that extraction must be carried out under extreme conditions of depth, pressure and temperature. The methane concentrations are also geographically dispersed, increasing the harvesting costs, undersea infrastructure costs, and transmission costs of bringing the gas to the surface. The fragility of the hydrates also requires that they be handled carefully, avoiding a sudden release of gas and resultant over-pressurization.

Environmentally, while CH_4 is a powerful greenhouse gas, a saving grace is that CH_4's half-life in the atmosphere is 7.5 years. CO_2 on the other hand has an atmospheric half-life of hundreds of years.

Another problem for CH_4 production from hydrates is the fact that shale gas from fracking is just coming into its own as a major source of competitive natural gas, thus reducing the commercial incentive to develop the hydrates. Unless the cost of producing CH_4 from hydrates can be reduced significantly this will remain an important barrier as long as shale gas is available in quantity.

The US is one of several countries with an active methane hydrate R&D program. Others include Russia, India, South Korea and Japan. Japan has been a leader in this research for many years, given its lack of indigenous energy resources and its heavy dependence on imports. Japan's recent problems with its nuclear power plants has further increased its dependence on imported LNG which is costly in the Asian market (several times higher than in the US market).

The US program was jump-started by the passage of The National Methane Hydrates R&D Act of 2000, which requires 'the development of a national methane hydrate R&D program that utilizes the talents of federal, private, and academic organizations.' The result is a joint public–private effort supported in part by several US government departments and agencies.

6.3.2 Fracking

Hydraulic fracturing is the fracturing of rock by a pressurized liquid. Some hydraulic fractures form naturally. Induced hydraulic fracturing or hydrofracturing, commonly known as fracking, is a technique in which water is mixed with sand and chemicals, and the mixture is injected at high pressure into a wellbore to create small fractures (typically less than 1 mm in length), along which fluids such as previously trapped oil and natural gas may migrate to the well. When hydraulic pressure is removed from the well, small grains of sand or aluminium oxide hold these fractures open once the rock achieves equilibrium. The technique is very common in wells for shale gas, tight gas, tight oil, and coal seam gas and hard rock wells. It is now also being considered for use in revitalizing existing hydrogeothermal wells.

It was first used commercially in 1998 in the Barnett Shale formation in Texas. Today it is being widely used in several shale regions in the US and its use is being explored actively in many other countries. It is also a large fossil fuel resource, and according to the IEA technically recoverable resources are estimated to be 7.3 quadrillion cubic feet for shale gas, 2.7 quadrillion cubic feet for tight gas, and 1.7 quadrillion cubic feet for coalbed methane. Current annual global consumption of natural gas is about 130 trillion cubic feet.

My feelings about shale gas (and oil) fracking are mixed. It represents a large, new fossil fuel resource but may present serious environmental concerns. Here is how I see the issues:

- Wells drilled into gas-rich shale deposits are usually quite deep, well below the underground aquifers supplying freshwater.
- The quantities of water required are large (millions of gallons per well) and create a huge demand on local water supplies.
- Major problems with fracking occur when the injected water is returned to the surface and has to be cleaned up or disposed of. Here is one place where extraction companies may be tempted to take shortcuts to reduce costs.
- The returned water not only has added chemicals that facilitate the fracturing but also heavy metals, uranium, and other contaminants that it releases from the shale along with the trapped CH_4 (and oil). Without these 'additives' the water could be returned to reservoirs or reused, but that is not the case. The water with fracking chemicals can be reinjected for reuse in further fracking, but to avoid the build-up of heavy metals and radioactivity these other 'additives' have to be removed and disposed of carefully. This costs money. Even returning the drilling water to reservoirs and other non-fracking uses requires water decontamination, again a costly process.
- Here is where I become wary of human behavior. The easiest and least costly thing to do with returned water is dump it in nearby lakes and streams when no one is watching, which I suspect is occasionally done. Water handling and cleanup costs are a major operating expense. Contaminants can disturb ecosystems and eventually get

into drinking water, which is why many people oppose fracking.

- Another problem with fracking is leakage of CH_4 from wellbores that are not fully sealed (again a cost issue), and from other underground cracks induced by the hydrofracturing that released CH_4 away from the wellbore. This kind of leakage has been blamed for the water supplies in homes that seem to be saturated with CH_4 and can be ignited.
- In addition, the use of trucks to haul in fracking water, return to their water sources, and, if necessary, remove the returned water, creates a lot of heavy traffic that is disturbing to communities along the way.

However, fracking is not all bad. There is lots of shale gas (and oil) to be extracted (decades worth), prices for natural gas have come down, natural gas can be substituted for coal in power generation (and release less CO_2 per unit of energy generated), and the prospect of long-term supplies of low-cost natural gas is beginning to attract industries back to the US from overseas locations. CH_4 can also be used in transportation as a compressed fuel or a starter chemical for alternative liquid fuels, reducing our dependence on imported oil.

A detailed review of water issues associated with fracking, *Shale Gas and Hydraulic Fracturing – Framing the Water Issue* by Olsson, Lindstrom, and Hoffman (41), concluded that:

- 'The emergence of shale gas and shale oil has quickly changed the landscape of opportunities for energy provision and security in different regions of the world.
- 'Fracking is a water-intensive activity, and, as the (shale) reserves are often found in dry areas, extraction poses additional challenges in what are often already water-stressed environments. The vast water quantities needed over the life span of a shale gas well, where water is used to fracture rock under high pressure, pile further stress on

local freshwater sources which are already needed for many different purposes. At times when water supplies are running short in a specific area it has to be transported to the fracking site from afar.

- 'Water quality is also under threat from fracking as well as the quantity available. Many chemicals used in the fracking fluid (the composition of which is often protected for commercial confidentiality reasons) have increasingly been found to be harmful both to the environment and to human health, yet poor regulations and legislation governing fracking often allow accidents which contaminate surrounding water sources. There is a need for greater responsibility, through developing codes of conduct and regulatory systems governing fracking so as to protect water resources and the environment.'

Given this complex context, where do I come out on fracking? My belief is that commercial mining of shale gas and oil is here to stay for at least the next several decades because of the attractive financial returns, the reduced carbon emissions associated with substituting natural gas for coal in power generation, and the national security benefits associated with an indigenous energy source. Weighing the pros and cons I conclude that what is needed is to create and enforce a strict regulatory regime at federal, state and local levels for fracking. Fracking gas is creating a new 'natural gas era' in the US and elsewhere and we will have to deal with it in as safe a manner as possible. Threats to ecosystems and water supplies are serious threats and require our utmost attention. Given the costs involved in addressing the cons I expect some attempted shortcuts and 'accidents', but that's an inevitable part of supplying energy needs. It is society's job to create disincentives for these shortcuts, educate the public about the threats, and keep the pressure on companies and government officials to adhere to and enforce the regulations.