Energy security and the environment

10

10.1 Introduction

All fossil fuels—coal, crude oil, and natural gas—release pollutants into the atmosphere when burned to provide energy. However, natural gas—being composed predominantly of methane which combusts to carbon dioxide and water—is considered the most environment-friendly fossil fuel. It is cleaner burning than coal or petroleum because it contains less carbon than some of its fossil fuel cousins. Natural gas once cleaned (Chapter 7: Process classification and Chapter 8: Gas cleaning processes) also contains much less sulfur and nitrogen compounds than, say coal, and when burned natural gas emits less ash (particulate matter) and soot into the air than coal or petroleum fuels. In fact, among the conventional fossil fuels (coal, crude oil, and natural gas), the consumption growth of natural gas outpaced the other fossil fuel types, i.e., coal and petroleum (BP, 2017). This is attributable to stronger demands of natural gas in industrial and residential heating, increased installations of natural gas-based electric power plants, and new discoveries of large natural gas deposits. In the 21st century, the world already experienced several times significant shortages and price hikes of natural gas, mainly due to imbalances between supply and demand.

Natural gas is the third most used energy source in the United States at 23% of the energy requirements, after crude oil and coal. Industry consumers are, by far, the largest consumer of natural gas in manufacturing goods, followed by utilities for electric power generation, residential consumers for heating homes and cooking, and then commercial users mainly for building heating (Speight and Islam, 2016). Industrial use of natural gas contribute to manufacturing a wide variety of goods including plastics, fertilizers, photographic films, inks, synthetic rubber, fibers, detergents, glues, methanol, ethers, insect repellents, and much more. Natural gas is popularly used in electric power generation. Natural gas burns cleaner and more efficiently than coal. It has less emission-related problems than other popular fossil fuels.

However, natural gas has only a limited market share as a transportation fuel, even though it can be used in regular internal combustion engines. This is mainly due to its low energy density per volume, unless natural gas is compressed under very high pressure. In addition, more than 50% of the residential homes in the United States use natural gas as the main heating fuel. It is obvious that any major disruption in natural gas supply would bring out unique but quite grave consequences in the nation's energy management, at least for a short term and for a certain affected region, since natural gas is heavily utilized by both electric power

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generating utilities and residential homes. Furthermore, the regional energy dependence problem has been somewhat mitigated by deregulation of utilities, which altered the business practices of electric utilities and natural gas industry. The deregulation allows natural gas customers to purchase natural gas from suppliers other than the local utility, thus providing choices for consumers and eventually resulting in better economic balance of the energy costs.

Thus natural gas is an extremely important source of energy for reducing pollution and maintaining a clean and healthy environment (Speight, 1993; Speight, 2007, 2014, 2017, 2018). In addition, as an abundant and secure source of energy in the United States because of the domestic reserves (BP, 2017), the use of natural gas also offers a number of environmental benefits over other sources of energy, particularly other fossil fuels. Furthermore, there are environmental concerns with the use of any fuel. As with other fossil fuels, burning natural gas produces carbon dioxide, which is a very important and effective greenhouse gas. Many scientists believe that increasing levels of carbon dioxide and other greenhouse gases in the atmosphere of the Earth are changing the global climate. However, there are issues that have been raised that are related to the means by which the carbon dioxide in ice cores (the leading evidence for increases on carbon dioxide in the atmosphere) have been measured that throw doubt upon the contribution to the carbon dioxide in the atmosphere by human activities (Speight and Islam, 2016).

Thus, as with other fuels, natural gas also affects the environment when it is produced, stored, and transported. Because natural gas is made up mostly of methane (another greenhouse gas), there is the potential for leaks of methane into the atmosphere from wells, storage tanks, and pipelines. In addition, exploring and drilling for natural gas will always have some impact on land and marine habitats but new technologies have greatly reduced the number and size of areas disturbed by drilling (often referred to as *environmental footprints*). Satellites, global positioning systems, remote sensing devices, and 3-D and 4-D seismic technologies make it possible to discover natural gas reserves while drilling fewer wells. Plus, use of horizontal drilling and directional drilling make it possible for a single well to produce gas from much bigger areas of the reservoirs (Speight, 2016).

Once brought from underground (Chapter 4: Composition and properties), the natural gas is refined to remove impurities such as water, other gases, sand, and other compounds (Chapter 6: History of gas processing and Chapter 7: Process classification). Some hydrocarbons (ethane, propane, and the butane isomers) are removed and sold separately, including propane and butane (Chapter 7: Process classification and Chapter 8: Gas cleaning processes). Other impurities, such as hydrogen sulfide are also removed and used to produce sulfur (Chapter 7: Process classification and Chapter 8: Gas cleaning processes), which is then also sold separately. After refining, the clean natural gas (methane) is transmitted through a network of pipelines, thousands of miles of which exist in the United States alone. From these pipelines, natural gas is delivered to the industrial and domestic consumers (Chapter 5: Recovery, storage, and transportation).

The use of fossil fuels for energy contributes to a number of environmental problems. Natural gas, as the cleanest of the fossil fuels, can be used in many ways to help reduce the emissions of pollutants into the atmosphere. Burning natural gas in the place of other fossil fuels emits fewer harmful pollutants into the atmosphere, and an increased reliance on natural gas can potentially reduce the emission of many of these most harmful pollutants (EIA, 2006). Pollutants emitted in the United States, particularly from the combustion of fossil fuels, have led to the development of many pressing environmental problems. Natural gas, emitting fewer harmful chemicals into the atmosphere than other fossil fuels, can help to mitigate some of these environmental issues.

On a unit basis, natural gas emits lower quantities of greenhouse gases and criteria pollutants than other fossil fuels. This occurs in part because natural gas is more easily fully combusted, and in part because processed (cleaned) natural gas contains fewer impurities than any other fossil fuel. For example, coal mined in the United States typically contains 1.6% w/w sulfur (a consumption-weighted national average). Crude oil burned at electric utility power plants ranges from 0.5% to 1.4% sulfur. Diesel fuel has less than 0.05%, while the current national average for motor gasoline is 0.034% sulfur. Comparatively, natural gas when used for power (electricity) generation has less than 0.005% sulfur compounds.

However, the issue of natural gas and any adverse effects on the environment may be due to leaks of methane which can outweigh any carbon dioxide production from combustion from natural gas (and other fossil fuel combustion). In fact, the occurrence of natural gas leaks into the atmosphere from oil and natural gas wells, storage tanks, pipelines, and processing plants are the source of approximately one-third of the total methane emissions and approximately 4% of total greenhouse gas emissions in the United States.

As long as many countries have fossil fuel-based economies, fossil fuel combustion will lead to environmental problems. In addition, the venting or leaking of natural gas into the atmosphere can have a significant effect with respect to greenhouse gases because methane, the principal component of natural gas, is much more effective in trapping these gases than carbon dioxide. The exploration, production, and transmission of natural gas, as well, can have adverse effects on the environment.

This chapter addresses the many environmental aspects related to the use of natural gas, including the environmental impact of natural gas relative to other fossil fuels and some of the potential applications for increased use of natural gas. These issues include: (1) greenhouse gas emissions, (2) smog, air quality, and acid rain, (3) industrial and electric generation emissions, and (4) pollution from the transportation sector—natural gas vehicles.

10.2 Natural gas and energy security

Energy security is the uninterrupted availability of energy sources at an affordable price (IEA, 2018) or, put another way, a particular aspect of energy security is assuring access to a ready supply of energy (US DOE, 2017). Thus energy security has many dimensions: long-term energy security mainly deals with timely investments to supply energy in line with economic developments and sustainable environmental needs. Short-term energy security focuses on the ability of the energy system to react promptly to sudden changes within the supply-demand balance. Lack of energy security is thus linked to the negative economic and social impacts of either physical unavailability of energy, or prices that are not competitive or are overly volatile (US DOE, 2017).

Historically, energy security for many countries was primarily associated with the supply of crude oil. Thus using the international oil market as the example, prices are allowed to adjust in response to changes in supply and demand, the risk of physical unavailability is limited to extreme events. However, in many instances, petro-politics (some time called geo-politics) does play a role thereby jeopardizing security of crude oil imports (Speight, 2011). Thus supply security concerns are primarily related to the economic damage caused by extreme price spikes. The concern for physical unavailability of supply is more prevalent in energy markets where transmission systems must be kept in constant balance, such as electricity and, to some extent, natural gas. This is particularly the case in instances where there are capacity constraints or where prices are not able to work as an adjustment mechanism to balance supply and demand in the short term. In fact, analysis of vulnerability for fossil fuel disruptions, e.g., is based not only on reserves within a country but also on risk factors such as net-import dependence and the political stability of suppliers. Resilience factors include the number of entry points for a country (e.g., ports and pipelines), the level of stocks, and the diversity of suppliers.

10.2.1 Reserves

Reserves are the amount of a resource available for recovery and/or production with the recoverable amount of natural gas being usually tied to the economic aspects of production.

In terms of reserves, natural gas is produced on all continents except Antarctica. The proven reserves of natural gas are of the order of 6588.8 trillion cubic feet (6588.8 Tcf; 1 Tcf $= 1 \times 10^{12}$ cubic feet) of which approximately 374 Tcf exist in the United States and Canada (BP, 2017). It should also be remembered that the total gas resource base (like any fossil fuel or mineral resource base) is dictated by economics. Therefore when resource data are quoted some attention must be given to the cost of recovering those resources. Most important, the economics must also include a cost factor that reflects the willingness to secure total, or a specific degree of, energy independence. The total proved reserves of natural gas are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions.

A common misconception about natural gas is that resources are being depleted at an alarming rate and the supplies are quickly running out. In fact, there is a vast amount of natural gas estimated to still be retrieved from a variety of reservoirs, including tight reservoirs and shale reservoirs. However, many proponents of the rapid-depletion theory believe that price spikes indicate that natural gas resources are depleted beyond the point of no return. However, price spikes of any commodity are not always caused by waning resources but can be the outcome of other forces—including foreign economic forces—that are operative in the marketplace.

10.2.2 Energy security

Energy security is the continuous and uninterrupted availability of energy to a specific country or region. The security of energy supply conducts a crucial role in decisions that are related to the formulation of energy policy strategies. The economies of many countries are dependent upon the energy imports (or energy exports) in the notion that their balance of payments is affected by the magnitude of the vulnerability that the countries have in crude oil and natural gas purchases and/or sales (Speight, 2011).

Energy security has been an on-again-off-again political issue in the United States since the first Arab oil embargo in 1973. Since that time, the speeches of various Presidents and the Congress of the United States have continued to call for an end to the dependence on foreign oil and gas by the United States. The congressional rhetoric of energy security and energy independence continues but meaningful suggestions of how to address this issue remain few and far between. Natural gas offers the United States some relief from the geopolitical factors that occur regularly (some would say *every day*) that interfere with crude oil production and supplies.

It is to be hoped that, as difficult as it is because of a variety of factors, reporting data on natural gas reserves in the United States has become less of a political act that statement of crude oil production and reserves in many countries (Speight and Islam, 2016). Nevertheless, the energy literature and numerous statements by officials of oil-and-gas-producing and oil-and-gas-consuming countries indicate that the concept of energy security is elusive. Definitions of energy security range from uninterrupted oil supplies to the physical security of energy facilities to support for biofuels and renewable energy resources. Historically, experts and politicians referred to *security of oil supplies* as *energy security*. Only recently policy makers started to include natural gas supplies in the portfolio of energy definitions.

The past decade has yielded substantial change in the natural gas industry. Specifically, there has been rapid development of technology allowing the recovery of natural gas from shale formations. Since 2000, rapid growth in the production of natural gas from shale formations in North America has dramatically altered the global natural gas market landscape. Indeed, the emergence of shale gas is perhaps the most intriguing development in global energy markets in recent memory.

The security aspects of natural gas are similar, but not identical to those of crude oil. Compared with imports of crude oil, natural gas imports play a smaller role in most importing countries—mainly because it is less costly to transport liquid crude oil and petroleum products than natural gas. Natural gas is transported by pipeline over long distances because of the pressurization costs of transmission; the need to finance the cost of these pipelines encourages long-term contracts that dampen price volatility. In fact, despite some gloom-and-doom prognoses for the depletion of crude oil reserves in the near future, the structure of energy consumption is not expected to significantly change. A marginal reduction of the crude oil influence till 2030 (up to 32%) and equalization of the energy balance of crude oil, natural gas, and coal is expected up to the mid-point of the 21st century.

Moreover, beginning with the Barnett shale in northeast Texas, the application of innovative new techniques involving the use of horizontal drilling with hydraulic fracturing has resulted in the rapid growth in production of natural gas from shale (Speight, 2016). Knowledge of the shale gas resource is not new as geologists have long known about the existence of shale formations, and accessing those resources was long held in the geology community to be an issue of technology and cost. In the past decade, innovations have yielded substantial cost reductions, making shale gas production a commercial reality. In fact, shale gas production in the United States has increased from virtually nothing in 2000 to over 10 billion cubic feet per day (bcfd, 1×10^9 ft^3 per day) in 2010, and it is expected to more than quadruple by 2040, reaching 50% or more of total US natural gas production by the decade starting in 2030.

Natural gas—if not disadvantaged by government policies that protect competing fuels, such as coal—stands to play a very important role in the US energy mix for decades to come. Rising shale gas production has already delivered large beneficial impacts to the United States. Shale gas resources are generally located in close proximity to end-use markets where natural gas is utilized in fuel industry, generate electricity, and heat homes. This offers both security of supply and economic benefits.

The *Energy Independence and Security Act of 2007* (originally named the *Clean Energy Act of 2007*) is an Act of Congress concerning the energy policy of the United States. The stated purpose of the act is "to move the United States toward greater energy independence and energy security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes.

The bill originally sought to cut subsidies to the petroleum industry in order to promote petroleum independence and different forms of alternative energy. These tax changes were ultimately dropped after opposition in the Senate, and the final bill focused on automobile fuel economy, development of biofuels, and energy efficiency in public buildings and lighting. It was, and still is, felt by many observers that there should have been greater recognition of the role that natural gas can play in energy security. In fact, viewed from the perspective of the energy-importing countries as a whole, diversification in oil supplies has remained constant over the last decade, while diversification in natural gas supplies has steadily increased. Given the increasing importance of natural gas in world energy use, this is an indicator of an increase in overall energy security (Cohen et al., 2011).

However, natural gas is an attractive fuel, and its attraction is growing because of its clean burning characteristics, compared to oil or coal, and because of its price advantage, on an energy equivalent basis, compared to oil. Accordingly, there are predictions of significant future growth in natural gas consumption worldwide and growth in the trade of natural gas by bringing so-called *stranded gas* (including *shale gas*) to market.

Current trends suggest that natural gas will gradually become a global commodity with a single world market, just like oil, adjusted for transportation differences. The outcome of a global gas market is inevitable; once this occurs, the tendency will be toward a world price of natural gas, as with oil today, and the prices of oil and gas each will reach a global equivalence based on energy content (Deutch, 2010).

10.3 Emissions and pollution

Natural gas is an extremely important source of energy for reducing pollution and maintaining a clean and healthy environment. In addition, natural gas offers an abundant and secure source of energy in the United States as well as a number of environmental benefits over other sources of energy, particularly other fossil fuels. In fact, the role that natural gas can play in the future of global energy is inextricably linked to its ability to help address environmental problems. With an increase in the concerns about air quality and climate change looming large, natural gas offers many potential benefits if it is used to displace energy-producing fuels that cause more pollution. The flexibility that natural gas brings to an energy system can also make it a good fit for the rise of variable renewable source of energy.

Natural gas burns more cleanly than other fossil fuels. It has fewer emissions of sulfur, carbon, and nitrogen than coal or oil, and it has almost no ash particles left after burning. Being a clean fuel is one reason that the use of natural gas, especially for electricity generation, has grown so much and is expected to grow even more in the future.

Of course, there are environmental concerns with the use of any fuel. As with other fossil fuels, burning natural gas produces carbon dioxide, which is the most important greenhouse gas. Many scientists believe that increasing levels of carbon dioxide and other greenhouse gases in the Earth's atmosphere are changing the global climate.

Natural gas, although often cited as a relatively clean fuel, is also capable of producing emissions that are detrimental to the environment. While the major constituent of natural gas is methane, there are components such as carbon dioxide (CO), hydrogen sulfide (H_2S), and mercaptans (thiols; R-SH), as well as trace amounts of sundry other emissions. The fact that methane has a foreseen and valuable end-use makes it a desirable product, but in several other situations it is considered a pollutant, having been identified a greenhouse gas.

Also, a characteristic feature of natural gas that contains hydrogen sulfide is the presence of carbon dioxide (generally in the range of 1−4% v/v). In cases where the natural gas does not contain hydrogen sulfide, there may also be a relative lack of carbon dioxide. A sulfur removal process must be very precise, since natural gas contains only a small quantity of sulfur-containing compounds that must be reduced several orders of magnitude. Most consumers of natural gas require less than 4 ppm in the gas.

Some of the nonhydrocarbon constituents of natural gas would not be expected to biologically degrade as these substances do not contain the chemical structure that are amenable to microbial metabolism. For this reason, hydrogen, nitrogen, and carbon dioxide would not be susceptible to biodegradation. Furthermore, carbon dioxide is the final product in the biological mineralization of organic compounds. Although volatilization largely determines environmental distribution of hydrocarbon gases, some constituents have sufficient aqueous solubility that they might be present in aqueous environments at sufficient levels and/or sufficient times to make them potentially available for microbial metabolism. Higher molecular weight hydrocarbon derivatives that are typically found in gas condensate streams (such as the C_5 and C_6 hydrocarbon derivatives) have been shown to be inherently biodegradable in the environment. Not surprisingly, environmental and natural resource-related permits are required for oil and gas operations. A state may handle compliance under a general environmental impact statement. Therefore further environmental analysis may not need to be undertaken on individual oil and gas operations that obtain permits to operate.

In terms of the standard test methods that can be applied, it is of primary importance to recognize that while the major constituent of natural gas is methane, there are components such as carbon dioxide (CO), hydrogen sulfide (H_2S), and mercaptans (thiols; R-SH), as well as trace amounts of sundry other emissions. The fact that methane has a foreseen and valuable end-use makes it a desirable product, but in several other situations it is considered a pollutant, having been identified as one of several greenhouse gases. In addition, the test method may be abbreviated for the analysis of lean natural gases containing negligible amounts of hexanes and higher hydrocarbons, or for the determination of one or more components, as required (Speight, 2018).

Finally, it is necessary to address the issue of particulate matter (including the highly carbonaceous soot) which occurs as a complex emission that is classified as either *suspended particulate matter*, *total suspended particulate matter*, or simply *particulate matter*. Particulate matter is not typically analyzed as a constituent of natural gas but may be a conspicuous constituents of process gas, especially when the process gas is an effluent from a catalytic reactor. Through time, attrition of the catalyst can result in the formation of fine (micro-size) particle that will exist the reactor as part of the gas low. In fact, process gas emissions associated with petroleum refining are more extensive than methane and carbon dioxide and typically include process gases, petrochemical gases, volatile organic compounds (VOCs), carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides (NO_x), particulates, ammonia (NH_3), and hydrogen sulfide (H_2S) that must be removed (Chapter 4: Composition and properties). These effluents may be discharged as air emissions and must be treated. Particulate matter emissions are typically determined through spectroscopic analysis of the captured particulate matter that has been collected on a sampling filter (Speight, 2018).

The main sources and pollutants of concern include VOCs) emissions from storage tanks during filling and due to tank breathing, floating roof seals in case of floating roof storage tanks, wastewater treatment units, Fischer–Tropsch (F-T) synthesis units, methanol synthesis units, and product upgrading units. Additional sources of fugitive emissions include nitrogen gas contaminated with methanol vapor from methanol storage facilities; methane (CH_4), carbon monoxide (CO), and hydrogen from synthesis gas (syngas) production units, and F-T or methanol synthesis units.

10.3.1 Greenhouse gas emissions

Global warming, or the *greenhouse effect*, is an environmental issue that deals with the potential for global climate change due to increased levels of atmospheric *greenhouse gases*. These are the gases in the atmosphere that serve to regulate the amount of heat that is kept close to the Earth's surface. It is speculated that an increase in these greenhouse gases will translate into increased temperatures around the globe, which would result in many disastrous environmental effects.

Exhaust gas emissions produced by the combustion of gas or other hydrocarbon fuels in turbines, boilers, compressors, pumps, and other engines for power and heat generation are a significant source of air emissions from natural gas processing facilities. Incineration of oxygenated by-products at gas-to-liquids (GTL) production facilities also generates carbon dioxide and NO_x emissions.

The principle greenhouse gases include water vapor, carbon dioxide, methane, nitrogen oxides, and some manufactures chemicals such as chlorofluorocarbons (CFCs). While most of these gases occur in the atmosphere naturally, levels have been increasing due to the widespread burning of fossil fuels by growing human populations. The reduction of greenhouse gas emissions has become a primary focus of environmental programs in many (but not all) countries around the world.

The majority of greenhouse gas emissions come from carbon dioxide directly attributable to the combustion of fossil fuels. Therefore reducing carbon dioxide emissions can play a huge role in combating the greenhouse effect and global warming. The combustion of natural gas emits almost 30% less carbon dioxide than oil, and just under 45% less carbon dioxide than coal.

One issue that has arisen with respect to natural gas and the greenhouse effect is the fact that methane, the principle component of natural gas, is itself a very potent greenhouse gas. In fact, methane has an ability to trap heat almost 21 times more effectively than carbon dioxide.

Sources of methane emissions include the waste management and operations industry, the agricultural industry, as well as leaks and emissions from the crude oil natural and gas industry itself. It is felt that the reduction in carbon dioxide emissions from increased natural gas use would strongly outweigh the detrimental effects of increased methane emissions. Thus the increased use of natural gas in the place of other, dirtier fossil fuels can serve to lessen the emission of greenhouse gases. Before describing the polluting nature of natural gas, it is worth reviewing the composition of the gas as a means of understanding the nature of the pollutants.

Briefly, natural gas is obtained principally from conventional crude oil and nonassociated gas reservoirs, and secondarily from coal beds, tight sandstones, and Devonian shale. Some is also produced from minor sources such as landfills. In the not too distant future, natural gas may also be obtained from natural gas hydrate deposits located beneath the sea floor in deep water on the continental shelves or associated with thick subsurface permafrost zones in the Arctic.

While the primary constituent of natural gas is methane (CH_4), it may contain smaller amounts of other hydrocarbons, such as ethane (C_2H_6) and various isomers of propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12}), as well as trace amounts of higher boiling hydrocarbons up to octane (C_8H_{18}). Nonhydrocarbon gases, such as carbon dioxide (CO_2), helium (He), hydrogen sulfide (H_2S), nitrogen (N_2), and water vapor (H_2O), may also be present (Chapter 4: Composition and properties). At the pressure and temperature conditions of the source reservoir, natural gas may occur as free gas (bubbles) or be dissolved in either crude oil or brine.

Pipeline-quality natural gas contains at least 80% methane and has a minimum heat content of 870 Btu per standard cubic foot (Chapter 4: Composition and properties). Most pipeline natural gas significantly exceeds both minimum specifications. Since natural gas has by far the lowest energy density of the common hydrocarbon fuels, by volume (not weight) much more of it must be used to provide a given amount of energy. Purified natural gas (specifically methane and *not* the higher boiling constituents) is also much less physically dense, weighing about half as much (55%) as the same volume of dry air at the same pressure. It is consequently buoyant in air, in which it is also combustible at concentrations ranging from 5% to 15% by volume.

10.3.2 Air pollutants

The Earth's atmosphere is a mixture primarily of the gases nitrogen and oxygen, totaling 99%; nearly 1% water; and very small amounts of other gases and substances, some of which are chemically reactive. With the exception of oxygen, nitrogen, water, and the inert gases, all constituents of air may be a source of concern owing either to their potential health effects on humans, animals, and plants, or to their influence on the climate.

The *gaseous pollutants* are carbon monoxide, nitrogen oxides, VOCs, and sulfur dioxide. These are reactive gases that in the presence of sunlight contribute to the formation of ground level ozone, smog, and acid rain. Methane, the principal ingredient in natural gas, is not classed as a VOC because it is not as chemically reactive as the other hydrocarbons, although it is a greenhouse gas.

The nongaseous *particulate matter* consists of metals and substances such as pollen, dust, and larger particles such as soot from wood fires or diesel fuel ignition.

The *greenhouse gases* are water vapor, carbon dioxide, methane, nitrous oxide, and a host of engineered chemicals, such as chlorofluorocarbons. These gases regulate the Earth's temperature and, when the natural balance of the atmosphere is disturbed particularly by an increase or decrease in the greenhouse gases, the Earth's climate could be affected.

The Earth's surface temperature is maintained at a habitable level through the action of certain atmospheric gases known as *greenhouse gases* that help trap the Sun's heat close to the Earth's surface. Most greenhouse gases occur naturally, but concentrations of carbon dioxide and other greenhouse gases in the Earth's atmosphere have been increasing since the Industrial Revolution with the increased combustion of fossil fuels and increased agricultural operations. Of late there has been concern that if this increase continues unabated, the ultimate result could be that more heat would be trapped, adversely affecting Earth's climate.

The major constituent of natural gas, methane, also directly contributes to the greenhouse effect. Its ability to trap heat in the atmosphere is estimated to be 21 times greater than that of carbon dioxide, so although methane emissions amount to only 0.5% of US emissions of carbon dioxide, they account for about 10% of the greenhouse effect of US emissions.

Water vapor is the most common greenhouse gas, at about 1% of the atmosphere by weight, followed by carbon dioxide at 0.04% and then methane, nitrous oxide, and man-made compounds such as the CFCs. Each gas has a different residence time in the atmosphere, from about a decade for carbon dioxide to 120 years for nitrous oxide and up to 50,000 years for some of the chlorofluorocarbons. Water vapor is omnipresent and continually cycles into and out of the atmosphere. In estimating the effect of these greenhouse gases on climate, both the global warming potential (heat-trapping effectiveness relative to carbon dioxide) and the quantity of gas must be considered for each of the greenhouse gases.

10.3.2.1 Emissions during exploration, production, and delivery

When exploration activities for natural gas reservoirs are on land, the activities may disturb vegetation and soil with the vehicles. Drilling a natural gas well on land may require clearing and leveling an area around the well site. Well drilling activities produce air pollution and may disturb people, wildlife, and water resources. Natural gas production can also produce large volumes of contaminated water which requires controlled handling, storage, and treatment so that there is no pollution of the land and other waters.

At sites where natural gas is produced at crude oil wells but is not economical to transport for sale or contains high concentrations of hydrogen sulfide (a toxic gas), it is burned (flared) at well sites. Natural gas flaring will give rise to products carbon dioxide, sulfur dioxide, nitrogen oxides, and many other compounds, depending on the chemical composition of the natural gas and on how well the natural gas burns in the flare. However, flaring is safer than releasing natural gas into the air and results in lower overall greenhouse gas emissions because carbon dioxide is not as strong a greenhouse gas as methane.

The extraction and production of natural gas, as well as other natural gas operations, do have environmental consequences and are subject to numerous laws and regulations. In some areas, development is completely prohibited so as to protect natural habitats, wetlands, and designated wilderness areas. Natural gas production is an industrial activity with the potential for environmental consequences most of which can be identified by application of a variety of standard test methods (Speight, 2014, 2018). Effects can range from water contamination related to drilling and disposal of drilling fluids, air quality degradation from internal combustion engines on drill rigs and trucks, excess dust from equipment transportation, impacts to solitude and night skies from noise and lighting, and safety concerns associated with the large number of vehicles needed to support drilling operations. While the horizontal drilling and hydraulic fracturing practices (Speight, 2016) expected to be used in developing a natural gas resource may have the potential to exert negative environmental effects on the surrounding area, when compared to development of conventional oil and gas resources this development method could result in fewer impacts than conventional vertical wells due to greater flexibility in the location of the well(s).

Hydraulic fracturing (commonly referred to as *fracking*, *fracing*, or *hydrofracking*) of shale, sandstone, and carbonate rock formations is used for production personnel and equipment to gain access to large reserves of natural gas that were previously too expensive to develop significantly reduce the land area that is disturbed to develop natural gas resources (Speight, 2016).

Determining which fracking technique is appropriate for well productivity depends largely on the properties of the reservoir rock from which to extract oil or gas. If the rock is characterized by low permeability, the technique involves drilling a borehole vertically until it reaches a lateral shale rock formation, at which point the drill turns to follow the rock for hundreds or thousands of feet in a horizontal direction (Speight, 2016). In contrast, conventional oil and gas sources are characterized by higher rock permeability, which naturally enables the flow of oil or gas into the wellbore with less intensive hydraulic fracturing techniques than the production of tight gas has required.

The procedure involves pumping liquids under high pressure into a well to fracture the rock, which allows natural gas to escape from the rock. Producing natural gas with this technique has some effects on the environment but, if approached correctly using a multidisciplinary team, the effects on the environment can be minimized. The associated horizontal and directional drilling techniques make it possible to produce more natural gas from a single well than in the past, so fewer wells are necessary to develop a natural gas field. It is necessary however, to advise caution when using hydraulic fracturing.

For example, poor well design construction and maintenance practices—that may be caused by the absence of the presence of a multidisciplinary team—can (or will) increase the chance of a well leak or blowout, so it is extremely important that every aspect of the life cycle of a well—from drilling to completion to well abandonment plugging—is properly executed to reduce any threat to the environment. In addition, the techniques require large amounts of water (and sand or other proppant that keeps the fractures open) which, in some areas of the United States, may affect aquatic habitats and the availability of water for other uses. Also, the hydraulic fracturing fluid, which may contain potentially hazardous chemicals that could be released through spills, leaks, faulty well construction, or other exposure pathways leads to contamination of the surrounding area. The large amounts of wastewater produced at the surface by hydraulic fracturing produces may contain dissolved chemicals and other contaminants that require treatment before disposal or reuse. Because of the quantities of water produced and the complexities inherent in treating some of the wastewater components, the correct treatment and disposal of the wastewater are important.

Any person involved in any aspect of natural exploration, production., processing, and use can (and should) play an important role in the environmental aspects of natural gas production are an important part defining the characteristics of natural gas insofar as it: (1) exist in a gaseous state at room temperature, (2) contains predominantly hydrocarbon compounds with one to four carbon atoms, which are the dominant hazard in the substance, and (3) that after additional fractionation, are sold on the open market in the United States as fungible products. The physical and chemical characteristics require that they be identified through the application of standard test methods that provide reliable data.

The environmental side effects of natural gas production start in what is called the upstream portion of the natural gas industry, beginning with selection of a geologically promising area for possible future natural gas production. An upstream firm will collect all available existing information on the geology and natural gas potential of the proposed area and may decide to conduct new geologic and geophysical studies.

Following analysis of the geologic and geophysical data, permission to drill and produce natural gas from owners of the land and relevant government permitting authorities is necessary. In making leasing and permitting decisions, the potential environmental impacts of future development are often considered. Such considerations include the projected numbers and extent of wells and related facilities, such as pipelines, compressor stations, water disposal facilities, as well as roads and power lines. For example, laying pipelines that transport natural gas from wells usually requires clearing land to bury the pipe. Natural gas wells and pipelines often have engines to run equipment and compressors, which produce air pollutants and noise.

Drilling a gas well involves preparing the well site by constructing a road to it if necessary, clearing the site, and flooring it with wood or gravel. The soil under the road and the site may be so compacted by the heavy equipment used in drilling as to require compaction relief for subsequent farming. In wetland areas, drilling is often accomplished using a barge-mounted rig that is floated to the site after a temporary slot is cut through the levee bordering the nearest navigable stream. However, the primary environmental concern directly associated with drilling is not the surface site but the disposal of drilling waste (spent drilling mud and rock cuttings, etc.).

Drilling of a typical gas well (6000 ft deep) results in the production of about 150,000 pounds of rock cuttings and at least 470 barrels of spent mud. Early industry practice was to dump spent drilling fluid and rock cuttings into pits dug alongside the well and just plow them over after drilling was completed or dump the cuttings directly into the ocean, if the operations are offshore. Currently, the operator must not discharge drilling fluids and solids without permission and it has to be determined whether such waste can be discharged or shipped to a special disposal facility.

Significant volumes of natural gas can also be produced from tight (low permeability) sandstone reservoirs (often referred to arbitrarily as *tight gas*) or shale reservoirs (often referred to as *shale gas*) and coal seams, all of which are unconventional reservoir rocks (Chapter 1: History and use and Chapter 3: Unconventional gas). Through the application of analytical programs (Speight, 2018), a better understanding of the underlying physics of natural gas production from these rocks and the relationship between well completion practices and productivity will be achieved (Speight, 2018). Using the various analytical methods, it will be possible to find ways to maximize recovery of natural gas from these rock formations which, in the mid-to-late 20th century, were considered to be unproductive. Emphasis (when resources of shale gas are to be developed) is typically (and rightly so) often placed on water management during resource development, including the enhancement of water treatment technologies. Resource development based on nothing more than emotional issues rather than on reliable analytical data is to be treated with extreme caution.

Exploration, development, and production activities emit small volumes of air pollutants, mostly from the engines used to power drilling rigs and various support and construction vehicles. As the number of wells increases, such as in the Gulf of Mexico, so do the emissions for exploratory drilling and development drilling, while emissions from supporting activities rise less directly. Offshore development entails some activities not found elsewhere (i.e., platform construction and marine support vessels), but the environmental effects from onshore activities, which include drilling pad and access road construction, especially for development drilling, are many times larger because of the much higher level of activity.

This practice is by no means as common as it was four decades ago and the minor venting and flaring that does occur now is regulated and may happen at several locations: the well gas separator, the lease tank battery gas separator, or a downstream natural gas plant. Whatever the reason for its use, flaring is wasteful economically and harmful environmentally. In many cases, efforts are made (or, should be made) to capture that natural gas, rather than burning it off.

All systems of pipes that transmit any fluid are subject to leaks and, in the case of natural gas, any leak will escape to the atmosphere. Thus throughout the entire process of producing, refining, and distributing natural gas there are losses or fugitive emissions. Production operations account for about 30% of the fugitive emissions, while transmission, storage, and distribution accounts for about 53% of the fugitive emissions.

At onshore and coastal sites, drilling wastes usually cannot be discharged to surface waters and are primarily disposed of by operators on their lease sites. If the drilling fluids are saltwater- or oil-based, they can cause damage to soils and groundwater and on-site disposal is often not permitted, so operators must dispose of such wastes at an off-site disposal facility. The disposal methods used by commercial disposal companies include underground injection, burial in pits or landfills, land spreading, evaporation, incineration, and reuse/recycling. In areas with subsurface salt formations, disposal in man-made salt caverns is an emerging, cost-competitive option. Such disposal poses very low risks to plant and animal life because the formations where the caverns are constructed are very stable and are located beneath any subsurface freshwater supplies. Water-based drilling wastes, if they can be shown to have minimal impact on aquatic life, offshore operators are allowed to discharge such waste into the sea. However, discharging oil-based drilling wastes into the sea is often prohibited and these are generally transported to shore for disposal.

If the drilling fluids are saltwater- or oil-based, they can cause damage to soils and groundwater and on-site disposal is often not permitted, so operators must dispose of such wastes at an off-site disposal facility. The disposal methods include underground injection, burial in pits or landfills, land spreading, evaporation, incineration, and reuse/recycling. In areas with subsurface salt formations, disposal in man-made salt caverns may be permitted; this form of disposal poses very low risks to plant and animal life because the formations where the caverns are constructed are very stable and are located beneath any subsurface freshwater supplies.

The disposal of produced water is often a significant problem for the drilling and production industry. The disposal process varies depending on whether the well is onshore or coproduction of a variable amount of water with the gas is offshore, the local requirements, and the composition of the unavoidable at most locations. Because the water is usually produced fluids, most onshore-produced water is disposed salty, its raw disposal or unintentional spillage on land of by pumping it back into the subsurface through on-site normally interferes with plant growth. In fact, injection water represents the largest volume waste stream generated and its disposal is not practical or economically viable and the produced water is piped or transported to an off-site treatment facility.

In recent years, new drilling technologies such as slim-hole drilling, horizontal drilling, multilateral drilling, coiled tubing drilling, and improved drill bits, have helped to reduce the generated quantity of drilling wastes. Another advanced drilling technology that provides pollution-prevention benefits is the use of synthetic drilling fluids that have a less severe environmental impact and their use results in a much cleaner well bore and less sidewall collapse.

In terms of transportation, there is also the potential for the occurrence of environmental contamination by natural gas.

Natural gas is distributed mainly via pipeline—in the United States more than one million miles of underground pipelines are connected between natural gas fields and major cities. Natural gas can be liquefied by cooling it to $-260°F$ (or, $-162°C$). The liquefied natural gas (LNG) has much more condensed volume which is 615 times lesser in volume compared to the room temperature natural gas and LNG has the fluidity and volume compactness just as other liquid fuels. Therefore LNG is much easier to store or transport and LNG in special tanks can be transported by trucks or ships. In this regard, LNG has some needed characteristics that it can be used as a transportation fuel.

At any point of this transportation train, it must be recognized that there is the potential for leakage and spillage of the gas.

10.3.2.2 Emissions during processing

Gas processing usually poses low environmental risk, primarily because natural gas has a simple and comparatively pure composition. Typical processes performed by a gas plant are separation of the heavier than methane hydrocarbons as liquefied petroleum gases, stabilization of condensate by removal of lighter hydrocarbons from the condensate stream, gas sweetening, and consequent sulfur production and dehydration sufficient to avoid formation of methane hydrates in the downstream pipeline.

Air pollutant emission points at natural gas processing facilities are the glycol dehydration unit reboiler vent, storage tanks and equipment leaks from components handling hydrocarbon streams that contain hazardous air pollutants (HAPs).

Thus potential environmental aspects associated with natural gas processing include the following: (1) air emissions, (2) wastewater, (3) hazardous materials, (4) wastes, and (5) noise. In terms of air emissions, fugitive emissions in natural gas processing facilities are associated with leaks in tubing; valves; connections; flanges; packings; open-ended lines; floating roof storage tank, pump, and compressor seals; gas conveyance systems, pressure relief valves, tanks or open pits/containments, and loading and unloading operations of hydrocarbons.

The identified HAP emission points at natural gas processing plants are the glycol dehydration unit reboiler vent, storage tanks and equipment leaks from components handling hydrocarbon streams that contain HAPs. Other potential HAP emission points are the tail gas streams from amine-treating processes and sulfur recovery units.

Methods vary for removing natural gas contaminants, such as hydrogen sulfide gas, carbon dioxide gas, nitrogen, and water (Chapter 6: History of gas processing and Chapter 7: Process classification). Commonly the hydrogen sulfide is converted to solid sulfur for sale (Chapter 6: History of gas processing and Chapter 7: Process classification). Likewise, the carbons and nitrogen are separated for sale to the extent economically possible but otherwise the gases are vented, while the water is treated before release. Compressor operation at gas plants has a similar impact to that of compressors installed at other locations.

It is sometimes necessary either to vent produced gas into the atmosphere or to flare (burn) it. Worldwide, most venting and flaring occurs when the cost of transporting and marketing gas coproduced from crude oil reservoirs exceeds the netback price received for the gas.

Emissions will result from gas sweetening plants only if the acid waste gas from the amine process is flared or incinerated. Most often, the acid waste gas is used as a feedstock in nearby sulfur recovery or sulfuric acid plants.

When flaring or incineration is practiced, the major pollutant of concern is sulfur dioxide. Most plants employ elevated smokeless flares or tail gas incinerators for complete combustion of all waste gas constituents, including virtually 100% conversion of hydrogen sulfide to sulfur dioxide. Little particulate, smoke, or hydrocarbons result from these devices, and because gas temperatures do not usually exceed 650°C (1200°F), significant quantities of nitrogen oxides are not formed. Some plants still use older, less-efficient waste gas flares. Because these flares usually burn at temperatures lower than necessary for complete combustion, larger emissions of hydrocarbons and particulate, as well as hydrogen sulfide, can occur.

This practice of venting is now by no means as common as it was a few decades ago when oil was the primary valuable product and there was no market for much of the coproduced natural gas. The venting and flaring that does occur now is regulated and may happen at several locations: the well gas separator, the lease tank battery gas separator, or a downstream natural gas plant.

10.3.2.3 Emissions during combustion

In theory, and often but not always in practice, natural gas burns more cleanly than other fossil fuels. It has fewer emissions of sulfur, carbon, and nitrogen than coal or oil, and it has almost no ash particles left after burning. Being a clean fuel is one reason that the use of natural gas, especially for electricity generation, has grown so much and is expected to grow even more in the future.

On a relative basis, natural gas is the cleanest of all the fossil fuels. Composed primarily of methane, the main products of the combustion of natural gas are carbon dioxide and water vapor, the same compounds we exhale when we breathe. Coal and petroleum are composed of much more complex molecules, with a higher carbon ratio and higher nitrogen and sulfur contents. Thus when combusted, coal and oil release higher levels of harmful emissions, including a higher ratio of carbon emissions, NO_x, and sulfur dioxide (SO_2). Coal and fuel oil also release ash particles into the environment, substances that do not burn but instead are carried into the atmosphere and contribute to pollution. The combustion of natural gas, on the other hand, releases very small amounts of sulfur dioxide and nitrogen oxides, virtually no ash or particulate matter, and lower levels of carbon dioxide, carbon monoxide, and other reactive hydrocarbons.

Natural gas is less chemically complex than other fuels, has fewer impurities, and its combustion accordingly results in less pollution. In the simplest case, complete combustive reaction of a molecule of pure methane (CH_4) with two molecules of pure oxygen produces a molecule of carbon dioxide gas, two molecules of water in vapor form, and heat.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Heat}$$

In practice, the combustion process is not always perfect and when the air supply is inadequate, carbon monoxide and particulate matter (soot) are also produced. In fact, since natural gas is never pure methane and small amounts of additional impurities are present, pollutants are also generated during combustion. Thus the combustion of natural gas also produces undesirable compounds but in significantly lower quantities compared to the combustion of coal, petroleum, and petroleum products.

The particulates produced by natural gas combustion are usually less than 1 μm (micrometer) in diameter and are composed of low-molecular weight hydrocarbons that are not fully combusted.

Pollutant emissions from the industrial sector and electric utilities contribute greatly to environmental problems in the United States. The use of natural gas to power both industrial boilers and processes and the generation of electricity can significantly improve the emissions profiles for these two sectors.

Natural gas is becoming an increasingly important fuel in the generation of electricity. As well as providing an efficient, competitively priced fuel for the generation of electricity, the increased use of natural gas allows for the improvement in the emissions profile of the electric generation industry. Power plants in the United States account for 67% of sulfur dioxide emissions, 40% of carbon dioxide emissions, 25% of nitrogen oxide emissions, and 34% of mercury emissions (National Environmental Trust, 2002, "Cleaning up Air Pollution from America's Power Plants"). Coal-fired power plants are the greatest contributors to these types of emissions. In fact, only 3% of sulfur dioxide emissions, 5% of carbon dioxide emissions, 2% of nitrogen oxide emissions, and 1% of mercury emissions come from noncoal-fired power plants.

Essentially, electric generation and industrial applications that require energy, particularly for heating, use the combustion of fossil fuels for that energy. Because of its clean burning nature, the use of natural gas wherever possible, either in conjunction with other fossil fuels, or instead of them, can help to reduce the emission of harmful pollutants.

10.4 Smog and acid rain

Acid rain occurs when the oxides of nitrogen and sulfur that are released to the atmosphere during the combustion of fossil fuels are deposited (as soluble acids) with rainfall, usually at some location remote from the source of the emissions. It is generally believed (the chemical thermodynamics is favorable) that acidic compounds are formed when sulfur dioxide and nitrogen oxide emissions are released from tall industrial stacks. Gases such as sulfur oxides (usually sulfur dioxide, SO_2) as well as the NO_x react with the water in the atmosphere to form acids:

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$2SO_2 + O_2 \rightarrow 2SO_3$$

$$SO_3 + H_2O \rightarrow H_2SO_4$$

$$2NO + H_2O \rightarrow 2HNO_2$$

$$2NO + O_2 \rightarrow 2NO_2$$

$$NO_2 + H_2O \rightarrow HNO_3$$

Acid rain has a pH less than 5.0 and predominantly consists of sulfuric acid (H_2SO_4) and nitric acid (HNO_3). As a point of reference, in the absence of anthropogenic pollution sources the average pH of rain is −6.0 (slightly acidic; neutral pH = 7.0). In summary, the sulfur dioxide that is produced during a variety of processes will react with oxygen and water in the atmosphere to yield environmentally detrimental sulfuric acid. Similarly, nitrogen oxides will also react to produce nitric acid. Smog and acid rain might be considered to be the end-point of emissions from the use of natural gas.

Particulate emissions also cause the degradation of air quality in the United States. These particulates can include soot, ash, metals, and other airborne particles.

Another acid gas, hydrogen chloride (HCl), although not usually considered to be a major emission, is produced from mineral matter and the brines that often accompany petroleum during production and is gaining increasing recognition as a contributor to acid rain. However, hydrogen chloride may exert severe local effects because it does not need to participate in any further chemical reaction to become an acid. Under atmospheric conditions that favor a buildup of stack emissions in the areas where hydrogen chloride is produced, the amount of hydrochloric acid in rainwater could be quite high.

In addition to hydrogen sulfide and carbon dioxide, natural gas may contain other contaminants, such as mercaptans (R-SH) and carbonyl sulfide (COS). The presence of these impurities may eliminate some of the sweetening processes since some processes remove large amounts of acid gas but not to a sufficiently low concentration. On the other hand, there are those processes that are not designed to remove (or are incapable of removing) large amounts of acid gases. However, these processes are also capable of removing the acid gas impurities to very low levels when the acid gases are there in low to medium concentrations in the gas.

At the global level there is concern that the increased use of any hydrocarbon-based fuels will ultimately raise the temperature of the planet (*global warming*), as carbon dioxide reflects the infrared or thermal emissions from the Earth, preventing them from escaping into space (*greenhouse effect*). If the potential for global warming becomes real will depend upon how emissions into the atmosphere are handled. There is considerable discussion about the merits and demerits of the global warming theory and the discussion is likely to continue for some time. Be that as it may, the atmosphere can only tolerate pollutants up to a limiting value. And that value needs to be determined. In the meantime, efforts must be made to curtail the use of noxious and foreign (nonindigenous) materials into the air.

There are a variety of processes which are designed for sulfur dioxide removal from gas streams (Speight, 2014) but scrubbing process utilizing limestone ($CaCO_3$) or lime [$Ca(OH)_2$] slurries have received more attention than other gas scrubbing processes (Chapter 7: Process classification and Chapter 8: Gas cleaning processes). Most of the gas scrubbing processes are designed to remove sulfur dioxide from the gas streams; some processes show the potential for removal of nitrogen oxide(s).

Natural gas pipelines and storage facilities have a very good safety record. This is very important because when natural gas leaks it can cause explosions. Since raw natural gas has no odor, natural gas companies add a smelly substance to it so that people will know if there is a leak. If you have a natural gas stove, you may have smelled this "rotten egg" smell of natural gas when the pilot light has gone out.

Natural gas has many uses, residentially, commercially, and industrially. Found in reservoirs underneath the Earth, natural gas is commonly associated with oil deposits. Production companies search for evidence of these reservoirs by using sophisticated technology that helps to find the location of the natural gas, and drill wells in the Earth where it is likely to be found.

Once brought from underground, the natural gas is refined to remove impurities like water, other gases, sand, and other compounds. Some hydrocarbons are removed and sold separately, including propane and butane. Other impurities are also removed, like hydrogen sulfide (the refining of which can produce sulfur, which is then also sold separately). After refining, the clean natural gas is transmitted through a network of pipelines, thousands of miles of which exist in the United States alone.

Global warming or *the greenhouse effect* is an environmental issue that deals with the potential for global climate change due to increased levels of atmospheric "greenhouse gases." There are certain gases in our atmosphere that serve to regulate the amount of heat that is kept close to the Earth's surface. Scientists theorize that an increase in these greenhouse gases will translate into increased temperatures around the globe, which would result in many disastrous environmental effects. In fact, the Intergovernmental Panel on Climate Change (IPCC) predicts in its "Third Assessment Report" released in February 2001 that over the next 100 years, global average temperatures will rise by between 2.4°F and 10.4°F.

The principle greenhouse gases include water vapor, carbon dioxide, methane, nitrogen oxides, and some engineered chemicals such as chlorofluorocarbons. While most of these gases occur in the atmosphere naturally, levels have been increasing due to the widespread burning of fossil fuels by growing human populations. The reduction of greenhouse gas emissions has become a primary focus of environmental programs in countries around the world.

One of the principle greenhouse gases is carbon dioxide. Although carbon dioxide does not trap heat as effectively as other greenhouse gases (making it a less potent greenhouse gas), the sheer volume of carbon dioxide emissions into the atmosphere is very high, particularly from the burning of fossil fuels. In fact, according to the EIA in its report "Emissions of Greenhouse Gases in the United States 2000," 81.2% of greenhouse gas emissions in the United States in 2000 came from carbon dioxide directly attributable to the combustion of fossil fuels.

Because carbon dioxide makes up such a high proportion of US greenhouse gas emissions, reducing carbon dioxide emissions can play a huge role in combating the greenhouse effect and global warming. The combustion of natural gas emits almost 30% less carbon dioxide than oil, and just under 45% less carbon dioxide than coal.

One issue that has arisen with respect to natural gas and the greenhouse effect is the fact that methane, the principle component of natural gas, is itself a very potent greenhouse gas. In fact, methane has an ability to trap heat almost 21 times more effectively than carbon dioxide.

According to the Energy Information Administration, although methane emissions account for only 1.1% of total US greenhouse gas emissions, they account for 8.5% of the greenhouse gas emissions based on global warming potential. Sources of methane emissions in the United States include the waste management and operations industry, the agricultural industry, as well as leaks and emissions from the oil and gas industry itself. A major study performed by the Environmental Protection Agency (EPA) and the Gas Research Institute (GRI) in 1997 sought to discover whether the reduction in carbon dioxide emissions from increased natural gas use would be offset by a possible increased level of methane emissions. The study concluded that the reduction in emissions from increased natural gas use strongly outweighs the detrimental effects of increased methane emissions. Thus the increased use of natural gas in the place of other, dirtier fossil fuels can serve to lessen the emission of greenhouse gases in the United States.

Smog and poor air quality is a pressing environmental problem, particularly for large metropolitan cities. Smog, the primary constituent of which is ground level ozone, is formed by a chemical reaction of carbon monoxide, nitrogen oxides, VOCs, and heat from sunlight. As well as creating that familiar smoggy haze commonly found surrounding large cities, particularly in the summertime, smog, and ground level ozone can contribute to respiratory problems ranging from temporary discomfort to long-lasting, permanent lung damage. Pollutants contributing to smog come from a variety of sources, including vehicle emissions, smokestack emissions, paints, and solvents. Because the reaction to create smog requires heat, smog problems are the worst in the summertime.

The use of natural gas does not contribute significantly to smog formation, as it emits low levels of nitrogen oxides, and virtually no particulate matter. For this reason, it can be used to help combat smog formation in those areas where ground level air quality is poor. The main sources of nitrogen oxides are electric utilities, motor vehicles, and industrial plants. Increased natural gas use in the electric generation sector, a shift to cleaner natural gas vehicles, or increased industrial natural gas use, could all serve to combat smog production, especially in urban centers where it is needed the most. Particularly in the summertime, when natural gas demand is lowest and smog problems are the greatest, industrial plants and electric generators could use natural gas to fuel their operations instead of other, more polluting fossil fuels. This would effectively reduce the emissions of smog causing chemicals, and result in clearer, healthier air around urban centers. For instance, a 1995 study by the Coalition for Gas-Based Environmental Solutions found that in the Northeast, smog and ozone-causing emissions could be reduced by 50%−70% through the seasonal switching to natural gas by electric generators and industrial installations.

Particulate emissions also cause the degradation of air quality in the United States. These particulates can include soot, ash, metals, and other airborne particles. A study (Union of Concerned Scientists, 1998, "Cars and Trucks and Air Pollution") showed that the risk of premature death for residents in areas with high airborne particulate matter was 26% greater than for those in areas with low particulate levels. Natural gas emits virtually no particulates into the atmosphere, in fact, emissions of particulates from natural gas combustion are 90% lower than from the combustion of oil, and 99% lower than burning coal.

Acid rain is another environmental problem that affects much of the Eastern United States, damaging crops, forests, wildlife populations, and causing respiratory and other illnesses in humans. Acid rain is formed when sulfur dioxide and nitrogen oxides react with water vapor and other chemicals in the presence of sunlight to form various acidic compounds in the air. The principle source of acid rain causing pollutants, sulfur dioxide and nitrogen oxides, are coal-fired power plants. Since natural gas emits virtually no sulfur dioxide, and up to 80% less nitrogen oxides than the combustion of coal, increased use of natural gas could provide for fewer acid rain causing emissions.

10.5 Natural gas regulations

No matter what one can hear from various pundits, it is advantageous to accept that natural gas is dangerous—when mixed with air, it can form an explosive mixture at specific low concentrations, between a lower explosion limit and an upper explosion limit. However, it can burn as a flame at the point of leakage. In an open, land installation the gas normally disperses quickly. However, in a closed system, simple explosions and boiling liquid, expanding vapor explosions can (will) cause serious damage. The latter is caused if a flame impinges on a vessel containing liquefied gas. Adequate ventilation is required by all safety codes for all enclosed spaces. It is possible to prevent a catastrophe by a chain of preventive measures. Insofar as the condition of the environment is important to floral and faunal life on Earth, any serious disadvantageous disturbance of the environment (pollution) can have serious consequences for continuation of this life.

Furthermore, all carbon-based fuels produce carbon dioxide and water when they are burned. Because of the higher atomic ratio of hydrogen to carbon atom, natural gas produces less carbon dioxide per unit of energy than higher molecular weight hydrocarbon derivatives (such as crude oil constituents) or coal. Also, natural gas impurities can be selectively and relatively easily removed and be completely converted by combustion, resulting in lower emissions of particulate matter. However, any releases of methane and ethane to the atmosphere should be minimized.

The gas industry has been highly regulated for many years mainly as it was regarded as a natural monopoly. In the last 30 years there has been a move away from price regulation and toward liberalization of natural gas markets. These movements have resulted in greater competition in the market and in a dynamic and innovative natural gas industry. Therefore a brief history of the regulation of the natural gas industry is necessary in this introductory chapter.

The regulation and deregulation of the natural gas industry is a 20th century phenomenon in the United States. Since regulation and deregulation are related to use of the commodity, it is appropriate that a brief review of the regulation and deregulation of the natural gas industry be presented in this chapter.

10.5.1 Historical aspects

The regulation of natural gas in the United States dates back to the beginnings of the industry. In the early days of the industry (mid-1800s), natural gas was in limited supply and fuel gas (methane) was manufactured from coal, to be delivered locally, generally within the same municipality in which it was produced. Local governments, seeing the natural monopoly characteristics of the natural gas market at the time, deemed natural gas distribution a business that affected the public interest to a sufficient extent to merit regulation. Because of the distribution network that was needed to deliver natural gas to customers, it was decided that one company with a single distribution network could deliver natural gas more cheaply than two companies with overlying distribution networks and markets. However, economic theory does not predict but *dictates* that a company in a monopoly position, with total control over its market and the absence of any competition will typically take advantage of its position and has incentives to charge overly high prices. The solution, from the point of view of the local governments, was to regulate the rates these natural monopolies charged, and set down regulations that prevented them from abusing their market power.

As the natural gas industry developed, so did the complexity of maintaining regulation. In the early 1900s, natural gas began to be shipped between municipalities. Thus natural gas markets were no longer segmented by municipal boundaries. The first intrastate pipelines began carrying gas from city to city. This new mobility of natural gas meant that local governments could no longer oversee the entire natural gas distribution chain. There was, in essence, a regulatory gap between municipalities. In response to this, state-level governments intervened to regulate the new *intrastate* natural gas market and determine rates that could be charged by gas distributors. This was done by creating public utility commissions and public service commissions to oversee the regulation of natural gas distribution. The first states to do so were New York and Wisconsin, which instituted commissions as early as 1907.

With the advent of technology that allowed the long-distance transportation of natural gas via interstate pipelines, new regulatory issues arose. In the same sense that municipal governments were unable to regulate natural gas distribution that extended beyond their areas of jurisdiction, the state governments were unable to regulate interstate natural gas pipelines.

Between 1911 and 1928, several states attempted to assert regulatory oversight of these interstate pipelines. However, in a series of decisions, the Supreme Court of the United States ruled that such state oversight of interstate pipelines violated interstate commerce because interstate pipeline companies were beyond the regulatory power of state-level government. Without any federal legislation dealing with interstate pipelines, these decisions essentially left interstate pipelines completely unregulated, the second regulatory gap. However, due to concern regarding the monopoly power of interstate pipelines, as well as conglomeration of the industry, the federal government saw fit to step in to fill the regulatory gap created by interstate pipelines.

In 1935, the US Federal Trade Commission stated some concern over the market power that may be exerted by merged electric and gas utilities. By this time, over a quarter of the interstate natural gas pipeline network was owned by only 11 holding companies; companies that also controlled a significant portion of gas production, distribution, and electricity generation. In response to this report, in 1935 Congress passed the Public Utility Holding Company Act to limit the ability of holding companies to gain undue influence over a public utility market. However, the law did not cover the regulation of interstate gas sales.

In the United States, the regulation of natural gas production has traditionally occurred primarily at the state level with most states that produce natural gas and crude oil issuing more rigorous standards that take primacy over federal regulations, as well as additional regulations that control areas not covered at the federal level, such as hydraulic fracturing. Within states, regulation is carried out by a range of agencies.

The specific regulations vary considerably among states, such as different depths for well casing, levels of disclosure on drilling and fracturing fluids, or requirements for water storage. Currently, many states that produce natural gas and crude oil have varying hydraulic fracturing regulations, specifically regulations related to (1) the disclosure of the components of hydraulic fracturing fluids, (2) the proper casing of wells to prevent aquifer contamination, and (3) management of wastewater from flow-back and produced water. The disposal of wastewater by underground injection has emerged as a concern for state regulators due to large interstate flows of wastewater to states with suitable geology for the water disposal as well as the potential for seismic activity near some well sites.

Techniques for treating industrial process wastewater in this sector include source segregation and pretreatment of concentrated wastewater streams. Typical wastewater treatment steps include: grease traps, skimmers, dissolved air floatation, or oil/water separators for separation of oils and floatable solids; filtration for separation of filterable solids; flow and load equalization; sedimentation for suspended solids reduction using clarifiers; biological treatment, typically aerobic treatment, for reduction of soluble organic matter biological oxygen demand (BOD); chemical or biological nutrient removal for reduction in nitrogen and phosphorus; chlorination of effluent when disinfection is required; and dewatering and disposal of residuals in designated hazardous waste landfills. Additional engineering controls may be required for (1) containment and treatment of volatile organics stripped from various unit operations in the wastewater treatment system, (2) advanced metals removal using membrane filtration or other physical/chemical treatment technologies, (3) removal of recalcitrant organics, cyanide, and nonbiodegradable chemical oxygen demand (COD) using activated carbon or advanced chemical oxidation, (4) reduction in effluent toxicity using appropriate technology (such as reverse osmosis, ion exchange, and activated carbon), and (5) containment and neutralization of nuisance odors.

Natural gas processing facilities use and manufacture significant amounts of hazardous materials, including raw materials, intermediate/final products, and byproducts. The handling, storage, and transportation of these materials should to be managed properly to avoid or minimize the environmental impacts from these hazardous materials.

Nonhazardous industrial wastes consist mainly of exhausted molecular sieves from the air separation unit as well as domestic wastes. Other nonhazardous wastes may include office and packaging wastes, construction rubble, and scrap metal.

Hazardous waste should be determined according to the characteristics and source of the waste materials and applicable regulatory classification. In GTL facilities, hazardous wastes may include biosludge; spent catalysts; spent oil, solvents, and filters (e.g., activated carbon filters and oily sludge from oil water separators); used containers and oily rags; mineral spirits; used sweetening; spent amines for CO_2 removal; and laboratory wastes.

Spent catalysts from GTL production are generated from scheduled replacements in natural gas desulfurization reactors, reforming reactors and furnaces, F-T synthesis reactors, and reactors for mild hydrocracking. Spent catalysts may contain zinc, nickel, iron, cobalt, platinum, palladium, and copper, depending on the particular process.

The principal sources of noise in natural gas processing facilities include large rotating machines (e.g., compressors, turbines, pumps, electric motors, air coolers, and fired heaters). During emergency depressurization, high noise levels can be generated due to release of high-pressure gases to flare and/or steam release into the atmosphere.

In terms of the development of unconventional natural gas and crude oil resources, a major environmental concern is the potential contamination of water courses. Apart from water, which makes up 99.5% v/v of the hydraulic fracturing fluid, the fluid also contains chemical additives to improve the process performance. The additives are varied and can include acid, friction reducer, surfactant, gelling agent, and scale inhibitor (Speight, 2016). The composition of the fracturing fluid is tailored to differing geological features and reservoir characteristics to address challenges, including scale build-up, bacterial growth, and proppant transport. Unfortunately, in the past many of the chemical compounds used in the hydraulic fracturing process lacked scientifically based maximum contaminant levels, making it more difficult to quantify their risk to the environment. Moreover, uncertainty about the chemical make-up of fracturing fluids persists because of the limitations on required chemical disclosure (Centner, 2013; Centner and O'Connell, 2014; Maule et al., 2013).

The measures required by state and federal regulatory agencies in the exploration and production of natural gas from deep tight formations have been very effective, e.g., in protecting drinking water aquifers from contamination. In fact, a series of federal laws govern most environmental aspects of natural gas development (Table 10.1). However, federal regulation may not always be the most effective way of assuring the desired level of environmental protection. Therefore most of these federal laws have provisions for granting primacy to the state governments, which have usually developed their own sets of regulations. By statute, the different states may adopt these standards of their own, but they must be at least as protective as the federal principles they replace and, as a result, may be more protective to address local conditions.

Table 10.1 Examples of Federal Laws (*listed alphabetically*) in the United States to monitor hydraulic fracturing projects

Act	Purpose
Clean Air Act	Limits air emissions from engines, gas processing equipment, and other sources associated with drilling and production
Clean Water Act	Regulation of surface discharges of water associated with natural gas and crude oil drilling and production, as well as storm water runoff from production sites
Energy Policy Act	Exempted hydraulic fracturing companies from some regulations; may disclose chemicals through a report submitted to the regulatory authority but in some instances, chemical information may be exempt from disclosure to the public as trade secrets
NEPA	Requires that exploration and production on federal lands be thoroughly analyzed for environmental impacts
NPDES	Requires tracking of any toxic chemicals used in fracturing fluids
Oil Pollution Act	Regulation of ground pollution risks relating to spills of materials or hydrocarbon derivatives into the water table; also regulated under the Hazardous Materials Transport Act
Safe Drinking Water Act	Directs the underground injection of fluids from natural gas and crude oil activities; disclosure of chemical content for underground injections; after 2005, see Energy Policy Act
TSCA	Suggestion that this act be used to regulate the reporting of hydraulic fracturing fluid information

NEPA, National Environmental Policy Act; *NPDES*, National Pollutant Discharge Elimination System; *TSCA*, Toxic Substance Control Act.
NB: The Fracturing Responsibility and Awareness of Chemicals Act (the FRAC Act) was an attempt to define hydraulic fracturing as a federally regulated activity under the Safe Drinking Water Act; no significant moves or passage of this act at the time of writing (https://www.congress.gov/bill/114th-congress/senate-bill/785/text).

State regulation of the environmental practices related to natural gas and crude oil development can more easily address the regional and state-specific character of the activities, compared to a one-size-fits-all management by the federal level. Some of these factors include: geology, hydrology, climate, topography, industry characteristics, development history, state legal structures, population density, and local economics and, thus, the regulation of natural gas and crude oil production is a detailed monitoring of each stage of the development through the many controls at the state level. Each state has the necessary powers to regulate, permit, and enforce all activities—from drilling and fracturing of the well, to production operations, to managing and disposing of wastes, to abandoning and plugging the production well(s). These state powers are a means of assuring that natural gas and crude oil operations do not have an adverse impact on the environment.

Moreover, because of the regulatory make-up of each state—which can vary from state-to-state—different states take different approaches to the regulation and enforcement of resource development, but the laws of each state generally give the state agency responsible for natural gas and crude oil development the discretion to require whatever is necessary to protect the environment, including human health.

In addition, most have a general prohibition against pollution from natural gas and crude oil production. Most of the state requirements are written into rules or regulations but some of the regulations may be added to permits on a case-by-case basis because of (1) environmental review, (2) on-site inspections, (3) commission hearings, and (4) public comments.

Finally, the organization of regulatory agencies within the different states where natural gas and crude oil is produced varies considerably. Some states have several agencies that oversee different aspects (with some inevitable overlap powers) of natural gas and crude oil operations, particularly the requirements that protect the environment. In different states, the various approaches have developed over time to create a structure that best serves the consumers, nonconsumers, and the various industries. The one constant is that each in each state where natural gas and crude oil is produced, there is one agency that has the responsibility for issuing permits for gas and oil development projects. The permitting agencies work with other agencies in the regulatory process and often serve as a central organizing body and a useful source of information about activities related to natural gas and crude production.

10.5.2 Federal regulations

In 1938, the federal government of the United States became involved directly in the regulation of interstate natural gas with the passage of the Natural Gas Act (NGA) which gave the Federal Power Commission (FPC, created in 1920 with the passage of the Federal Water Power Act) jurisdiction over regulation of interstate natural gas sales. The FPC was charged with regulating the rates that were charged for interstate natural gas delivery, as well as limited certification powers.

The rationale for the passage of the NGA was the concern over the heavy concentration of the natural gas industry, and the monopolistic tendencies of interstate pipelines to charge higher than competitive prices due to their market power. While the NGA required that "just and reasonable" rates for pipeline services be enforced, it did not specify any particular regulation of prices of natural gas at the wellhead. The NGA also specified that no new interstate pipeline could be built to deliver natural gas into a market already served by another pipeline. In 1942, these certification powers were extended to cover any new interstate pipelines. This meant that, in order to build an interstate pipeline, companies must first receive the approval of the FPC.

From 1954 to 1960, the FPC attempted to deal with producers and their rates on an individual basis and each producer was treated as an individual public utility, and rates were set based on each producer's cost of service. However, this turned out to be administratively unfeasible, as there were so many different producers and rate cases that a backlog developed. As a result, in 1960, the FPC decided to set rates based on geographic areas in which rates were set for all wells in a particular region. By 1970, rates had been set for only two of the five producing areas. To make matters worse, for most of the areas, prices were essentially frozen at 1959 levels. The problem with determining rates for a particular area based on cost-of-service methodologies was that there existed many wells in each area, with vastly different production costs.

In the 1970s and 1980s, a number of gas shortages and price irregularities indicated that a regulated market was not best for consumers, or the natural gas industry. Into the 1980s and early 1990s, the industry gradually moved toward deregulation, allowing for healthy competition and market-based prices. These moves led to a strengthening of the natural gas market, lowering prices for consumers and allowing for a great deal more natural gas to be discovered.

Since the Energy Policy Act passed in 2005, natural gas and crude oil production in the United States has grown significantly and this rapid growth—along with continued reports of environmental effects—has led to renewed calls for the federal government to provide increased regulation or guidance. This pressure led to the introduction to Congress in 2009 of the Fracturing Responsibility and Awareness of Chemicals Act (the FRAC Act) to define hydraulic fracturing as a federally regulated activity under the Safe Drinking Water Act (Table 10.1). The proposed requires the energy industry to disclose the chemical additives used in the hydraulic fracturing fluid. The Act went did not receive any action, was reintroduced in 2011, and appears to have been held in limbo since that time.

In the absence of new federal regulations, the various states that produce natural gas and crude oil by hydraulic fracturing have continued to use existing natural gas and crude oil and environmental regulations to manage natural gas and crude oil development, as well as introducing individual state regulations for hydraulic fracturing (Table 10.1). In fact, the current regulations are comprised of an overlapping collection of federal, state, and local regulations and permitting systems and these regulations cover different aspects of the development and production of a natural gas and crude oil with the intention that the regulations combine to manage any potential impact on the surrounding environment, including any effects on water management. However, the hydraulic fracturing process that has not previously been regulated under current laws and, therefore, in terms of water management, emissions management, and site activity, the existing regulations are being (must be) reassessed for suitability for application to the hydraulic fracturing process. In the meantime, many states (including Wyoming, Arkansas, and Texas) have already implemented regulations requiring disclosure of the materials used in hydraulic fracturing fluids and the United States Department of the Interior has indicated an interest in requiring similar disclosure for sites on federal lands.

The Bureau of Land Management's (BLM) of the Department of the Interior has proposed draft rules for natural gas and crude oil production on public lands and these proposals would require disclosure of the chemical components used in hydraulic fracturing fluids. The proposed rule requires that an operations plan should be submit to the relevant authority—prior to initiation of the hydraulic fracturing project—that would allow the Bureau of Land Management to evaluate groundwater protection designs based on (1) a review of the local geology, (2) a review of any anticipated surface disturbance, and (3) a review of the proposed management and disposal of project-related fluids. In addition, the Bureau of Land Management would require submittal of the information necessary to confirm wellbore integrity before, during, and after the stimulation operation. Furthermore, before hydraulic fracturing commenced, the company would have to certify that the fluids comply with all applicable Federal, state, and local laws, rules, and regulations. After the conclusion of the hydraulic fracturing stage of the project, a follow-up report would be required in which the actual events that occurred during fracturing activities would be summarized and this report would have to include the specific chemical make-up of the hydraulic fracturing fluid.

On April 17, 2012, the United States EPA released new performance standards and national emissions standards for HAPs in the natural gas and crude oil industries. These rules include the first federal air standards for hydraulically fractured gas wells, along with requirements for other sources of pollution in the natural gas and crude oil industry that currently are not regulated at the federal level. These standards require either flaring or *green completion* on natural gas wells developed prior to January 1, 2015, with only green completions allowed for wells developed on and after that date.

Briefly, *green completion* requires natural gas companies capture the gas at the wellhead immediately after well completion instead of releasing it into the atmosphere or flaring the gas. Thus the green completion systems are systems to reduce methane losses during well completion. After a new well completion or workover, the well bore and formation must be cleaned of debris and fracturing fluid. Conventional methods for doing this include producing the well into an open pit or tank to collect sand, cuttings, and reservoir fluids for disposal. Typically, the natural gas that is produced is vented or flared and the large volume of natural gas that is lost may not only affect regional air quality. When using green completion systems, gas and hydrocarbon liquids are physically separated from other fluids (a form of wellhead gas processing)—there is no venting or flaring of the gas—and delivered directly into equipment that holds or transports the hydrocarbon derivatives for productive use. Furthermore, by using portable equipment to process natural gas and natural gas condensate, the recovered gas can be directed to a pipeline as sales gas. The use of truck-mounted or trailer-mounted portable systems can typically recover more than half of the total gas produced.

Currently, the natural gas industry is regulated to a lesser extent by the Federal Energy Regulatory Commission (FERC). While FERC does not deal exclusively with natural gas issues; it is the primary rule making body with respect to the minimal regulation of the natural gas industry.

Opening up the natural gas industry and the move away from strict regulation has allowed for increased efficiency and technological improvements. Natural gas is now being obtained more efficiently, cheaply, and easily than ever before. However, the search for more natural gas to serve our ever-growing demand requires new techniques and knowledge to obtain it from hard-to-reach places.

Deregulation and the move toward cleaner burning fuels have created an enormous market for natural gas across the country. New technologies are continually developed that allow natural gas to be used in new ways and it is becoming the fuel of choice in the United States and in many countries throughout the world.

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