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Eugene Coyle
Technological University Dublin, Eugene.Coyle@tudublin.ie

William Grimson
Technological University Dublin

Biswajit Basu
Trinity College Dublin

Mike Murphy
Technological University Dublin, mike.murphy@tudublin.ie

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Chapter 1

Reflections on Energy, Greenhouse Gases, and Carbonaceous Fuels

EUGENE D. COYLE, WILLIAM GRIMSON, BISWAJIT BASU, AND MIKE MURPHY

Abstract

In this chapter, we review the history of man's dependence on carbonaceous fuels for survival, beginning with pre-industrial civilizations, during which charcoal was processed for thousands of years to smelt iron and copper. In the eighteenth and nineteenth centuries, however, coke and coal became prime energy resources which powered the engine rooms of the industrial revolution. Accompanying the economic and societal benefits of this period was the recognition of the damage resulting from smog owing to excessive burning of coal, which affected both human health and the natural environment. These pivotal centuries laid the foundation for the advancement of scientific knowledge and discovery which underpinned both engineering developments and the sciences of the natural world, including earth science, atmospheric science, and meteorology. These developments in turn led to our modern understanding of climate change and the effect of greenhouse gases.

Today coal, petroleum, and natural gas still play a vital role in our global energy mix. While scientists and engineers have developed clean coal technologies such as carbon capture and storage, it is important to question whether such technologies can offset the growing carbon footprint caused by the use of carbonaceous fuels. This challenge is complicated by the growth in scale of total global world energy demand, the scale of economic investment required to implement such technologies, and the race against time to minimize the damage resulting from continued use of fossil fuel energy.

1.1. Introduction: Man's Quest for Energy

Humankind has always needed energy, and while the source and usage of energy have changed over time some patterns have remained constant. In earlier times food was the key source of energy for people and their livestock. This form of energy not only allowed our race to survive but dictated in part how civilization developed. Societies worldwide focused on developing new and sustainable food sources. The storage of food and its distribution was a factor in how groups learned to organize themselves communally, best survive periods of shortage, and also benefit from occasional abundances. The discovery of methods of processing and preserving food meant that new sources of food could be used with increased efficiency and increasingly less waste. People migrated across continents, seas, and oceans in response to sometimes complex social pressures, but certainly the search for food and reliable sources of food was a common factor in their movements. There may be a greater urgency today than heretofore to identifying sustainable sources of energy, increasing the efficiency of energy usage, and finding new sources of energy due to expanding world population, depletion of energy resources, and growing environmental concerns; but there is no question that similar patterns have been in evidence for thousands of years. And there is something timeless and circular about modern society growing crops that once would have been considered food, but now are solely intended to produce energy as biofuels.

The history of how energy is and was used illustrates how competing usages dictate the exploitation of resources, often to the detriment of the original but less powerful first adopters. Charcoal as fuel for cooking has a long history and is still in demand today for use in barbecues. Yet more than five thousand years ago, people found that it was useful in smelting of iron and in the Bronze Age applied it to the production of copper and more valuably, bronze. These and subsequent developments caused the clearing of woodlands and competed with land once intended only for agricultural purposes. The use of banks to divide land facilitated the retention of some trees which were then coppiced to provide a source of charcoal. By the thirteenth century Europeans had learned of the Chinese explosive gunpowder, which created a new demand for charcoal yet again. The military use of gunpowder necessitated the casting of cannons, requiring a considerable amount of charcoal. These factors put pressure on supplies of wood suitable for charcoal production, leading to the introduction of restrictions in certain countries. By the eighteenth century the demand for charcoal to support the iron industry was so high that an alternative was desirable, and this was found in the form of coke. Not only could coke replace charcoal for many industrial purposes, but a byproduct of coke production was a combustible gas that could be used in households. Not surprisingly coal and coke producers encouraged the use of their products, further reducing the demand for charcoal. The historical relationship between coke and charcoal demonstrate how a single energy source can have many interacting uses and drivers for its exploitation, and that the resultant interrelationships between users and suppliers are complex.

During World Wars I and II and their aftermath, the world witnessed both the horror of the destructive power of nuclear energy and the potential promise of an efficient, reliable and clean source of electrical energy. The debate on the future mix of nuclear power in global energy provision, which had to address such issues as nuclear waste disposal, nuclear power plant accidents and their environmental and social consequence, and the continued development and dependence on nuclear energy from an armaments perspective, continues today (these issues are explored further in chapter 7). Furthermore, the general argument that environmental factors are not the only ones that influence decisions on energy production also applies to what might be called green or clean technologies. Lobby groups pushing their own agendas have not always supported their stances with high quality economic and environmental data. As a result, the informed public has rightly become more robust in questioning the latest projects to harness power through renewable and sustainable sources, whether those involve estuary barrages, wave power, offshore wind, solar power, or bioenergy. Apart from searching for new solutions and developing new methods of production, energy engineers have a clear responsibility to help inform policy makers and the general public of the pros and cons of each means of energy production.

The world has truly become a global village. The challenges to achieving global economic security and sustainable living—in a world of increasing population and multivariable levels of wealth and social inequality—are complex and vast. The relationship between man and machine, productivity and industrial development, marches on. Whether in cities of the so-called developed nations or in the rapidly expanding urban population centers of the developing world, concern for the atmosphere that sustains Earth's ecosystem is of growing importance. Air pollution affects the overall balance and ultimate health of the ecosystem. It is instructive to briefly review the nature and composition of Earth's atmosphere and to explore the important role played by carbonaceous fuels throughout human history.

1.2. Earth's Atmosphere and Greenhouse Gases

1.2.1. Climate Variability

Climate variability is one of the great discussion points and climate change one of the great concerns of humankind today. Research in climate science and meteorology is long established and it is therefore fitting to briefly review the writings of a selected band of pioneering thought leaders of the nineteenth century in their contemplations of Earth's atmosphere and its makeup.

In the 1820s, Jean Baptiste Joseph Fourier calculated that, based on its size and distance from the sun, planet Earth should be considerably cooler than it actually is, assuming it is warmed only by the effects of incoming solar radiation. He examined various possible sources of the additional observed heat, and ultimately concluded that the Earth's atmosphere acts in some way as an insulator, thus retaining quantities of incoming solar heat. This observation may be considered the earliest scientific contribution to what today is commonly known as the greenhouse effect.[1]

Forty years later John Tyndall identified the radiative properties of water vapor and CO_2 in controlling surface temperatures. In 1861, after two years of painstaking experiments, Tyndall published a lengthy paper packed with results. Among the findings, he reported that moist air absorbs thirteen times more heat than dry, purified air.[2] Tyndall observed that:

> The waves of heat speed from our earth through our atmosphere towards space. These waves dash in their passage against the atoms of oxygen and nitrogen, and against the molecules of aqueous vapor. Thinly scattered as these latter are, we might naturally think meanly of them as barriers to the waves of heat.[3]

In the early twentieth century, Swedish scientist Svante Arrhenius asked whether the mean temperature of the ground was in any way influenced by the presence of the heat-absorbing gases in the atmosphere. This question was debated throughout the early part of the twentieth century and is still a main concern of earth scientists today. Arrhenius went on to become the first person to investigate the effect that doubling atmospheric carbon dioxide would have on global climate and was awarded the 1903 Nobel Prize for Chemistry.[4]

It is well understood that Earth's atmosphere comprises a layer of gases surrounding the planet and retained by gravity.[5] Extending from Earth's surface, the atmosphere protects life on Earth by absorbing ultraviolet solar radiation, warming the surface through heat retention (the *greenhouse effect*), and reducing temperature extremes between day and night through a process called *diurnal variation*. The air we breathe contains approximately 78.1% nitrogen, 20.9% oxygen, 0.9% argon, 0.04% carbon and small amounts of other gases. These other gases, often referred to as trace gases, also comprise the *greenhouse gases*.

An atmospheric greenhouse gas (GHG) can absorb and emit radiation within the thermal infrared (IR) range of the electromagnetic spectrum of light.[6] The primary greenhouse gases of Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and tropospheric ozone.[7] Solar radiation passing through the atmosphere heats the surface of the Earth. Some of the energy returns to the atmosphere as long-wave heat energy radiation, some energy is captured by the layer of gases that surrounds the Earth, and the remainder passes into space. The concentration and proportional mix of these gases in the atmosphere influence climate stability and changes in composition can result in climate change. Since the commencement of the industrial revolution, human activity such as the burning of fossil fuels, the release of industrial chemicals, the removal of forests that would otherwise absorb carbon dioxide, and their replacement with intensive livestock ranching, has changed the types and quantities of gases in the atmosphere. This in turn has substantially increased the capacity of the atmosphere to absorb heat energy and emit it back to Earth. Some greenhouse gases stay in the atmosphere for only a few hours or days, while others remain for decades, centuries, or even millennia. Greenhouse gases emitted today will drive climate change long into the future, and the process cannot be quickly reversed.[8]

1.2.2. Carbonaceous Fuels

Carbon dioxide emissions come from combustion of carbonaceous fuels such as coal, oil and natural gas. Carbon dioxide has an atmospheric lifetime of about one hundred years; methane, twelve years; and nitrous oxide, one hundred fourteen years. Methane is up to twenty-five times more effective than carbon dioxide in the capture of heat in the atmosphere and its radiative effect is approximately seventy times larger, however it exists in much smaller concentrations and therefore its overall environmental impact is significantly less. In addition to its production through farming livestock, rice cultivation, and coal mining, there are large quantities of methane in arctic permafrost ice[9] and below ocean sediments. Release of such gas could result in major environmental damage; large-scale release has not occurred in recent history, but remains a point of genuine concern.

Isn't it ironic that the natural elements of coal, gas, and oil, having sustained human life over thousands of years, are now viewed to a certain degree as offenders, responsible for the pollution that has upset the balance of nature? It is, of course, mankind that has created the current instability through insatiable exploitation of Earth's resources. It is therefore mankind's responsibility to ensure every effort be made to redress the damage done and to work toward a more sustainable eco-environment.

1.2.3. Fossil Fuels Through History

Fossil fuels are formed by natural processes such as the anaerobic decomposition of buried dead organisms, through exposure to heat and pressure in the Earth's crust over time periods of typically millions of years. Containing high percentages of carbon, fossil fuels include coal, petroleum, and gas. They range from volatile materials with low carbon to hydrogen ratios, such as methane (CH_4), to liquid petroleum, to nonvolatile materials composed of almost pure carbon, such as anthracite coal.[10] George Agricola is credited as the first scientist to have articulated the biogenic of fossil fuel creation. His most famous work, the *De re metallica libri xii*, a treatise on mining and extractive metallurgy, was published in 1556. Agricola described and illustrated how ore veins occur in and on the ground, making the work an early contribution to the developing science of geology.[11]

In 2011, fossil fuel consumption in the United States totaled eighty quadrillion British thermal units (Btu). The US Energy Information Administration (EIA) estimated that 80% of that energy was derived from fossil fuels, specifically 35.3% from petroleum, 19.6% from coal, and 26.8% from natural gas. Nuclear energy and renewable energy accounted for 8.3% and 9.1%, respectively.[12]

Fossil fuels are non-renewable resources because they take millions of years to form, and reserves are being depleted much faster than new ones are being made. The burning of fossil fuels produces over twenty-two billion tonnes of carbon dioxide (CO_2) per year, but it is estimated that natural processes can only absorb about half of that amount. This causes a net increase of eleven billion tonnes of atmospheric carbon dioxide per year.

1.2.3.1. Coal

One of Earth's most valued natural resources, coal has been a provider of warmth and energy to humankind for hundreds, if not thousands of years. Resulting from decaying woodland vegetation, compressed by rain water and repeatedly added to through further additional mineral vegetation deposit over hundreds of thousands of years, peat was formed which over time hardened to lignite (brown coal) and then to coal, a dark colored sedimentary rock made of both inorganic and organic matter. With many different classifications of grade and composition, also referred to as coal rank, coal is primarily composed of carbon, while also containing elements of hydrogen, oxygen, nitrogen, aluminum, silicon, iron, sulfur and calcium. Coal can in fact contain as many as one hundred twenty inorganic compound trace elements with over seventy of the naturally occurring elements of the periodic table. Designated coal types range from lignite to flame coal, sub-bituminous, bituminous through to nonbaking coal and anthracite, classified in accordance with percentage element composition. The particles of organic matter in coal are referred to as macerals, indicative of plants or parts of plants including bark, roots, spores and seeds, which originally contributed to a particular coal formation. Coal rank is determined by the percentage of fixed carbon, moisture, volatile matter, and calorific value in British thermal units after the sulfur and mineral-matter content have been subtracted.[13]

Coal is the world's most abundant and widely distributed fossil fuel, accounting for more than one quarter of global primary energy demand. With global proven reserves totaling nearly one trillion tonnes it remains one of the most important sources of energy for the world, particularly for power generation.[16] Coal fuels high percentages of electricity to the United States (49%), India (69%), China (79%), Poland (92%), and South Africa (97%), and supplies in excess of forty percent of the global electricity generation requirements, including Germany and much of central Europe. More than twenty-three percent of total world energy and thirty-six percent of world electricity is produced by coal, with a projected growth of 2.4% annually in the consumption of electricity between 2005 and 2030. Over the last decade demand for coal has outpaced that for gas, oil, nuclear power, and renewable energy sources. North America, the former Soviet Union, and Pacific Asia combined account for more than eighty percent of proven coal reserves. Global coal production in 2009 topped 6.9 billion tonnes, with China producing approximately 46 percent, the United States 16 percent, and Australia and India equal producers at roughly 6 percent. Bituminous coal dominates world production, followed by lignite and coking coal. Sixty percent of coal is produced through underground mining. Australia and Indonesia are the two main coal exporting countries. Most coal-producing nations produce for their home markets exclusively, and import the balance required to meet national demand. In spite of environmental concerns, coal is expected to continue to be the second greatest global source of energy through 2030.[17]

Coal-fired power plants, however, are facing new challenges owing to increased competition from natural gas and new air pollutant regulations advanced by the EPA in 2011, requiring in particular reduced emissions of mercury, acid gases, and soot.[18] Average CO_2 emissions from coal-fired power plants are roughly double those from natural gas plants, approximately 2,250 and 1,135 pounds per megawatt hour, respectively. Coal-fired plant retirements are projected to rise to nine thousand megawatts by 2014, with a reduction in generating capacity from coal of well in excess of ten percent.[19]

Carbon and the Industrial Revolution

Socio-techno-economic factors all played their part in how industrial revolutions originated, developed, transformed and then eventually evolved to a post-revolution industrial society. One of the key factors undoubtedly was the availability of energy and invariably that source of energy was coal. In Great Britain Matt Ridley noted that it was not just the availability of coal but that for other and existing sources "there was never going to be enough wind, water or wood in England to power the factories, let alone in the right place."[14] Of course this comment has to be qualified in that we now know that there was and is sufficient energy available from wind and water, but the technology and know-how did not exist to harness the levels of energy required by industries such as iron and transport. Ridley refers exclusively to windmills, water mills, and charcoal. Another point Ridley makes is that the widespread use of horses required a huge amount of food (itself an energy source) that required up to one-third of the available arable land—land required to feed a growing population. It was therefore necessary to abandon renewable sources of energy if the Industrial Revolution was to take off. But the picture was complex, as technological innovation was required in order to exploit coal at an economic advantage. Effective water pumps were required for mining, and new transport solutions were needed to deliver coal to where it was to be used. Steam engines for both pumps and early trains, as well as the rapidly expanding rail network, required machines to manufacture and shape the necessary parts, and it was coal that ultimately provided the power.

Coal as it was used during the Industrial Revolution came at an additional cost in terms of a set of disadvantages. First, it was dirty, resulting in huge amounts of ash. Second, it produced a range of toxic flue gases as well as carbon dioxide. Third, the production of coal left its mark on the landscape and more importantly on the men and their families who carried out the mining. And because coal was abundant, there were few incentives to investigate alternatives or even to be much concerned with efficiency. A plentiful supply of coal replaced a number of largely clean energy sources, but this was not considered an issue as long as profits were increasing. Of course today clean—or more correctly cleaner—coal technology (such as flue gas scrubbing) has been developed, but the long-term damage cannot be undone.

Some of the problems that accompany coal mining include:

- *Acid mine drainage* results when coal beds and surrounding strata containing medium to high amounts of sulfur (sulphide compounds) are disrupted by mining, thereby exposing sulphides to air and water.
- Atmospheric sulfur oxides (SO_x) and subsequent acid decomposition, such as acid rain, result from the burning of medium to high-sulfur coal.
- The quality of surface and ground water may be adversely affected by the disposal of the ash and sludge that result from the burning of coal and flue gases.
- Environmental greenhouse gas emissions result from the release of carbon dioxide (CO_2) and nitrogen oxides (NO_x) through the burning of coal.

- Additional trace elements are released through burning of coal.

Developments both during and subsequent to the Industrial Revolution also resulted in great benefits to society. The Enlightenment provided the stimulus for creative development and innovation, an increased interchange of knowledge coupled with a new entrepreneurial vigour.[15]

1.2.3.2. Petroleum[20]

Petroleum, also termed crude oil, contains hydrocarbons and other organic compounds. It is found in natural formations beneath the Earth's surface. It is derived from ancient organic materials such as zooplankton and algae. Petroleum is recovered mostly through oil drilling. Colonel Edwin Laurentine Drake is credited as the first person to have successfully drilled for oil in the United States. Employed by the Seneca Oil Company in 1858 to investigate oil deposits in Pennsylvania, Drake devised a 10-foot long cast-iron drive pipe which struck bedrock at 32 feet. The following morning crude oil was seen to be rising up and oil was brought to the surface using a hand-pitcher pump.[21]

The discovery of oil triggered an oil rush in America, fueled by an American law which conferred ownership of underground resources to the landowner. During this period, crude oil was refined into kerosene and was used to light homes and businesses. In 1863 John D. Rockefeller entered the fray and concentrated his business on the refining, transportation, and distribution of petroleum. After founding the Standard Oil Company in 1870, Rockefeller became the dominant figure in the late nineteenth century petroleum industry. Exploration in other parts of the United States, in particular Texas, and in countries including Russia, Dutch East Indies, Indonesia, Venezuela, Trinidad, and Mexico opened up the market with competition from companies including the Royal Dutch Company and Shell. It wasn't until around 1910 that oil began to overtake coal as the primary global energy driver. This was largely due to the rapid growth of the automobile industry and the necessity for widespread availability and supply of gasoline.[22]

Today, petroleum is refined and separated into a range of consumer products, including gasoline (petrol), kerosene (paraffin), asphalt (bitumen), and chemical reagents used to make plastics and pharmaceuticals. Petroleum is used in manufacturing a wide variety of materials, and it is estimated that the world consumes up to eighty-eight million barrels per day. The term petroleum strictly refers to crude oil, however in common usage it includes all liquid, gaseous, and solid hydrocarbons. Under certain surface pressure and temperature conditions, lighter hydrocarbons including methane, ethane, propane, and butane exist as gases, while pentane (C_5H_{12}) and heavier organic compounds exist in the form of liquids or solids.[23]

An oil well produces predominantly crude oil, with some natural gas dissolved in it. Because the pressure is lower at the surface than underground, some of the gas will come out of solution and be recovered (or burned) as *associated gas* or *solution gas*. A gas well produces predominantly natural gas, however because the underground temperature and pressure are higher than at the surface, the gas may contain heavier hydrocarbons such as pentane, hexane, and heptane in the gaseous state. At surface conditions these will condense out of the gas to form natural gas condensate. The proportion of light hydrocarbons in the petroleum mixture varies greatly among different oil fields, ranging from as much as 97 percent by weight in the lighter oils to as little as 50 percent in the heavier oils and bitumens.

Within the Organization of Petroleum Exporting Countries (OPEC), the five Middle Eastern countries Saudi Arabia, Iran, Iraq, Kuwait, and United Arab Emirates accounted for seventy percent of oil reserves in 2009, with Saudi Arabia alone accounting for twenty-six percent of total OPEC reserves.[24] Non-OPEC production accounts for about sixty percent of current global oil supply. China has emerged as the largest oil consuming country in the world with annual growth rate of about seven percent.

Global crude oil consumption grew by 0.6 million barrels per day (b/d) in 2012, reaching 88 million b/d. OECD consumption actually declined by 1.2% in line with trends over recent years. Non-OECD consumption grew by 2.8%. China had the largest consumption growth at 5.5% (505,000 b/d).

1.2.3.3. Natural Gas

Natural gas is found in deep underground natural rock formations or associated with other hydrocarbon reservoirs in coal beds and as methane clathrates. As discussed above, petroleum is also found in proximity to and with natural gas. Most natural gas was created over time by either a biogenic or thermogenic mechanism. *Biogenic gas* is created by *methanogenic* organisms (microorganisms that produce methane as a metabolic byproduct in anoxic conditions) in marshes, bogs, landfills, and shallow sediments. Deeper in the earth, at greater temperature and pressure, *thermogenic gas* is created from buried organic material.[25]

Natural gas is often informally referred to simply as *gas*, especially when compared to other energy sources such as oil or coal. In the nineteenth century, natural gas was obtained as a byproduct of producing oil, since the small, light gas carbon chains came out of solution as the extracted fluids underwent pressure reduction from the reservoir to the surface. If unwanted, natural gas was burned off at source in the oil field. Today, unwanted gas may be returned to the reservoir through injection wells. Where economical, gas may be transported using a network of pipelines. By converting gas into a form of liquid gasoline or diesel, it may also be exported as a liquid, commonly referred as *gas to liquid* (GTL), or to a jet fuel by applying the *Fischer-Tropsch process* (a collection of chemical reactions that converts a mixture of carbon monoxide and hydrogen into liquid hydrocarbons).

Before natural gas can be used as a fuel, it must undergo processing to remove impurities, including water, to meet the specifications of marketable natural gas. The byproducts of processing include ethane, propane, butanes, pentanes, and higher molecular weight hydrocarbons, hydrogen sulfide (which may be converted into pure sulfur), carbon dioxide, water vapor, and sometimes helium and nitrogen.

Natural gas extracted from oil wells is called *casinghead* gas or *associated* gas. The natural gas industry is extracting an increasing quantity of gas from challenging resource types, including *sour gas*, *tight gas*, *shale gas*, and *coalbed methane*.

The world's largest proven gas reserves are located in Russia, at approximately 48 terra (10^{12}) cubic meters. Russia is frequently the world's largest natural gas extractor. Other major proven resources (in billion cubic meters) exist in Iran (26,370 in 2006), Qatar (25,790 in 2007), Saudi Arabia (6,568 in 2006) and the United Arab Emirates (5,823 in 2006).

The world's largest gas field is Qatar's offshore North Field, estimated to have twenty-five trillion cubic meters of gas in place.[26] The second largest natural gas field is the South Pars Gas Field in Iranian waters in the Persian Gulf. Located next to Qatar's North Field, it has an estimated reserve of eight to fourteen trillion cubic meters of gas.

1.2.3.4. Shale Gas

Shale is a fine-grained, clastic sedimentary rock composed of mud that is a mix of flakes of clay minerals and tiny fragments of other minerals, notably quartz, calcite, feldspar, and dolomite. The ratio of clay to other minerals is variable. Shale is characterized by breaks along thin laminae or parallel layering or bedding less than one centimeter in thickness, called *fissility*.[27] Shale is easy to break or split, slate-like, into smaller planar sheets. Oil shale occurs where organic material is present in the process of producing the sedimentary rock. Extraction of gas and oil is carried out by heating the shale to temperatures in the region of 475°C. It is estimated that there are about nine hundred trillion cubic meters of unconventional gas such as shale gas, of which one hundred eighty trillion may be recoverable.[28]

Shale gas was first extracted as a resource in Fredonia, New York in 1821, in shallow, low-pressure fractures.[29] In the mid-1800s James Young, a Scottish chemist, devised a method of extracting from shale an oil product which he then distilled to yield kerosene, naphtha, heavier lubricating oils, and paraffin wax. Fuel (kerosene) to provide lighting was an important use of the shale oil at the end of the industrial revolution. The shale residue gave rise to shale bings (small hills or tips) which are still a feature of the landscape today in West Lothian, Scotland.

Horizontal drilling began in the 1930s, and in 1947 a well was first fracked[30] in the United States. Work on industrial-scale shale gas production did not begin until the 1970s, when declining production potential from conventional gas deposits in the United States spurred the federal government to invest in research, development, and demonstration projects that ultimately led to directional and horizontal drilling, microseismic imaging, and massive hydraulic fracturing. Up until the public and private demonstration projects of the 1970s and 1980s, drilling in shale was not considered to be commercially viable.

Approximately thirty countries have oil shale in quantities that are economically extractable and they include Brazil, China, Germany, Russia, Sweden, and the United States. Worldwide peak production occurred in the 1980s (forty-six million metric tons).[31] Allix et al. note that "current estimates of the volumes recoverable from shale oil deposits are in the trillions of barrels, but recovery methods are complicated and expensive . . . but may soon become economically viable."[32]

As with many sources of energy, the use of shale gives rise to environmental issues. Two major disadvantages of oil recovery from shale is the huge amounts of waste rock (spent shale) and the requirement for large quantities of water in the post-extraction treatment. To mitigate the waste problem, one company, Shell, has investigated *in situ* extraction of oil based on a method first developed in Sweden using electric heaters. Trials have also investigated the use of high temperature injected steam. As the United States has the largest oil shale deposits in the world and bearing in mind its policy of being as independent as possible of other oil suppliers, it is likely that the exploitation of these deposits and the development of extraction methods will intensify.

There are growing fears among concerned citizens about the social and environmental impacts of hydrofracking, not least in the United States. The New York Marcellus Shale formation extends from West Virginia to southern New York. Lobby groups such as the Nature Conservancy[33] point out that high volume horizontal fracturing (hydrofracking) would necessitate use of millions of gallons of water per fracking treatment. The water used also contains oil, grease, and small amounts of other chemicals and it is estimated that up to forty percent of this water will return to the surface, resulting in various degrees of environmental pollution.

1.2.4 Clean Fossil Fuels: Future Challenges and Prospects

1.2.4.1. Overview

While there has been a substantial growth in generation of power from renewable and green sources, coal will remain a significant source of fuel for power generation due to the requirements of availability, security and diversity of supply. It is therefore important to review the state of the art in the field of Clean Coal Technologies (CCTs) and how such technologies may help reduce carbon emissions going forward.

The primary drawback associated with the use of traditional coal is that modern coal-fired power plants operate at low efficiencies and emit large amounts of pollutants. This drawback can be circumvented by instead using clean coal. CCT is a product of several generations of technological advances. Since the process of combustion is the key for energy generation, CCT has led to more efficient combustion of coal with reduced emissions of greenhouse gases (GHGs), including carbon dioxide, sulfur dioxide, and nitrogen oxide. The market for CCT is steadily growing owing to the imminent need to reduce GHGs and improve upon power plant efficiency.

One of the biggest challenges in the implementation of CCT is that the quality of coal is extremely variable and that coal combustion structurally produces more pollutants than other fossil fuels. Coal is also a major ingredient in the production of steel. A further concern is China; the world's largest and fastest growing economy ranks number one in coal production, accounting for more than forty percent of global production. The extensive use of coal worldwide, coupled with a large number of old, inefficient power plants lacking proper emission control equipment, adds to the pollution generated through burning coal.

Given the likelihood that coal will continue to feature prominently in the energy mix for decades to come, adaptation and deployment of CCT in both new and existing plants, where possible, is essential. Power plants being built today are more efficient and emit ninety percent less pollutants (SO_2, NOx, particulates and mercury) than plants built in the 1970s. There are three stages to achieving clean coal:

1. Controlling and reducing pollutants (excluding CO_2),
2. Deploying advanced technologies, and
3. Installing CO_2 capture and storage.

1.2.4.2. Advanced Technologies

To control and reduce pollutants it is necessary to remove the source of pollution before burning, avoid production of pollutions during combustion, and remove pollutants prior to stack emission.

Plant efficiency and pollutant emission reduction can be improved upon by deploying advanced technologies and improving the thermodynamic cycle of power generation. For example, there is a modern shift from steam-cycle plants to gas-cycle plants. Advanced ultra-supercritical (USC) parameters for steam are used in some plants. Further to the use of these parameters for steam conditions, other advanced technologies incorporated include several clean air technologies; innovative design of burners, new schemes for combustion in the boiler furnace, new design of steam superheaters and systems for gas cleaning.

In fluidized bed combustion technology, limestone and dolomite are added during the coal combustion process to mitigate sulfur dioxide formation.

An integrated gasifier combined cycle uses heat and pressure in the thermodynamic cycle to convert coal into a gas/liquid phase. The coal in this transformed phase can be further refined, resulting in reduced environmental impact. The heat energy from the gas turbine is also used to power a steam turbine. This technology has the potential to improve the thermodynamic system efficiency of a coal plant to fifty percent.

Flue gas desulfurization, or scrubber technology, removes large quantities of sulfur, particulate matter, and other impurities from the emissions. Low Nitrogen Oxide (NOx) burners help reduce the generation of NO_x, a set of gases which contribute to ground-level ozone. This is achieved by restricting oxygen and manipulating the combustion process. Selective Catalytic Reduction (SCR) achieves NO_x reductions of between eighty and ninety percent. Electrostatic Precipitators remove particulates from emissions by electrically charging particles and then capturing them on collection plates.

1.2.4.3. Carbon Capture and Storage

There is a long term view toward achieving effective capture and storage of carbon dioxide. CO_2 emissions from burning of coal are calculated based on the *emission factor*, EF_C, where

$$EF_C = (CR \times CC \times CE \times 44)/(HV \times 12)$$

HV is the heating value of the fuel (12–32 MJ/kg), CC is the carbon content of the coal (60–90%), CE is the combustion efficiency (0.9–0.95), and CR is an opportune conversion rate (0.2778 in the case of kWh).[34]

Carbon capture and storage requires capturing CO_2 emissions and then storing them either in geologic formations or deep in the ocean bed where the gas is then dissolved under pressure. CCS technologies under development include:

- Post-combustion capture: This involves capture from the flue gases and necessitates use of an amine as solvent and chilled ammonia.
- Pre-combustion capture: Here, integrated gasifier combined cycling is used to isolate and capture CO_2 before it is released to the atmosphere.
- Oxy-Coal combustion process: This is an improved combustion process using pure oxygen in the boiler, resulting in significant reduction in the dilution of CO_2 in the exhaust gas stream.

Improved efficiency of power plants will reduce the levels of CO_2 emissions, however, carbon capture and storage would be a more effective solution. Unfortunately, CCS technologies require energy to implement and operate, reducing overall plant performance. Other pollutant emissions are also created in the CCS process, including limestone and ammonia. This technology is still at an early stage of development and can be considered as a future technology.

The development of CCT is growing worldwide with active research and development in both the US and Europe. If successful, CCT will play a vital role in allowing the continued worldwide use of abundant coal resources, in an affordable and sustainable manner. Such advanced technologies can contribute significantly to the areas of mercury control and carbon capture and storage, while also assisting in the reduction of SO_2 and NO_x emissions. Zero emissions through carbon sequestration, is a long-term objective.

While developments in clean coal technologies mark a welcome phase in the history of coal as a power fuel, there are considerable challenges relating to economic cost, plant refurbishment, effective utilization, and wide scale global deployment of such technologies. There is a sense of a race against time in the proposition that clean coal technologies may significantly offset the damaging effects of carbon emissions or that deployment will justify the further and continued exploitation of coal as a principal source of energy going forward. Even if CCT doesn't allow current levels of coal utilization to be sustainable, effective development of clean technologies could result in justification for the use of coal in reduced quantities in the energy mix until such time that carbon free renewable technologies reach mature status and can be shown to be effective for deployment. The future for nuclear energy, debated in chapter 7, will also influence the viability for significant investment in clean coal and related technologies.

Notes

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2. John Tyndall, "On Radiation Through the Earth's Atmosphere," *Notices of the Proceedings of the Meetings of the Members of the Royal Institution of Great Britain with Abstracts of the Discourses of the Evening Meetings*, vol. 4: 1862–1866 (London: W. Nicol, 1866), 4–8.
3. Ibid., 5.

4. "Svante Arrhenius (1859–1927)," NASA Earth Observatory, last modified 2013, http://earthobservatory.nasa.gov/Features/Arrhenius/.
5. Atmosphere: Greek *atmos* (vapor) and *sphaira* (sphere).
6. With longer wavelengths than those of visible light, IR extends from the nominal red edge of the visible spectrum at 0.74 micrometres (µm) to 300 µm. This range of wavelengths corresponds to a frequency range of approximately 1 to 400 THz. The existence of infrared radiation was first discovered in 1800 by astronomer William Herschel.
7. Ozone (O_3), a triatomic allotrope of oxygen, is much less stable than the diatomic allotrope, O_2. When occurring in the lower atmosphere, O_3 is an air pollutant. The ozone layer in the upper atmosphere, however, is a protector against excess ingress of electromagnetic radiation.
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30. Hydraulic fracturing, or fracking, is the fracturing of various rock layers by a pressurized liquid.
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32. Ibid., 5.
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