Chapter 2
Natural Gas

2.1 Introduction

Natural gas is the fastest-growing primary energy source in the International Energy Outlook 2003 (IEO 2003) forecast. Natural gas consumption is projected to nearly double between 2001 and 2025, with the most robust growth in demand expected among the developing nations. Because it is a cleaner fuel than oil or coal and not as controversial as nuclear power, natural gas is expected to be the fuel of choice for many countries in the future.

Natural gas combustion is clean and emits less CO_2 than all other petroleum-derivate fuels, which makes it makes favorable in terms of the greenhouse effect. Natural gas is used across all sectors, in varying amounts, including in industrial, residential, electricity generation, commercial, and transportation sectors.

Natural gas consists of 85–95% methane, which is the simplest hydrocarbon. Natural gas is the cleanest-burning alternative fuel. Exhaust emissions from natural gas vehicles (NGVs) are much lower than those from gasoline-powered vehicles. Combustion of natural gas results in the production of less carbon dioxide compared with the combustion of diesel, but the loss in efficiency when the Otto process is used means that carbon dioxide emissions increase. All in all, combustion of natural gas in a gasoline engine gives rise to about as much carbon dioxide as the combustion of diesel in a diesel engine, measured in units of energy.

Natural gas is one of the most widely used forms of energy today. Natural gas is a cleaner-burning fuel than either gasoline or diesel. However, natural gas also contains active compounds, such as sulfur, and inert compounds, such as nitrogen and carbon dioxide. Natural gas has a high octane number (110–130) and therefore has potential for use in a high-compression engine. It is a fossil fuel and is extracted from gas sources in bedrock. It is less dense than air and a carries a certain risk of explosion. Natural gas can be stored in compressed form and is then known as compressed natural gas (CNG), or at a low temperature (111 K) in liquid form, known as liquefied natural gas (LNG). LNG has been considered as an option for fueling automobiles.

A. Demirbas, *Methane Gas Hydrate*,

Table 2.1 Typical combustion properties of natural gas

Ignition point	876 K
Flammability limits	4–16 vol% (in air)
Theoretical flame temperature (stoichiometric air-to-fuel ratio)	2,233 K
Maximum flame velocity	0.3 m/s
Specific gravity (relative density)	0.583
Water vapor content	16–32 mg/m^3
Sulfur content	5.5 mg/m^3
Higher heating value (dry basis)	36.0–40.2 MJ/m^3

The composition of pipeline natural gas varies depending on the source and the processing of the gas. Typically, natural gas consists of over 90% methane and small amounts of ethane and other hydrocarbons. It may also contain nitrogen, carbon dioxide, and trace amounts of water vapor. Natural gas at ambient temperatures and pressures is a gas. As is typical of gases, it has a very low energy density compared with other fuels. The typical combustion properties of natural gas are gives in Table 2.1. On average, 0.921 m^3 of natural gas has the same energy content as 1.12 L of gasoline. This makes use of natural gas as a transportation fuel at ambient temperatures and pressures unfeasible. To use natural gas as a transportation fuel, it must be either compressed or liquefied to increase its volumetric energy density (Demirbas 2002).

The vapors of many liquid fuels such as gasoline and liquefied petroleum gas (LPG) are denser than air. As they evaporate, gasoline and LPG vapors tend to accumulate around the source and pose an explosion hazard. Natural gas requires a greater concentration in air and a higher temperature to ignite than gasoline. In the event of a leak or accident, natural gas will ignite at 811 K and between 5 and 15% concentration in air. Gasoline will ignite at only 533 K and 1.5% concentration in air.

Ventilation must be provided in CNG vehicle maintenance garages and vehicle storage buildings through ceiling exhaust systems to prevent hazardous CNG accumulations. In vehicle operation, as the pressure regulators reduce the CNG pressure, the temperature will drop, causing water vapor in the natural gas to condense. The condensed water will restrict or block fuel flow. CNG vehicle fueling stations normally dehydrate the natural gas to prevent water condensation.

Use of CNG as a transport-sector fuel requires investment in a dramatically different fuel supply system. Gas has to be taken from a gas distribution system, usually at a pressure of 0.3–1 MPa, and compressed to 20 MPa into CNG tanks of vehicles. Without intermediate storage at the CNG vehicle filling station, a slow-fill system is used that only has compressors. About 8 h is required for refueling the vehicles. For a more rapid fill, but usually no faster than 5 min, larger compressors and intermediate storage are required.

Over the next 20 years, the role of natural gas in global energy consumption will increase substantially. The speed of the transition to natural gas will be driven by environmental constraints, increased demand, and new technologies. A potential source of natural gas lies in the enormous worldwide gas hydrate reserves. It was estimated that the size of this resource ranges up to 20,000 trillion cubic meters (Kvenvolden 1993). These deposits can cause problems and safety concerns relating to drilling, production of oil and gas, and building and operation of pipelines. Naturally occurring gas hydrates are normally found at the seafloor or in shallow sediments where the pressures and temperatures are conducive to hydrate formation.

2.2 Definition and History

Natural gas is formed deep underground, usually in areas around coal and oil. It is composed primarily of methane. It does, however, contain other chemical species, such as butane and propane. If the mixture is composed only of these species, it is called dry natural gas, as there will be no liquid components at standard pressure and temperature. Natural gas might also contain nonhydrocarbon compounds, such as water vapor, carbon dioxide, and hydrogen sulfide.

Natural gas is a mixture of lightweight alkanes. Natural gas contains methane (CH_4), ethane (C_2H_6), propane (C_3H_8), *n*-butane and isobutane (C_4H_{10}), and pentanes (C_5H_{12}). The C_3, C_4, and C_5 hydrocarbons are removed before the gas is sold. The commercial natural gas supplied to the customer is therefore primarily a mixture of methane and ethane. The propane and butanes removed from natural gas are usually liquefied under pressure and sold as LPGs. Natural gas is found to consist mainly of the lower paraffins, with varying quantities of carbon dioxide, carbon monoxide, hydrogen, nitrogen, and oxygen, and in some cases also hydrogen sulfide and possibly ammonia. The chemical composition of natural gas is given in Table 2.2.

For hundreds of years, natural gas has been known as a very useful substance. The ancient peoples of Persia, Greece, and India discovered natural gas many centuries ago. About 2,500 years ago, the Chinese discovered that the energy in natural gas could be harnessed, and used to heat water. In the early days of the natural gas industry, the gas was mainly used to light streetlamps, and the occasional house. The Chinese piped the gas from shallow wells and burned it under large pans to evaporate seawater to obtain salt.

Natural gas was known in England as early as 1659, but it did not replace coal gas as an important source of energy in the world until after World War II.

Natural gas was first used in America in 1816 in gas lamps to illuminate the streets of Baltimore. Soon after, in 1821, William Hart dug the first successful American natural gas well in Fredonia, New York. The Fredonia Gas Light Company opened its doors in 1858 as the nation's first natural gas company. By 1900, natural gas had been discovered in 17 states. In the past 40 years, the use of natural gas has grown.

Historically, world natural gas reserves and natural gas usage have generally trended upward. Most of this usage of natural gas was near the wells that produced it owing to the lack of long-range pipelines or transport. In 1925, the first all-

Table 2.2 Chemical composition of natural gas

Component	Typical analysis (vol%)	Range (vol%)
Methane	94.9	87.0–96.0
Ethane	2.5	1.8–5.1
Propane	0.2	0.1–1.5
Isobutane	0.03	0.01–0.3
n-Butane	0.03	0.01–0.3
Isopentane	0.01	Trace to 0.14
n-Pentane	0.01	Trace to 0.14
Hexane	0.01	Trace to 0.06
Nitrogen	1.6	1.3–5.6
Carbon dioxide	0.7	0.1–1.0
Oxygen	0.02	0.01–0.1
Hydrogen	Trace	Trace to 0.02

welded pipeline over 200 miles in length was built, running from Louisiana to Texas. The growth in such pipeline networks and the cheap price of natural gas led to an expansion in its use. Between the turn of the twentieth century and 1970, usage and production of natural gas increased 50-fold. However, production of natural gas in the USA peaked in 1973, and by 1980, the USA began to import natural gas from other countries. Despite high rates of increase in natural gas consumption, particularly over the past decade, most regional reserves-to-production ratios are substantial.

2.3 Origin of Natural Gas

Natural gas is generally considered a nonrenewable fossil fuel. It comes from the decomposition of organic matter, just like oil and coal. Unlike oil and coal, though, it can come from almost any organic matter, whereas coal comes only from plant matter and oil comes almost exclusively from plankton and microplankton remains. Natural gas can come from both of these sources as well.

Decay and millions of years of geological stresses have transformed the complicated organic compounds that once made up living plants or animals into a mixture of alkanes. Natural gas is considered a fossil fuel because most scientists believe that natural gas was formed from the remains of tiny sea animals and plants that died 200–400 million years ago. When these tiny sea animals and plants died, they sank to the bottom of the oceans, where they were buried by layers of sediment that turned into rock. Over the years, the layers of sedimentary rock became thousands of feet thick, subjecting the energy-rich plant and animal remains to enormous pressure.

Most scientists believe that the pressure, combined with the heat of the earth, changed this organic mixture into petroleum and natural gas. Eventually, concentrations of natural gas became trapped in the rock layers like wet sponge traps water.

Natural gas can also come from unconventional sources. It is produced by decay of dead plant matter in swamps and rice fields. Animals, such as cattle and termites, produce large quantities as a by-product of digestion. These sources, though, cannot be tapped for energy use. Other unconventional sources, such as landfills, manure digesters, and wastewater treatment plants, are used to produce natural gas. China produces enough gas from manure digesters to provide cooking and lighting for over six million homes.

2.4 Natural Gas Resources

Natural gas is commercially produced from oil fields and natural gas fields. Gas produced from oil wells is called casinghead gas or associated gas. The natural gas industry is producing gas from increasingly more challenging resource types: sour gas, tight gas, shale gas, coal-bed methane, and methane gas hydrate. The world's largest gas field by far is Qatar's offshore North Field, estimated to have 25 trillion cubic meters of gas – enough to last more than 200 years at optimum production levels. The second-largest natural gas field is the South Pars Gas Field in Iranian waters in the Persian Gulf. It has estimated reserves of 8–14 trillion cubic meters of gas.

Natural gas is found around the world, but the largest reserves are in the former Soviet Union and the Middle East. Natural gas reserves are given Table 2.3. Since the mid-1970s, world natural gas reserves have generally trended upward each year. Natural gas reserves in the industrialized countries also increased between 2002 and 2003 by 18 trillion cubic feet (TCF). The decrease was largely offset by the enormous upward revision of gas reserves in Azerbaijan from 4 TCF in 2002 to 30 TCF in 2003 (IEO-AEO 2002).

Table 2.3 World natural gas reserves ($\times 10^6\,m^3$) (IEA 2003)

Country	Reserve	Country	Reserve
Russia	47,573	Pakistan	71
Iran	23,002	India	65
Qatar	14,400	Former Yugoslavia	48
Saudi Arabia	6,216	Yemen	48
United Arab Emirates	6,000	Brunei	39
USA	5,196	Hungary	37
Algeria	4,500	Thailand	36
Venezuela	4,180	Papua New Guinea	35
Nigeria	3,500	Croatia	34
Iraq	3,100	Bangladesh	30
Turkmenistan	2,860	Myanmar	28
Australia	2,548	Austria	25
Uzbekistan	1,875	Syria	24
Kazakhstan	1,841	Ireland	20

Table 2.3 (continued)

Country	Reserve	Country	Reserve
The Netherlands	1,770	Vietnam	19
Canada	1,691	Slovakia	14
Kuwait	1,690	Mozambique	13
Norway	1,246	France	11
Ukraine	1,121	Cameroon	11
Mexico	835	The Philippines	10
Oman	821	Afghanistan	10
Argentina	777	Turkey	9
UK	736	Congo	9
Bolivia	680	Sudan	9
Trinidad and Tobago	665	Tunisia	8
Germany	343	Taiwan	8
Indonesia	262	Namibia	6
Peru	246	Rwanda	6
Italy	229	New Zealand	6
Brazil	221	Bulgaria	6
Malaysia	212	Israel	4
Poland	144	Angola	4
China	137	Equatorial Guinea	4
Libya	131	Japan	4
Azerbaijan	125	Côte d'Ivoire	3
Colombia	122	Ethiopia	3
Ecuador	105	Gabon	3
Romania	102	Ghana	3
Egypt	100	Czech Republic	3
Chile	99	Guatemala	3
Bahrain	91	Albania	3
Denmark	76	Tanzania	2
Cuba	71		

Another potentially large source of natural gas is methane hydrates. These are solid, crystalline features that are composed of a combination of methane, water ice, and other gases. The methane and gases are trapped in the lattice structure of the water ice, which, like coal beds, can hold much more natural gas than normal rock features. These hydrate formations are usually found on the ocean floor, where there is high pressure and near-freezing temperatures.

2.5 Natural Gas Production, Consumption, and Distribution

As is the case with oil, natural gas is unevenly distributed throughout the world. More than one third of the world's original gas endowment was in the territory of the former Soviet Union. The second-largest gas resource, located in the Middle East, comprised about 22% of the world total. About 38% of the world's remaining gas is in the former Soviet Union and 25% is located in the Middle East. South

America, Europe, Africa, and Asia/Oceania are each projected to contain less than 10% of the world's remaining gas.

The largest supplier of natural gas imports to western Europe is Russia, and those imports are continuing to grow. In the first 7 months of 2002, western European imports of Russian gas increased by 5.4% compared with the same period in 2001. Russia has plans to increase its presence in western European markets by building a pipeline that would bypass Ukraine and Poland (to avoid high transport fees and unauthorized diversion of gas) and initially transport gas from the Yamal Peninsula in western Siberia to Finland, Sweden, and Denmark. The intention is to extend the pipeline subsequently to the Netherlands via Germany and then along the floor of the North Sea to the UK (IEO 2003).

The world distribution of natural gas mirrors that of oil, which might be expected since oil and gas are often generated and reservoired together. However, the Middle East, although containing a very significant amount of gas, does not dominate world gas supply as it does world oil supply. The Worldwide Statistical Survey (WSS 2006) statistical survey contains the latest data on natural gas reserves, gross and marketed production, international trade, consumption, and prices of the main contracts in 1999. The evolution of gas transportation and distribution networks, underground gas storage capacities, as well as demand prospects are also compiled in this document. The study includes natural gas statistics for 102 countries and detailed comments for the major countries. World natural gas production has been maintained at a level of about 2,300 billion cubic meters a year during the last 5 years, and it is not expected to be affected by the decrease in production in Russia.

Beyond 2000 there are projections to 2100 by different authors, with modeling. These scenarios imply that the amount of gas produced from 2000 to 2300 would be 20 times the most likely technical estimate of the conventional and unconventional gas combined, making them utterly implausible. The present world gas production is not showing any drastic change.

Consumption of natural gas worldwide is projected to increase by an average of 2.8% annually from 2001 to 2025, compared with projected annual growth rates of 1.8% for oil consumption and 1.5% for coal consumption. Natural gas consumption in 2025, at 176 TCF, is projected to be nearly double the 2001 total of 90 TCF. The natural gas share of total energy consumption is projected to increase from 23% in 2001 to 28% in 2025.

Around the world, natural gas use is increasing for a variety of reasons, including prices, environmental concerns, fuel diversification and/or energy security issues, market deregulation, and overall economic growth. Figure 2.1 shows production and consumption trends of natural gas in the last few decades.

The USA consumes about 2.4 TCF more natural gas per year than it produces. Germany imports even more gas than the USA (2.6 TCF per year) and Japan slightly less (2.3 TCF per year). North America is the leading consumer of natural gas, but is also a leading producer. The former USSR region leads the world in gas production, and is second in consumption. Europe ranks third in natural gas consumption, but has to import 4.1 TCF per year. Asia/Oceania must also import

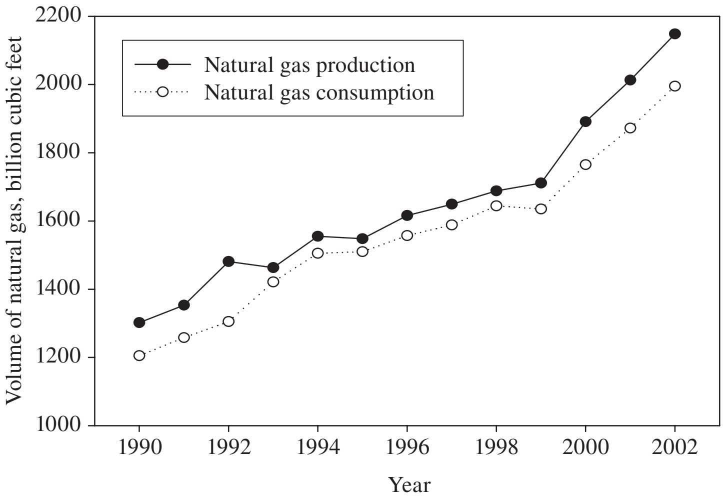

Fig. 2.1 Production and consumption trends of natural gas in the world

natural gas to satisfy demand. The other regions are relatively minor producers and consumers of gas. Compared with oil, only moderate amounts of natural gas are traded on world markets. The low density of gas makes it more expensive to transport than oil. A section of pipe in oil service can hold 15 times more energy than when it is used to transport high-pressure gas. For this reason, gas pipelines must have a larger diameter for a given energy movement. Compression adds to the disparity between the transportation costs of the two fuels. An oil pumping station uses energy to overcome frictional losses, but a gas line requires a large amount of energy to compress the gas before pipeline friction is even encountered.

Pipeline transportation is not always feasible because of the growing geographic distance between gas reserves and markets. Also, since potential political instabilities may affect long pipeline routes, importing countries may wish to diversify supply sources. Although natural gas can be piped in a gaseous state, it needs to be liquefied so that it can be economically transported by ship. A full LNG chain consists of a liquefaction plant, low-temperature, pressurized, transport ships, and a regasification terminal. World LNG trade is currently about 60 million metric tons per year, some 65% of which is imported by Japan. Other importers include France, Spain, Korea, Belgium, Taiwan, and Italy. Indonesia accounts for 39% of LNG exports, with Algeria in second place with 24%. Other exporters include Malaysia, Brunei, Australia, Abu Dhabi, and Libya. The USA imports and exports about one million metric tons of LNG per year. No grassroots LNG project has been commissioned since 1989 owing to intense competition with other fuels, notably oil.

The global market for natural gas is much smaller than that for oil because gas transport is difficult and costly, owing to the relatively low energy content in relation to volume. Currently, only about 16% of global gas production is traded internationally, with less than 4% of the trade accounted for by LNG. In spite of the high cost of gas transportation and the remote location of some future supply regions, increasing international trade in natural gas is expected.

The generation of electricity is an important use of natural gas. However, the electricity generated from natural gas is generally more expensive than that generated using coal because of increased fuel costs. Natural gas can be used to generate electricity in a variety of ways. These include (1) conventional steam generation, similar to coal-fired power plants in which heating is used to generate steam, which in turns runs a turbine with an efficiency of 30–35%, (2) a centralized gas turbine, in which hot gases from natural gas combustion are used to turn the turbine, and (3) a combined cycle unit, in which both steam and hot combustion gases are used to turn the turbine with an efficiency of 50–60%.

2.6 Compressed Natural Gas

CNG is odorless, colorless, and tasteless. It consists mostly of methane and is drawn from gas wells or is obtained in conjunction with crude oil production. An odorant is normally added to CNG for safety reasons.

Typically, to use CNG as a transportation fuel, natural gas is taken from a gas distribution system at pressures ranging from 0.3 to 1 MPa, compressed at a fueling station, and stored in cylinders on vehicles at pressures of about 20 MPa. Currently, the international NGV industry has not set a standardized CNG pressure. At 20 MPa, the volumetric energy density of CNG is about one fourth that of gasoline. Thus, with all efficiencies being equal, a CNG vehicle requires a tank 4 times the size of a gasoline tank for the same driving range. Liquefying natural gas by cooling it to approximately 400 K increases its energy density. LNG is typically stored at low pressures between 0.07 and 0.34 MPa to maintain its liquid state, but LNG is not available in most markets. Increasing the travel distance between refueling increases the investment, the weight of the storage tank, and the space needed to make it possible to use CNG. Natural gas has an octane value of 130, which is considerably higher than that of gasoline, which usually ranges between 84 and 97. The higher octane value of CNG generally gives very good engine performance characteristics (Demirbas 2002).

Despite the large difference in volumetric energy density between gasoline and CNG, the impact of CNG energy density on engine performance is less dramatic. As a gas, it has few cold-start problems. Its higher octane value allows for higher engine compression ratios than can be used with gasoline alone. Higher compression ratios allow for higher power and fuel efficiency. However, for the same compression ratio, the amount of natural gas air/fuel mixture that can be burned in each piston stroke is 10–15% less than for gasoline. Thus, there is a 10–15% loss of engine output power (Demirbas 2002).

To use CNG safely, technicians and drivers need to know what the differences are and how to work with them. Other subjects that must be understood are natural gas combustion and storage, working with high-pressure conduits, connectors, regulators, and cylinders, safety codes and industry standards, and recommended CNG cylinder inspections. Detailed hands-on training for installation and maintenance technicians should normally be provided by the conversion kit manufacturers (Demirbas 2002).

In general, the use of natural gas results in cleaner and longer-lasting engines. Less carbon builds up on spark plugs, in engine oil, and in the combustion chamber. Natural gas has higher ignition temperatures than gasoline, which increases the importance of maintaining proper ignition system operation.

The toxic emissions with CNG, without exception, are lower than for any other hydrocarbon fuel. This is a direct result of the fact that CNG is a single hydrocarbon, 90% methane, whereas all of the other fuels are a mix of hydrocarbons. LPG is a relatively simple mix of propane, butane, and pentane, in contrast to the complex mix that makes up the gasoline and diesel typically purchased at the service station. Combustion of gasoline and diesel results in emission into the air of methanol, formaldehyde, aldehydes, acrolein, benzene, toluene, xylene, etc., some of which are not yet part of any established emission standard but certainly are not beneficial to peoples' health (Demirbas 2002).

Soot emission from hydrocarbon flames is an important subject since it plays an important role in relation to both heat transfer by radiation and air pollution (Shahad and Mohammed 2000). The use of CNG in internal combustion engines permits operation with decreased NO_x emissions without increasing soot formation or specific fuel consumption.

The production, processing, transportation, and compression of natural gas to the CNG fuel that is used by vehicles results in less environmental impact than the production, transportation, and processing of crude oil and the transportation of gasoline or diesel to the service stations. Less carbon dioxide is produced by combustion of natural gas than by combustion of both diesel fuel and gasoline, which makes natural gas engines favorable also in terms of the greenhouse effect.

2.7 Liquefied Natural Gas

LNG is a product of natural gas which consists primarily of methane. Its properties are those of liquid methane, slightly modified by minor constituents. One property which differentiates LNG from LPG is the low critical temperature, about 200 K. This means that natural gas cannot be liquefied at ordinary temperatures simply by increasing the pressure, as is the case with LPG; instead, natural gas must be cooled to cryogenic temperatures to be liquefied and must be well insulated to be held in the liquid state. The reduction in volume makes natural gas much more cost-efficient to transport over long distances where pipelines do not exist. Where movement of natural gas by pipelines is not possible or economic, it can be transported by specially designed cryogenic sea vessels (LNG carriers) or cryogenic road tankers. LNG is shipped around the world in specially constructed seagoing vessels.

Until 2003, LNG prices closely followed oil prices. Since then, LNG prices to Europe and Japan have been lower than oil prices. In the USA in 2008, regular-grade motor gasoline retail prices averaged $ 3.26 per gallon, diesel fuel retail prices averaged $ 3.80 per gallon, and LNG retail prices averaged $ 3.36 per gallon (EIA 2009).

The natural gas fed into the LNG plant is treated to remove water, corrosive acid gases (H_2S and CO_2) and other components, such as dust, helium, and heavy hydrocarbons (ethane, propane, and butane). LNG typically contains more than 90% methane. The purification process can be designed to give almost 100% methane. The density of LNG is roughly 0.41–0.5 kg/L, depending on temperature, pressure, and composition. The heating value of LNG depends on the source of gas that is used and the process that is used to liquefy the gas. The higher heating value of LNG is 24 MJ/L at 109 K.

In its liquid state, LNG is not explosive and cannot burn. For LNG to burn, it must first vaporize, then mix with air in the proper proportions (the flammable range is 5–15%), and then be ignited.

Modern LNG storage tanks are typically the full containment type, which is a double-wall construction with a reinforced concrete outer wall and a high-nickel steel inner tank, with extremely efficient insulation between the walls. LNG must be kept cold to remain a liquid, independent of pressure. LNG is transported in specially designed ships with double hulls protecting the cargo systems from damage or leaks. Transportation and supply is an important aspect of the gas business, since LNG reserves are normally quite distant from consumer markets.

2.8 Contribution of Natural Gas to Global Warning

Table 2.2 shows the chemical composition of natural gas. Methane is by far the largest component, its presence accounting for about 95% of the total volume. Other components are ethane, propane, butane, pentane, nitrogen, carbon dioxide, water vapor, and traces of other gases. Very small amounts of sulfur compounds are also present. Since methane is the largest component of natural gas, the properties of methane are generally used when comparing the properties of natural gas with those of other fuels. Global warming has been increasingly associated with carbon dioxide levels. The gases (they consist of three or more atoms) with higher heat capacities than those of oxygen and nitrogen cause the greenhouse effect.

$$\begin{array}{llll} CH_4 & +\ 2O_2 & \rightarrow\ CO_2 & +\ 2H_2O \\ 1.00\,\mathrm{g} & & \quad 2.75\,\mathrm{g} & \end{array} \tag{2.1}$$

$$\begin{array}{llll} 2C_4H_{10} & +\ 13O_2 & \rightarrow\ 8CO_2 & +\ 10H_2O \\ 1.00\,\mathrm{g} & & \quad 3.03\,\mathrm{g} & \end{array} \tag{2.2}$$

$$\begin{array}{lll} C & +\ O_2 & \rightarrow\ CO_2 \\ 1.00\,\mathrm{g} & & \quad 3.66\,\mathrm{g} \end{array} \tag{2.3}$$

From Eq. 2.1, among the fossil fuels, natural gas is the least responsible for CO_2 emissions. Natural gas is the cleanest-burning petroleum-based fuel. Combustion of LPG produces more CO_2 than combustion of natural gas (Eq. 2.2). The highest amount of CO_2 occurs according to Eq. 2.3. Thus, the responsibility of the fossil fuel increases with increasing carbon number. In addition, overall CO_2 emissions can be reduced by combustion of biomass because it is a CO_2-neutral fuel.

The percentage of carbon in LNG is the lowest in carbon-intensive fossil fuels (Davies 2001) and thus LNG has the lowest pollution potential when compared with other fossil fuels. Exhaust emissions from NGVs are much lower than those from equivalent gasoline-powered vehicles. For instance, NGV emissions of carbon monoxide are approximately 70% lower, non-methane organic gas emissions are 89% lower, and oxides of nitrogen emissions are 87% lower. In addition to these reductions in pollutants, NGVs also emit significantly lower amounts of greenhouse gases and toxins than do gasoline-powered vehicle. Dedicated NGVs produce little or no evaporative emissions during fueling and use. For gasoline-powered vehicles, evaporative and fueling emissions account for at least 50% of a vehicle's total hydrocarbon emissions. Dedicated NGVs also can reduce carbon dioxide exhaust emissions by almost 20%. Diesel exhaust is under review as a hazardous air pollutant.

Environmental concerns such as global warming have resulted in calls for increased use of natural gas. This is because when natural gas is burned, it gives off only half as much carbon dioxide per unit of energy produced as does coal, and 25% less than oil, virtually no sulfur dioxide, and only small amounts of nitrous oxides. Carbon dioxide is a greenhouse gas, whereas sulfur dioxide and nitrous oxides produced by oil and coal combustion cause acid rain.

Natural gas is mostly composed of methane and other light hydrocarbons. Both the carbon and the hydrogen in methane combine with oxygen when natural gas is burned, giving off heat. As mentioned earlier, reduced carbon dioxide emissions may not be the end of the story when it comes to natural gas and global warming. Methane is itself a greenhouse gas, and molecule for molecule can trap more heat than carbon dioxide and in this way counterbalances the carbon dioxide benefits of burning natural gas instead of oil and coal (Surmen and Demirbas 2003; Demirbas 2000).

2.9 Use of Natural Gas

For hundreds of years, natural gas has been known as a very useful substance. The Chinese discovered a very long time ago that the energy in natural gas could be harnessed, and used to heat water. In the early days of the natural gas industry, the gas was mainly used to light streetlamps, and the occasional house. However, with much improved distribution channels and technological advancements, natural gas is being used in ways never thought possible.

Table 2.4 Natural gas use in Europe by sector

Sector	Use (%)	Percentage of total
Industrial	43	38
Residential	22	25
Electricity generation	18	20
Commercial	14	15
Transportation	3	2

Natural gas is one of the most widely used forms of energy today. It is commonly used to heat and cool homes and businesses. Natural gas is a very versatile fuel which can be used for space and water heating, which have traditionally been the predominant uses of natural gas, representing about 75 and 15% of natural gas use, respectively. In the future, increasing concerns about urban air pollution may lead to increased use of natural gas by industry and for electricity generation, cooking, mechanical power, and heating.

The generation of electricity is the other main use of natural gas. Producing electricity from natural gas is generally more expensive than using other methods because of increased fuel costs. Natural gas can be used to generate electricity in many different ways. Natural gas power plants generate more than a couple of hundred megawatts using the same technology as coal-fired power plants. Natural gas is burned to produce heat, which boils water, creating steam, which passes through a turbine to generate electricity. Natural gas is one of the most widely used forms of energy today.

Natural gas is used by industrial, residential, electricity generation, commercial, and transportation sectors. Natural gas is used across all sectors, in varying amounts. Table 2.4 shows natural gas use by sector. The industrial sector accounts for the greatest proportion of natural gas use in the USA, with the residential sector consuming the second-greatest quantity of natural gas. The proportions of petroleum products, natural gas, coal nuclear power, and other energy sources consumed in the USA in 2002 were 39, 24, 22, 8, and 7%, respectively (EIA–AEO 2002).

2.9.1 Industrial Uses

Natural gas has innumerable uses in industry, and new applications are being developed every day. It is used to provide the base ingredients for such varied products as plastics, fertilizers, antifreeze, and fabrics. In fact, industry is the largest consumer of natural gas, accounting for 43% of natural gas use across all sectors. Natural gas is the second most used energy source in industry, trailing only electricity. Lighting is the main use of energy in the industrial sector, and accounts for the tremendous electricity requirements of this sector.

Industrial applications for natural gas also include the same uses as found in residential and commercial settings – heating, cooling, and cooking. Natural gas is also used for waste treatment and incineration, preheating of metals (particularly for iron and steel), drying and dehumidification, glass melting, food processing, and fueling industrial boilers. Natural gas may also be used as a feedstock for the manufacturing of a number of chemicals and products. Gases such as butane, ethane, and propane may be extracted from natural gas to be used as a feedstock for fertilizers and pharmaceutical products.

Natural gas as a feedstock is commonly found as a building block for methanol, which in turn has many industrial applications. Natural gas is converted to what is known as synthesis gas, which is a mixture of hydrogen and carbon oxides formed through a process known as steam reforming. In this process, natural gas is exposed to a catalyst, which causes oxidization of the natural gas when it is brought into contact with steam. This synthesis gas, once formed, may be used to produce methanol, which in turn is used to produce substances such as formaldehyde, acetic acid, and methyl *tert*-butyl ether, which is used as an additive for cleaner-burning gasoline. Methanol may also be used as a fuel source in fuel cells.

Industrial consumers reap great benefits from operating natural gas cogeneration or combined heat and power and combined cooling, heat, and power systems, similar to those used in commercial settings. For instance, natural gas may be used to generate electricity needed in a particular industrial setting. The excess heat and steam produced from this process can be harnessed to fulfill other industrial applications, including space heating, water heating, and powering industrial boilers.

Natural gas co-firing technologies are also helping to increase industrial energy efficiency, and reduce harmful atmospheric emissions. Co-firing is the process in which natural gas is used as a supplemental fuel in the combustion of other fuels, such as coal, wood, and biomass. For example, a traditional industrial wood boiler would simply burn wood to generate energy. However, in this type of boiler, a significant amount of energy is lost, and harmful emissions are very high. Adding natural gas to the combustion mix can have a twofold effect. Combustion of natural gas results in emission of fewer harmful substances into the air than combustion of a fuel such as wood. Since the energy needed to power the natural gas boiler remains constant, adding natural gas to the combustion mix can reduce harmful emissions.

2.9.2 Residential Use

Natural gas is one of the cheapest forms of energy available to the residential consumer. Table 2.5 shows the residential energy costs per unit. According to the US Department of Energy, the cost of natural gas costs is less than 30% of the cost of electricity. Not only is natural gas cheap for the residential consumer, it also has a number of varied uses. The best known uses for natural gas around the home are natural gas heating and cooking. Cooking with a natural gas range or oven can provide many benefits, including easy temperature control, self-ignition and self-cleaning, as well as costing approximately half as much as cooking with an electric range.

Table 2.5 Residential energy costs per unit

Electricity	Propane	Kerosene	No. 2 heating oil	Natural gas
100	39.3	37.5	32.1	27.1

Natural gas appliances are also rising in popularity owing to their efficiency and cost-effectiveness. Some examples of other natural gas appliances include space heaters, clothes dryers, pool heaters, fireplaces, barbecues, garage heaters, and outdoor lights.

Natural gas fuel cells and microturbines both offer residential consumers the possibility to disconnect from their local electricity distributor, and generate just enough electricity to meet their needs. Although this technology is still in its infancy, it is very promising in being able to offer independent, reliable, efficient, environmentally friendly electricity for residential needs.

2.9.3 Electricity Generation using Natural Gas

Natural gas can be used to generate electricity in a variety of ways. The most basic natural-gas-fired electricity generation consists of a steam generation unit, where fossil fuels are burned in a boiler to heat water and produce steam, which then turns a turbine to generate electricity. Natural gas may be used for this process, although these basic steam units are more typical of large coal or nuclear generation facilities. These basic steam generation units have fairly low energy efficiency. Typically, only 33–35% of the thermal energy used to generate the steam is converted into electric energy in these types of units.

Gas turbines and combustion engines are also used to generate electricity. In these types of units, instead of heating steam to turn a turbine, hot gases from burning fossil fuels (particularly natural gas) are used to turn the turbine and generate electricity.

Many of the new natural-gas-fired power plants are what are known as “combined-cycle” units. In these types of generating facilities, there is both a gas turbine and a steam unit, all in one.

Natural gas is one of the leading energy sources for distributed generation. Fuel cells are becoming an increasingly important technology for the generation of electricity. They are much like rechargeable batteries, except instead of using an electric recharger, they use a fuel, such as natural gas, to generate electric power even when they are in use. Fuel cells for distributed generation offer a multitude of benefits, and are an exciting area of innovation and research for distributed generation applications.

The industrial sector, which is the world’s largest consumers of natural gas, will account for 43% of projected natural gas use in 2030. In the electric power sector, natural gas is an attractive choice for new generating plants because of its relative fuel efficiency and low carbon dioxide emissions. Electricity generation will account for 35% of the world's total natural gas consumption in 2030 (Demirbas 2006).

2.9.4 Commercial Use

Commercial uses of natural gas are very similar to residential uses. The commercial sector includes public and private enterprises, including office buildings, schools, churches, hotels, restaurants, and government buildings. The main uses of natural gas in this sector include space heating, water heating, and cooling. For restaurants and other establishments that require cooking facilities, natural gas is a popular choice to fulfill these needs. Natural gas is the primary energy source for space and water heating, cooking, and drying, and also accounts for about 13% of energy used in commercial cooling.

Space heating accounts for 36% of commercial energy use, lighting for 19%, cooling for 12%, water heating for 8%, cooking for 6%, drying for 3%, and other uses for 16%.

2.9.5 Natural Gas in the Transportation Sector

Natural gas has long been considered an alternative fuel for the transportation sector. Most NGVs operate using CNG. This compressed gas is stored in a tube-shaped storage tank, in a similar fashion to a car's gasoline tank, attached to the rear, top, or undercarriage of the vehicle. A CNG tank can be filled in a similar manner, and in a similar amount of time, as a gasoline tank.

NGVs offer many benefits, from improving public health and the environment to aiding the transition to fuel cell vehicles. Compared with vehicles fueled by conventional diesel and gasoline, NGVs can produce significantly lower amounts of harmful emissions such as nitrogen oxides, particulate matter, and toxic and carcinogenic pollutants. NGVs can also reduce emissions of carbon dioxide, the primary greenhouse gas. NGV and natural gas infrastructure development can facilitate the transition to this technology.

Despite the large difference in volumetric energy density between gasoline and CNG, the impact of CNG energy density on engine performance is less dramatic. As a gas, it has few cold-start problems. Its higher octane value allows for higher engine compression ratios than can be used with gasoline alone. Higher compression ratios allow for higher power and fuel efficiency. However, for the same compression ratio, the amount of natural gas air/fuel mixture that can be burned in each piston stroke is 10–15% less than for gasoline. Because of this, there is a 10–15% loss of engine output power.

2.10 Importance of Natural Gas

Concerns about acid rain and global warming will no doubt result in increased use of natural gas in the future. Two areas which could see expanded use of natural gas are fuel cells and transportation. Fuel cells are used to generate electricity, and operate something like a battery. The difference is that the energy for fuel cells comes from hydrogen, which can be made from natural gas. Fuel cells eliminate the need for turbines and generators, and can operate at efficiencies as high as 60%. Fuel cells also operate at low temperatures, thus reducing emissions of acid rain causing nitrous oxides, which are formed during high-temperature combustion of any fuel.

Concern over urban air pollution may lead to increased use of natural gas as a transportation fuel in the future. Natural gas burns far more cleanly than gasoline and diesel fuel, producing fewer nitrous oxides, unburned hydrocarbons, and particulates. NGVs require large storage tanks for their fuel. Therefore, the main market may not be for private use, but may be for vehicles and trucks which are used within cities.

Advances in technology over the last two decades and changes in the energy industry are leading to natural gas becoming the best cooling material. Natural gas cooling equipment is available in sizes to meet virtually every need – from air conditioning in residential homes to large-scale industrial refrigeration and process cooling. Today's natural gas cooling equipment is efficient and economical. Natural gas systems can save as much as 50% over the cost of conventional electric cooling equipment.

2.11 Environmental Impacts

Natural gas is the cleanest-burning alternative fuel. Exhaust emissions from NGVs are much lower than those from equivalent gasoline-powered vehicles. For instance, NGV emissions of carbon monoxide are approximately 70% lower, non-methane organic gas emissions are 89% lower, and oxides of nitrogen emissions are 87% lower. In addition to these reductions in pollutants, NGVs also emit significantly lower amounts of greenhouse gases and toxins than do gasoline vehicles. Dedicated NGVs produce little or no evaporative emissions during fueling and use. For gasoline vehicles, evaporative and fueling emissions account for at least 50% of a vehicle's total hydrocarbon emissions. Dedicated NGVs can also reduce carbon dioxide exhaust emissions by almost 20%. Diesel exhaust is under review as a hazardous air pollutant.

Per unit of energy, natural gas contains less carbon than any other fossil fuel, and thus produces lower carbon dioxide emissions per vehicle mile traveled. Although NGVs do emit methane, another principal greenhouse gas, any slight increase in methane emissions would be more than offset by a substantial reduc-

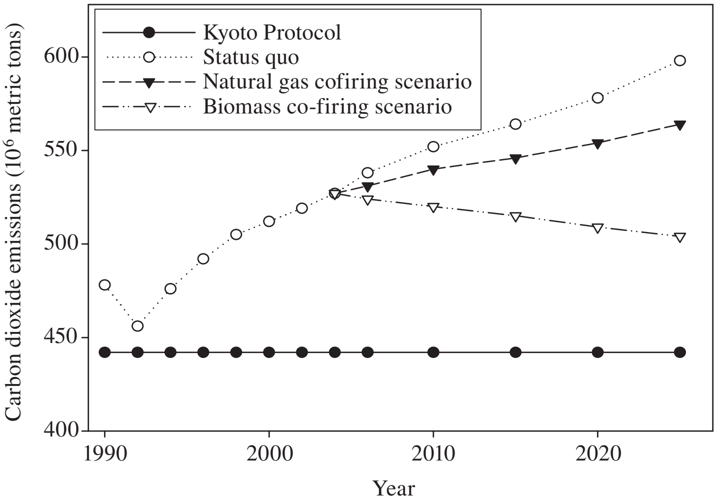

Fig. 2.2 Scenarios of co-firing of natural gas and biomass as fuels to reduce fossil-fuel-based CO_2 emissions

tion in carbon dioxide emissions. NGVs also emit very low levels of carbon monoxide (approximately 70% lower than a comparable gasoline-powered vehicle) and volatile organic compounds. Although these two pollutants are not themselves greenhouse gases, they play an important role in helping to break down methane and some other greenhouse gases in the atmosphere, and thus increase the global rate of methane decomposition. Figure 2.2 shows plots of scenarios of co-firing of natural gas and biomass as fuels to reduce fossil-fuel-based carbon dioxide emissions.

Natural gas could be considered the most environmentally friendly fossil fuel, because it has the lowest carbon dioxide emissions per unit of energy and because it is suitable for use in high-efficiency combined-cycle power stations. Because of the energy required to liquefy and to transport LNG, its environmental performance is inferior to that of natural gas, although in most cases LNG is still superior to alternatives such as fuel oil or coal. CNG has a much lower environmental impact than other hydrocarbon fuels when the process from production in the fields to filling of the vehicle tanks is taken into account. The toxic emissions with CNG, without exception, are lower than for any other hydrocarbon fuel. This is a direct result of the fact that CNG is a single hydrocarbon, 90% methane, whereas all of the other fuels are a mix of hydrocarbons.

Soot emission from hydrocarbon flames is an important subject since it plays an important role in relation to both heat transfers by radiation and air pollution (Shabad and Mohammed 2000). The use of CNG in internal combustion engines permits operation with decreased NO_x emissions without increasing soot formation or specific fuel consumption. The production, processing, transportation, and compression of natural gas to the CNG fuel that is used by vehicles results in less environmental impact than the production, transportation, and processing of crude oil and the transportation of gasoline or diesel to the service stations. Less carbon dioxide is produced by combustion of natural gas than by combustion of both diesel fuel and gasoline, which makes natural gas engines favorable in terms of the greenhouse effect.

2.12 Summary

Natural gas is the fastest-growing primary energy source in the International Energy Outlook 2003 (IEO 2003) forecast. Natural gas consumption is projected to nearly double between 2001 and 2025, with the most robust growth in demand expected among the developing nations.

Natural gas is formed deep underground, usually in areas around coal and oil. It is composed primarily of methane, but also contains other chemical species, such as butane and propane. If the mixture is composed only of these species, it is called dry natural gas, as there will be no liquid components at standard pressure and temperature. Natural gas might also contain nonhydrocarbon compounds, such as water vapor, carbon dioxide, and hydrogen sulfide.

Over the next 20 years, the role of natural gas in global energy consumption will increase substantially. The speed of the transition to natural gas will be driven by environmental constraints, increased demand, and new technologies. A potential source of natural gas lies in the enormous worldwide gas hydrate reserves. It is estimated that the size of this resource ranges up to 20,000 trillion cubic meters. These deposits can cause problems and safety concerns relating to drilling, production of oil and gas, and building and operation of pipelines. Naturally occurring gas hydrates are normally found at the seafloor or in shallow sediments where the pressures and temperatures are conducive to hydrate formation.

Natural gas is generally considered a nonrenewable fossil fuel. Most scientists believe that natural gas was formed from the remains of tiny sea animals and plants that died 200–400 million years ago. When these tiny sea animals and plants died, they sank to the bottom of the oceans, where they were buried by layers of sediment that turned into rock. Over the years, the layers of sedimentary rock became thousands of feet thick, subjecting the energy-rich plant and animal remains to enormous pressure, and transforming their constituent compounds into a mixture of alkanes.

For hundreds of years, natural gas has been known as a very useful substance. The Chinese discovered a very long time ago that the energy in natural gas could be harnessed, and used to heat water. In the early days of the natural gas industry, the gas was mainly used to light streetlamps, and the occasional house. However, with much improved distribution channels and technological advancements, natural gas is being used in ways never thought possible.

Natural gas is used in industrial, residential, electricity generation, commercial, and transportation sectors. Natural gas is used across all sectors, in varying amounts. The industrial sector accounts for the greatest proportion of natural gas use in the USA, with the residential sector consuming the second-greatest quantity of natural gas.

Concerns about acid rain and global warming will no doubt result in increased use of natural gas in the future. Two areas which could see expanded use of natural gas are fuel cells and transportation. Fuel cells are used to generate electricity, and operate something like a battery. The difference is that the energy for fuel cells comes from hydrogen, which can be made from natural gas. Fuel cells eliminate the need for turbines and generators, and can operate at efficiencies as high as 60%.

References

Davies P (2001) The new challenge of natural gas. Paper presented at OPEC and the global energy balance: towards a sustainable future, Vienna, 28 September 2001

Demirbas A (2000) Recent advances in biomass conversion technologies. Energy Educ Sci Technol 6:19–40

Demirbas A (2002) Fuel properties of hydrogen, liquefied petroleum gas (LPG), and compressed natural gas (CNG) for transportation. Energy Sources 24:601–610

Demirbas A (2006) Global biofuel strategies. Energy Educ Sci Technol 17:27–63

EIA (2009) Official energy statistics from the US Government. Energy Information Administration, Washington

EIA–AEO (2002) Natural gas uses. Energy Information Administration–International Energy Outlook, Washington

IEA (2003) Gas statistics. International Energy Agency, Paris

IEO (2003) Natural gas trends. http://www.eia.doe/iea/overview.html. Accessed May 2003

Kvenvolden K (1993) Gas hydrates – geological perspective and global change. Rev Geophys 31:173–187

Shahad HAK, Mohammed YKA (2000) Investigation of soot formation and temperature field in laminar diffusion flames of LPG-air mixture. Energy Convers Manage 41:1897–1916

Surmen Y, Demirbas A (2003) Cofiring of biomass and lignite blends: resource facilities; technological, environmental and economic issues. Energy Sources 25:175–187

WSS (2006) Natural gas in the world. http://www.cedigaz.org/about_us/about_us.htm