

Chapter 1: Overview and Conclusions

PURPOSE AND OUTLINE OF THE STUDY

Despite its vital importance to the national economy, natural gas has often been overlooked, or at best taken for granted, in the debate about the future of energy in the U.S. Over the past two or three years this has started to change, and natural gas is finding its place at the heart of the energy discussion.

There are a number of reasons for this shift. The recent emergence of substantial new supplies of natural gas in the U.S., primarily as a result of the remarkable speed and scale of shale gas development, has heightened awareness of natural gas as a key component of indigenous energy supply and lowered prices well below recent expectations. Instead of the anticipated growth of natural gas imports, the scale of domestic production has led producers to seek new markets for natural gas, such as an expanded role in transportation. Most importantly for this study, there has been a growing recognition that the low carbon content of natural gas relative to other fossil fuels could allow it to play a significant role in reducing carbon dioxide (CO₂) emissions, acting as a “bridge” to a low-carbon future.

Within this context, the MIT study of *The Future of Natural Gas* seeks to inform the discussion around natural gas by addressing a fundamental question: *what is the role of natural gas in a carbon-constrained economy?*

In exploring this question, we seek to improve general understanding of natural gas, and examine a number of specific issues. How much natural gas is there in the world, how expensive is it to develop, and at what rate can it be produced? We start from a global perspective, and then look in detail at U.S. natural gas resources, paying particular attention to the extent and cost of shale gas resources, and whether these supplies can be developed and produced in an environmentally sound manner.

Having explored supply volumes and costs, we use integrated models to examine the role that natural gas could play in the energy system under different carbon-constraining mechanisms or policies. It is important to recognize that *the study does not set out to make predictions or forecasts of the likelihood or direction of CO₂ policy in the U.S.* Rather, we examine a number of different scenarios and explore their possible impacts on the future of natural gas supply and demand.

Natural gas is important in many sectors of the economy — for electricity generation, as an industrial heat source and chemical feedstock, and for water and space heating in residential and commercial buildings. Natural gas competes directly with other energy inputs in these sectors. But it is in the electric power sector — where natural gas competes with coal, nuclear, hydro, wind and solar — that inter-fuel competition is most intense. We have, therefore, explored in depth how natural gas performs in the electric power sector under different scenarios. We have also taken a close look at the critical interaction between intermittent forms of renewable energy, such as wind and solar, and gas-fired power as a reliable source of backup capacity.

We look at the drivers of natural gas use in the industrial, commercial and residential sectors, and examine the important question of whether natural gas, in one form or another, could be a viable and efficient substitute for gasoline or diesel in the transportation sector. We also examine the possible futures of global natural gas markets, and the geopolitical significance of the ever-expanding role of natural gas in the global economy. Finally, we make recommendations for research and development priorities and for the means by which public support should be provided.

HIGH-LEVEL FINDINGS

The findings and recommendations of the study are discussed later in this chapter, and covered in detail in the body of this report. Nevertheless, it is worth summarizing here the highest level conclusions of our study:

1. *There are abundant supplies of natural gas in the world*, and many of these supplies can be developed and produced at relatively low cost. In the U.S., despite their relative maturity, natural gas resources continue to grow, and the development of low-cost and abundant unconventional natural gas resources, particularly shale gas, has a material impact on future availability and price.
2. Unlike other fossil fuels, natural gas plays a major role in most sectors of the modern economy — power generation, industrial, commercial and residential. It is clean and flexible. *The role of natural gas in the world is likely to continue to expand under almost all circumstances*, as a result of its availability, its utility and its comparatively low cost.
3. In a carbon-constrained economy, the relative importance of natural gas is likely to increase even further, as it is one of the most cost-effective means by which to maintain energy supplies while reducing CO₂ emissions. This is particularly true in the electric power sector, where, in the U.S., *natural gas sets the cost benchmark against which other clean power sources must compete to remove the marginal ton of CO₂*.
4. In the U.S., a combination of demand reduction and displacement of coal-fired power by gas-fired generation is the lowest-cost way to reduce CO₂ emissions by up to 50%. For more stringent CO₂ emissions reductions, further de-carbonization of the energy sector will be required; but *natural gas provides a cost-effective bridge to such a low-carbon future*.
5. Increased utilization of existing natural gas combined cycle (NGCC) power plants provides a relatively, low-cost short-term opportunity to reduce U.S. CO₂ emissions by up to 20% in the electric power sector, or 8% overall, with minimal additional capital investment in generation and no new technology requirements.
6. Natural gas-fired power *capacity* will play an increasingly important role in providing backup to growing supplies of intermittent renewable energy, in the absence of a breakthrough that provides affordable utility-scale storage. But in most cases, increases in renewable power generation will be at the expense of natural gas-fired power *generation* in the U.S.
7. The current supply outlook for natural gas will contribute to greater competitiveness of U.S. manufacturing, while the use of more efficient technologies could offset increases in demand and provide cost-effective compliance with emerging environmental requirements.
8. Transformation of the current approach to appliance standards to one based on full fuel cycle analysis will enable better comparison of different energy supply options in commercial and residential applications.
9. Natural gas use in the transportation sector is likely to increase, with the primary benefit being reduced oil dependence. Compressed natural gas (CNG) will play a role, particularly for high-mileage fleets, but the advantages of liquid fuel in transportation suggest that *the chemical conversion of gas into some form of liquid fuel may be the best pathway to significant market penetration*.

10. International gas trade continues to grow in scope and scale, but its economic, security and political significance is not yet adequately recognized as an important focus for U.S. energy concerns.
11. Past research, development, demonstration and deployment (RDD&D) programs supported with public funding have led to significant advances for natural gas supply and use.

BACKGROUND

The Fundamental Characteristics of Natural Gas

Fossil fuels occur in each of the three fundamental states of matter: in solid form as coal; in liquid form as oil and in gaseous form as natural gas. These differing physical characteristics for each fuel type play a crucial part in shaping each link in their respective supply chains: from initial resource development and production through transportation, conversion to final products and sale to customers. Their physical form fundamentally shapes the markets for each type of fossil fuel.

Natural gas possesses remarkable qualities. Among the fossil fuels, it has the lowest carbon intensity, emitting less CO₂ per unit of energy generated than other fossil fuels. It burns cleanly and efficiently, with very few non-carbon emissions. Unlike oil, natural gas generally requires limited processing to prepare it for end use. These favorable characteristics have enabled natural gas to penetrate many markets, including domestic and commercial heating, multiple industrial processes and electrical power.

Natural gas also has favorable characteristics with respect to its development and production. The high compressibility and low viscosity of

natural gas allows high recoveries from conventional reservoirs at relatively low cost, and also enables natural gas to be economically recovered from even the most unfavorable subsurface environments, as recent developments in shale formations have demonstrated.

These physical characteristics underpin the current expansion of the unconventional resource base in North America, and the potential for natural gas to displace more carbon-intensive fossil fuels in a carbon-constrained world.

On the other hand, because of its gaseous form and low energy density, natural gas is uniquely disadvantaged in terms of transmission and storage. As a liquid, oil can be readily transported over any distance by a variety of means, and oil transportation costs are generally a small fraction of the overall cost of developing oil fields and delivering oil products to market. This has facilitated the development of a truly global market in oil over the past 40 years or more.

By contrast, the vast majority of natural gas supplies are delivered to market by pipeline, and delivery costs typically represent a relatively large fraction of the total cost in the supply chain. These characteristics have contributed to the evolution of regional markets rather than a truly global market in natural gas. Outside North America, this somewhat inflexible pipeline infrastructure gives strong political and economic power to those countries that control the pipelines. To some degree, the evolution of the spot market in Liquefied Natural Gas (LNG) is beginning to introduce more flexibility into global gas markets and stimulate real global trade. The way this trade may evolve over time is a critical uncertainty that is explored in this report.

The Importance of Natural Gas in the Energy System

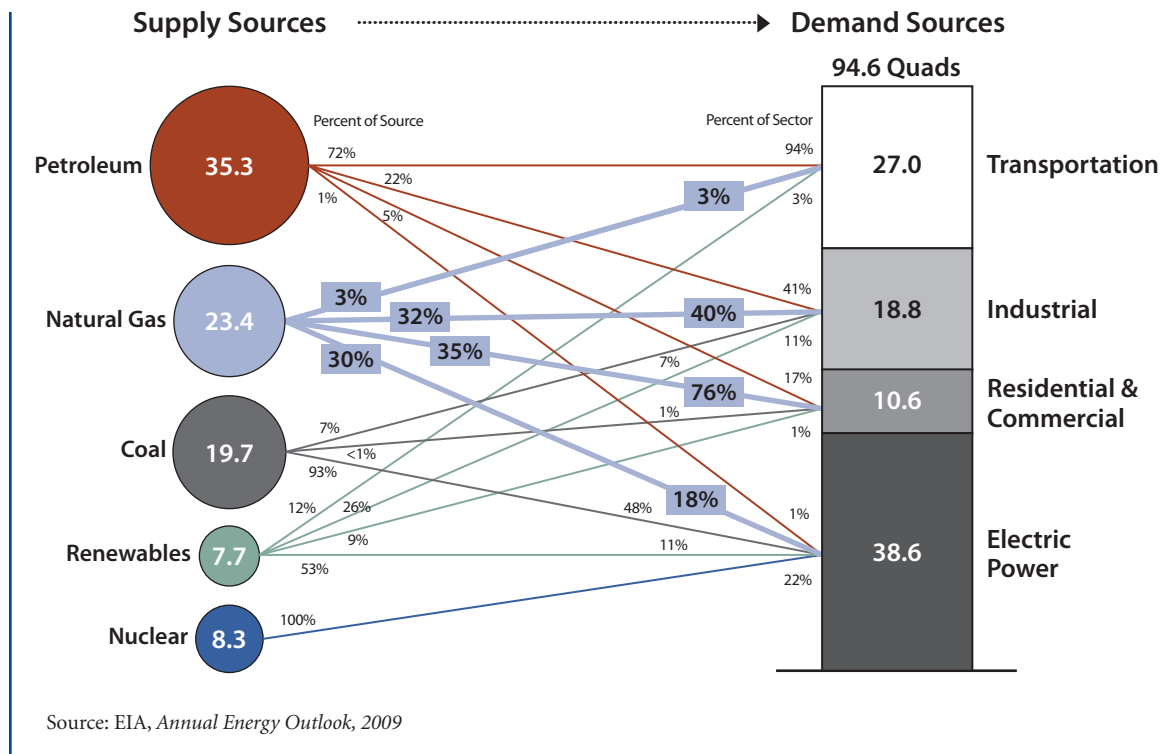
Natural gas represents a very important, and growing, part of the global energy system. Over the past half century, natural gas has gained market share on an almost continuous basis, growing from some 15.6% of global energy consumption in 1965 to around 24% today. In absolute terms, global natural gas consumption over this period has grown from around 23 trillion cubic feet (Tcf) in 1965 to 104 Tcf in 2009, a more than fourfold increase.

Within the U.S. economy, natural gas plays a vital role. Figure 1.1 displays the sources and uses of natural gas in the U.S. in 2009, and it reveals a number of interesting features that are explored in more detail in the body of this report. At 23.4 quadrillion British thermal units (Btu)¹, or approximately 23 Tcf, gas represents a little under a quarter of the total energy supply in the U.S., with almost all of this supply now

coming from indigenous resources. Perhaps of more significance, is the very important role that natural gas plays in all sectors of the economy, with the exception of transport. Very approximately, the use of natural gas is divided evenly between three major sectors: industrial, residential and commercial, and electric power. The 3% share that goes to transport is almost all associated with natural gas use for powering oil and gas pipeline systems, with only a tiny fraction going into vehicle transport.

In the Residential and Commercial sectors, natural gas provides more than three-quarters of the total primary energy, largely as a result of its efficiency, cleanliness and convenience for uses such as space and hot water heating. It is also a major primary energy input into the Industrial sector, and thus the price of natural gas has a very significant impact on the competitiveness of some U.S. manufacturing industries. While natural gas provided 18% of the primary fuel for power generation in 2009,

Figure 1.1 Sources and Use of Primary Energy Sources in the U.S. with Natural Gas Highlighted (quadrillion Btu), 2009



it provided 23% of the produced electricity, reflecting the higher efficiency of natural gas plants. As will be seen later in this report, natural gas-fired capacity represents far more than 23% of total power generating capacity, providing a real opportunity for early action in controlling CO₂ emissions.

A Brief History of Natural Gas in the U.S.

The somewhat erratic history of natural gas in the U.S. over the last three decades or so provides eloquent testimony to the difficulties of forecasting energy futures, particularly for natural gas. It also serves as a reminder of the need for caution in the current period of supply exuberance.

The development of the U.S. natural gas market was facilitated by the emergence of an interstate natural gas pipeline system, supplying local distribution systems. This market structure was initially viewed as a natural monopoly and was subjected to cost-of-service regulation by both the Federal government and the states. Natural gas production and use grew considerably under this framework in the 1950s, 1960s and into the 1970s.

Then came a perception of supply scarcity. After the first oil embargo, energy consumers sought to switch to natural gas. However, the combination of price controls and tightly regulated natural gas markets dampened incentives for domestic gas development, contributing to a perception that U.S. natural gas resources were limited. In 1978, convinced that the U.S. was running out of natural gas, Congress passed the Power Plant and Industrial Fuel Use Act (FUA) that essentially outlawed the building of new gas-fired power plants. Between 1978 and 1987 (the year the FUA was repealed), the U.S. added 172 Gigawatts (GW) of net power generation capacity. Of this, almost 81 GW was new coal capacity, around 26% of today's entire coal fleet. About half of the remainder was nuclear power.

By the mid 1990s, wholesale electricity markets and wellhead natural gas prices had been deregulated; new, highly efficient and relatively inexpensive combined cycle gas turbines had been deployed and new upstream technologies had enabled the development of offshore natural gas resources. This contributed to the perception that domestic natural gas supplies were sufficient to increase the size of the U.S. natural gas market from around 20 Tcf/year to much higher levels. New gas-fired power capacity was added at a rapid pace.

Between 1989 after the repeal of the FUA and 2009, the U.S. added 306 GW of generation capacity, 88% of which was gas fired and 4% was coal fired.² Today, the nameplate capacity of this gas-fired generation is significantly under-utilized, and the anticipated large increase in natural gas use has not materialized.

By the turn of the 21st century, a new set of concerns arose about the adequacy of domestic natural gas supplies. Conventional supplies were in decline, unconventional natural gas resources remained expensive and difficult to develop and overall confidence in gas plummeted. Natural gas prices started to rise, becoming more closely linked to the oil price, which itself was rising. Periods of significant natural gas price volatility were experienced.

This rapid buildup in natural gas price, and perception of long-term shortage, created economic incentives for the accelerated development of an LNG import infrastructure. Since 2000, North America's rated LNG capacity has expanded from approximately 2.3 billion cubic feet (Bcf)/day to 22.7 Bcf/day, around 35% of the nation's average daily requirement.

This expansion of LNG capacity coincided with an overall rise in the natural gas price and the market diffusion of technologies to develop affordable unconventional gas. The game-changing potential of these technologies, combined with the large unconventional

resource base, has become more obvious over the last few years, radically altering the U.S. supply picture. We have once again returned to a period where supply is seen to be abundant. New LNG import capacity goes largely unused at present, although it provides a valuable supply option for the future.

These cycles of perceived “feast and famine” demonstrate the genuine difficulty of forecasting the future and providing appropriate policy support for natural gas production and use. They underpin the efforts of this study to account for this uncertainty in an analytical manner.

Major Uncertainties

Looking forward, we anticipate policy and geopolitics, along with resource economics and technology developments, will continue to play a major role in determining global supply and market structures. Thus, any analysis of the future of natural gas must deal explicitly with multiple uncertainties:

- *The extent and nature of the greenhouse gas (GHG) mitigation measures that will be adopted:* the U.S. legislative response to the climate threat has proved quite challenging. However, the Environmental Protection Agency (EPA) is developing regulations under the Clean Air Act, and a variety of local, state and regional GHG limitation programs have been put in place. At the international level, reliance upon a system of voluntary national pledges of emission reductions by 2020, as set out initially in the Copenhagen Accord, leaves uncertainty concerning the likely structure of any future agreements that may emerge to replace the Kyoto Protocol. The absence of a clear international regime for mitigating GHG emissions in turn raises questions about the likely stringency of national policies in both industrialized countries and major emerging economies over coming decades.
- *The likely technology mix in a carbon-constrained world,* particularly in the power sector: the relative costs of different technologies may shift significantly in response to RD&D, and a CO₂ emissions price will affect the relative costs. Moreover, the technology mix will be affected by regulatory and subsidy measures that will skew economic choices.
- *The ultimate size and production cost of the natural gas resource base,* and the environmental acceptability of production methods: much remains to be learned about the performance of shale gas plays, both in the U.S. and in other parts of the world. Indeed, even higher risk and less well-defined unconventional natural gas resources, such as methane hydrates, could make a contribution to supply in the later decades of the study’s time horizon.
- *The evolution of international natural gas markets:* very large natural gas resources are to be found in several areas outside the U.S., and the role of U.S. natural gas will be influenced by the evolution of this market — particularly the growth and efficiency of trade in LNG. Only a few years back, U.S. industry was investing in facilities for substantial LNG imports. The emergence of the domestic shale gas resource has depressed this business in the U.S., but in the future, the nation may again look to international markets.

Of these uncertainties, the last three can be explored by applying technically grounded analysis: lower cost for carbon capture and sequestration (CCS), renewables and nuclear power; producible resources of different levels and regional versus global integrated markets. In contrast, the shape and size of GHG mitigation measures is likely to be resolved only through complex ongoing political discussions at the national level in the major emitting countries and through multilateral negotiations.

The analysis in this study is based on three policy scenarios:

1. A business-as-usual case, with no significant carbon constraints;
2. GHG emissions pricing, through a cap-and-trade system or emissions tax, leading to a 50% reduction in U.S. emissions below the 2005 level, by 2050.
3. GHG reduction via U.S. regulatory measures without emissions pricing: a renewable portfolio standard and measures forcing the retirement of some coal plants.

Our analysis is long term in nature, with a 2050 time horizon. We do not attempt to make detailed short-term projections of volumes, prices or price volatility, but rather focus on the long-term consequences of the carbon mitigation scenarios outlined above, taking into account the manifold uncertainties in a highly complex and interdependent energy system.

MAJOR FINDINGS AND RECOMMENDATIONS

In the following section we summarize the major findings and recommendations for each chapter of the report.

Supply

Globally, there are abundant supplies of natural gas, much of which can be developed at relatively low cost. The mean projection of remaining recoverable resource in this report is 16,200 Tcf, 150 times current annual global natural gas consumption, with low and high projections of 12,400 Tcf and 20,800 Tcf, respectively. Of the mean projection, approximately 9,000 Tcf could be developed economically with a natural gas price at or below \$4/ Million British thermal units (MMBtu) at the export point.

Unconventional natural gas, and particularly shale gas, will make an important contribution to future U.S. energy supply and CO₂ emission-reduction efforts. Assessments of the recoverable volumes of shale gas in the U.S. have increased dramatically over the last five years, and continue to grow. The mean projection of the recoverable shale gas resource in this report is approximately 650 Tcf, with low and high projections of 420 Tcf and 870 Tcf, respectively. Of the mean projection, approximately 400 Tcf could be economically developed with a natural gas price at or below \$6/MMBtu at the wellhead. While the pace of shale technology development has been very rapid over the past few years, there are still many scientific and technological challenges to overcome before we can be confident that this very large resource base is being developed in an optimum manner.

Although there are large supplies, global conventional natural gas resources are concentrated geographically, with 70% in three countries: Qatar, Iran and Russia. There is considerable potential for unconventional natural gas supply outside North America, but these resources are largely unproven with very high resource uncertainty. Nevertheless, unconventional supplies could provide a major opportunity for diversification and improved security of supply in some parts of the world.

The environmental impacts of shale development are challenging but manageable. Shale development requires large-scale fracturing of the shale formation to induce economic production rates. There has been concern that these fractures can also penetrate shallow freshwater zones and contaminate them with fracturing fluid, but there is no evidence that this is occurring. There is, however, evidence of natural gas migration into freshwater zones in some areas, most likely as a result of sub-standard well completion practices by a few operators. There are additional environmental

challenges in the area of water management, particularly the effective disposal of fracture fluids. Concerns with this issue are particularly acute in regions that have not previously experienced large-scale oil and natural gas development, especially those overlying the massive Marcellus shale, and do not have a well-developed subsurface water disposal infrastructure. It is essential that both large and small companies follow industry best practices; that water supply and disposal are coordinated on a regional basis and that improved methods are developed for recycling of returned fracture fluids.

Natural gas trapped in the ice-like form known as methane hydrate represents a vast potential resource for the long term. Recent research is beginning to provide better definition of the overall resource potential, but many issues remain to be resolved. In particular, while there have been limited production tests, the long-term producibility of methane hydrates remains unproven, and sustained research will be required.

MAJOR RECOMMENDATIONS

Government-supported research on the fundamental challenges of unconventional natural gas development, particularly shale gas, should be greatly increased in scope and scale. In particular, support should be put in place for a comprehensive and integrated research program to build a system-wide understanding of all subsurface aspects of the U.S. shale resource. In addition, research should be pursued to reduce water usage in fracturing and to develop cost-effective water recycling technology.

A concerted coordinated effort by industry and government, both state and Federal, should be organized so as to minimize the environmental impacts of shale gas

development through both research and regulation. Transparency is key, both for fracturing operations and for water management. Better communication of oil- and gas-field best practices should be facilitated. Integrated regional water usage and disposal plans and disclosure of hydraulic fracture fluid components should be required.

The U.S. should support unconventional natural gas development outside U.S., particularly in Europe and China, as a means of diversifying the natural gas supply base.

The U.S. government should continue to sponsor methane hydrate research, with a particular emphasis on the demonstration of production feasibility and economics.

U.S. Natural Gas Production, Use and Trade: Potential Futures

In a carbon-constrained world, a level playing field — a CO₂ emissions price for all fuels without subsidies or other preferential policy treatment — maximizes the value to society of the large U.S. natural gas resource.

Under a scenario with 50% CO₂ reductions to 2050, using an established model of the global economy and natural gas cost curves that include uncertainty, the principal effects of the associated CO₂ emissions price are to lower energy demand and displace coal with natural gas in the electricity sector. *In effect, gas-fired power sets a competitive benchmark against which other technologies must compete in a lower carbon environment.* A major uncertainty that could impact this picture in the longer term is technology development that lowers the costs of alternatives, in particular, renewables, nuclear and CCS.

A more stringent CO₂ reduction of, for example, 80% would probably require the complete de-carbonization of the power sector. This makes it imperative that the development of competing low-carbon technology continues apace, including CCS for both coal and natural gas. It would be a significant error of policy to crowd out the development of other, currently more costly, technologies because of the new assessment of the natural gas supply. Conversely, it would also be a mistake to encourage, via policy and long-term subsidy, more costly technologies to crowd out natural gas in the short to medium term, as this could significantly increase the cost of CO₂ reduction.

The evolution of global natural gas markets is unclear; but under some scenarios, the U.S. could import 50% or more of its natural gas by 2050, despite the significant new resources created in the last few years. Imports can prevent natural gas-price inflation in future years.

MAJOR RECOMMENDATIONS

To maximize the value to society of the substantial U.S. natural gas resource base, U.S. CO₂ reduction policy should be designed to create a “level playing field,” where all energy technologies can compete against each other in an open marketplace conditioned by legislated CO₂ emissions goals. A CO₂ price for all fuels without long-term subsidies or other preferential policy treatment is the most effective way to achieve this result.

In the absence of such policy, interim energy policies should attempt to replicate as closely as possible the major consequences of a “level playing field” approach to carbon-emissions reduction. At least for the near term, that would entail facilitating energy demand reduction and displacement of some coal generation with natural gas.

Natural gas can make an important contribution to GHG reduction in coming decades, but investment in low-emission technologies, such as nuclear, CCS and renewables, should be actively pursued to ensure that a mitigation regime can be sustained in the longer term.

Natural Gas for Electric Power

In the U.S., around 30% of natural gas is consumed in the electric power sector. Within the power sector, gas-fired power plants play a critical role in the provision of peaking capacity, due to their inherent ability to respond rapidly to changes in demand. In 2009, 23% of the total power generated was from natural gas, while natural gas plants represented over 40% of the total generating capacity.

In a carbon-constrained world, the power sector represents the best opportunity for a significant increase in natural gas demand, in direct competition with other primary energy sources. Displacement of coal-fired power by gas-fired power over the next 25 to 30 years is the most cost-effective way of reducing CO₂ emissions in the power sector.

As a result of the boom in the construction of gas-fired power plants in the 1990s, there is a substantial amount of underutilized NGCC capacity in the U.S. today. In the short term, displacement of coal-fired power by gas-fired power provides an opportunity to reduce CO₂ emissions from the power sector by about 20%, at a cost of less than \$20/ton of CO₂ avoided. This displacement would use existing generating capacity, and would, therefore, require little in the way of incremental capital expenditure for new generation capacity. It would also significantly reduce pollutants such as sulfur dioxide (SO₂), nitrous oxide (NO_x), particulates and mercury (Hg).

Natural gas-fired power generation provides the major source of backup to intermittent renewable supplies in most U.S. markets. If policy support continues to increase the supply of intermittent power, then, in the absence of affordable utility-scale storage options, additional natural gas *capacity* will be needed to provide system reliability. In some markets, existing regulation does not provide the appropriate incentives to build incremental capacity with low load factors, and regulatory changes may be required.

In the short term, where a rapid increase in renewable generation occurs without any adjustment to the rest of the system, increased renewable power displaces gas-fired power generation and thus reduces demand for natural gas in the power sector. In the longer term, where the overall system can adjust through plant retirements and new construction, increased renewables displace baseload generation. This could mean displacement of coal, nuclear or NGCC generation, depending on the region and policy scenario under consideration. For example, in the 50% CO₂ reduction scenario described earlier, where gas-fired generation drives out coal generation, increased renewable penetration as a result of cost reduction or government policy will reduce natural gas generation on a nearly one-for-one basis.

MAJOR RECOMMENDATIONS

The displacement of coal generation with NGCC generation should be pursued as the most practical near-term option for significantly reducing CO₂ emissions from power generation.

In the event of a significant penetration of intermittent renewable production in the generation technology mix, policy and regulatory measures should be developed to facilitate adequate levels of investment in natural gas generation capacity to ensure system reliability and efficiency.

END USE GAS DEMAND

In the U.S., around 32% of all natural gas consumption is in the Industrial sector, where its primary uses are for boiler fuel and process heat; and 35% of use is in the Residential and Commercial sectors, where its primary application is space heating. Only 0.15% of natural gas is used as a vehicle transportation fuel.

Industrial, Commercial and Residential

Within the Industrial sector, there are opportunities for improved efficiency of the Industrial boiler fleet, replacing less-efficient natural gas boilers with high-efficiency, or super-high efficiency boilers with conversion efficiencies up to 94%. There are also opportunities to improve the efficiency of natural gas use in process heating and to reduce process heating requirements through changes in process technologies and material substitutions.

Our analysis suggests that conversion of coal-fired boilers in the Industrial sector to high-efficiency gas boilers could provide a cost-effective option for compliance with new hazardous air pollutant reductions and create significant CO₂ reduction opportunities at modest cost, with a potential to increase natural gas demand by up to 0.9 Tcf/year.

Natural gas and natural gas liquids (NGLs) are a principal feedstock in the chemicals industry and a growing source of hydrogen production for petroleum refining. Our analysis of selected cases indicates that a robust domestic market for natural gas and NGLs will improve the competitiveness of manufacturing industries dependent on these inputs.

Natural gas has significant advantages in the Residential and Commercial sectors due in part to its cleanliness and life cycle energy efficiency. However, understanding the comparative cost-effectiveness and CO₂ impacts of different energy options is complex. Comparison of

end use or “site” energy efficiencies can be misleading, since it does not take into account full system energy use and emissions (such as the efficiency and emissions of electricity generation). However, quantitatively accounting for the full system impacts from the “source” can be challenging, requiring a complex end-to-end, full fuel cycle (FFC) analysis that is not generally available to the consumer or to the policy maker.

Consumer and policy maker choices are further complicated by the influence of local climatic conditions and regional energy markets. The primary energy mix of the regional generation mix fundamentally affects “site versus source” energy and emissions comparisons. And the local climate has a major influence on the best choice of heating and cooling systems, particularly the appropriate use of modern space conditioning technologies such as heat pumps. Consumer information currently available to consumers does not facilitate well-informed decision making.

Expanded use of combined heat and power (CHP) has considerable potential in the Industrial and large Commercial sectors. However, cost, complexity and the inherent difficulty of balancing heat and power loads at a very small scale make residential CHP a much more difficult proposition.

MAJOR RECOMMENDATIONS

Improved energy efficiency metrics, which allow consumers to accurately compare direct fuel and electricity end uses on a full fuel cycle basis, should be developed.

Over time, these metrics should be tailored to account for geographical variations in the sources of electric power supply and local climate conditions.

Transportation

The ample domestic supply of natural gas has stimulated interest in its use in transportation. There are multiple drivers: the oil-natural gas price spread on an energy basis generally favors natural gas, and today that spread is at historically high levels; an opportunity to lessen oil dependence in favor of a domestically supplied fuel, including natural gas-derived liquid fuels with modest changes in vehicle and/or infrastructure requirements and reduced CO₂ emissions in direct use of natural gas.

Compressed natural gas (CNG) offers a significant opportunity in U.S. heavy-duty vehicles used for short-range operation (buses, garbage trucks, delivery trucks), where payback times are around three years or less and infrastructure issues do not impede development. However, for light passenger vehicles, even at 2010 oil-natural gas price differentials, high incremental costs of CNG vehicles lead to long payback times for the average driver, so significant penetration of CNG into the passenger fleet is unlikely in the short term. Payback periods could be reduced significantly if the cost of conversion from gasoline to CNG could be reduced to the levels experienced in other parts of the world such as Europe.

LNG has been considered as a transport fuel, particularly in the long-haul trucking sector. However, as a result of operational and infrastructure considerations as well as high incremental costs and an adverse impact on resale value, LNG does not appear to be an attractive option for general use. There may be an opportunity for LNG in the rapidly expanding segment of hub-to-hub trucking operations, where infrastructure and operational challenges can be overcome.

Energy density, ease of use and infrastructure considerations make liquid fuels that are stable at room temperature a compelling choice in the Transportation sector. The chemical conversion of natural gas to liquid fuels could provide an attractive alternative to CNG. Several pathways are possible, with different options yielding different outcomes in terms of total system CO₂ emissions and cost. Conversion of natural gas to methanol, as widely practiced in the chemicals industry, could provide a cost-effective route to manufacturing an alternative, or supplement, to gasoline, while keeping CO₂ emissions at roughly the same level. Gasoline engines can be modified to run on methanol at modest cost.

MAJOR RECOMMENDATIONS

The U.S. government should consider revision to its policies related to CNG vehicles, including how aftermarket CNG conversions are certified, with a view to reducing up-front costs and facilitating CNG-gasoline capacity.

The U.S. government should implement an open fuel standard that requires automobile manufacturers to provide tri-flex fuel (gasoline, ethanol and methanol) operation in light-duty vehicles. Support for methanol fueling infrastructure should also be considered.

Infrastructure

The continental U.S. has a vast, mature and robust natural gas infrastructure, which includes: over 300,000 miles of transmission lines; numerous natural gas-gathering systems; storage sites; processing plants; distribution pipelines and LNG import terminals.

Several trends are having an impact on natural gas infrastructure. These include changes in

U.S. production profiles, with supplies generally shifting from offshore Gulf of Mexico back to onshore; shifts in U.S. population, generally from the Northeast and Midwest to the South and West and growth in global LNG markets, driven by price differences between regional markets.

The system generally responds well to market signals. Changing patterns of supply and demand have led to a significant increase in infrastructure development over the past few years with West to East expansions dominating pipeline capacity additions. Infrastructure limitations can temporarily constrain production in emerging production areas such as the Marcellus shale — but infrastructure capacity expansions are planned or underway. Demand increases and shifts in consumption and production are expected to require around \$210 billion in infrastructure investment over the next 20 years.

Much of the U.S. pipeline infrastructure is old — around 25% of U.S. natural gas pipelines are 50 years old or older — and recent incidents demonstrate that pipeline safety issues are a cause for concern. The Department of Transportation (DOT) regulates natural gas pipeline safety and has required integrity management programs for transmission and distribution pipelines. The DOT also supports a small pipeline safety research program, which seems inadequate given the size and age of the pipeline infrastructure.

Increased use of natural gas for power generation has important implications for both natural gas and electric infrastructures, including natural gas storage. Historically, injections and withdrawals from natural gas storage have been seasonal. Increased use of natural gas for power generation may require new high-deliverability natural gas storage to meet more variable needs associated with power generation.

MAJOR RECOMMENDATIONS

Analysis of the infrastructure demands associated with potential shift from coal to gas-fired power should be undertaken.

Pipeline safety technologies should be included in natural gas RD&D programs.

END USE EMISSIONS VERSUS SYSTEM-WIDE EMISSIONS

When comparing GHG emissions for different energy sources, attention should be paid to the entire system. In particular, the potential for leakage of small amounts of methane in the production, treatment and distribution of coal, oil and natural gas has an effect on the total GHG impact of each fuel type. The modeling analysis in Chapter 3 addresses the system-wide impact, incorporating methane leakage from coal, oil and natural gas production, processing and transmission. In Chapter 5 we do not attempt to present detailed full-system accounting of CO₂ (equivalent) emissions for various end uses, although we do refer to its potential impact in specific instances.

The CO₂ equivalence of methane is conventionally based on a Global Warming Potential (GWP)³ intended to capture the fact that each GHG has different radiative effects on climate and different lifetimes in the atmosphere. In our considerations, we follow the standard Intergovernmental Panel on Climate Change (IPCC) and EPA definition that has been widely employed for 20 years. Several recently published life cycle emissions analyses do not appear to be comprehensive, use common assumptions or recognize the progress made by producers to reduce methane emissions, often to economic benefit. We believe that a lot more work is required in this area before a common understanding can be reached. Further discussion can be found in Appendix 1A.

MAJOR RECOMMENDATIONS

The EPA and the U.S. Department of Energy (DOE) should co-lead a new effort to review, and update as appropriate, the methane emission factors associated with natural gas production, transmission, storage and distribution. The review should have broad-based stakeholder involvement and should seek to reach a consensus on the appropriate methodology for estimating methane emissions rates. The analysis should, to the extent possible: (a) reflect actual emissions measurements; (b) address fugitive emissions for coal and oil as well as natural gas; and (c) reflect the potential for cost-effective actions to prevent fugitive emissions and venting of methane.

MARKETS AND GEOPOLITICS

The physical characteristics of natural gas, which create a strong dependence on pipeline transportation systems, have led to local markets for natural gas – in contrast to the global markets for oil.

There are three distinct regional gas markets: North America, Europe and Asia, with more localized markets elsewhere. The U.S. gas market is mature and sophisticated, and functions well, with a robust spot market. Within the U.S. market, the price of oil, (which is set globally) compared to the price of natural gas (which is set regionally) is very important in determining market share when there is the opportunity for substitution. Over the last decade or so, when oil prices have been high, the ratio of the benchmark West Texas Intermediate oil price to the Henry Hub natural gas price has been consistently higher than any of the standard rules of thumb.

International natural gas markets are in the early stages of integration, with many impediments to further development. While increased LNG trade has started to connect these markets, they remain largely distinct with respect to supply patterns, pricing and contract structures, and market regulation. If a more integrated market evolves, with nations pursuing gas production and trade on an economic basis, there will be rising trade among the current regional markets and the U.S. could become a substantial net importer of LNG in future decades.

Greater international market liquidity would be beneficial to U.S. interests. U.S. prices for natural gas would be lower than under current regional markets, leading to more gas use in the U.S. Greater market liquidity would also contribute to security by enhancing diversity of global supply and resilience to supply disruptions for the U.S. and its allies. These factors ameliorate security concerns about import dependence.

As a result of the significant concentration of conventional gas resources globally, policy and geopolitics play a major role in the development of global supply and market structures. Consequently, since natural gas is likely to play a greater role around the world, natural gas issues will appear more frequently on the U.S. energy and security agenda. Some of the specific security concerns are:

- Natural gas dependence, including that of allies, could constrain U.S. foreign policy options, especially in light of the unique American international security responsibilities.
- New market players could introduce impediments to the development of transparent markets.
- Competition for control of natural gas pipelines and pipeline routes is intense in key regions.
- Longer supply chains increase the vulnerability of the natural gas infrastructure.

MAJOR RECOMMENDATIONS

The U.S. should pursue policies that encourage the development of an efficient and integrated global gas market with transparency and diversity of supply.

Natural gas issues should be fully integrated into the U.S. energy and security agenda, and a number of domestic and foreign policy measure should be taken, including:

- **integrating energy issues fully into the conduct of U.S. foreign policy, which will require multiagency coordination with leadership from the Executive Office of the President;**
 - **supporting the efforts of the International Energy Agency (IEA) to place more attention on natural gas and to incorporate the large emerging markets (such as China, India and Brazil) into the IEA process as integral participants;**
 - **sharing know-how for the strategic expansion of unconventional resources; and**
 - **advancing infrastructure physical- and cyber-security as the global gas delivery system becomes more extended and interconnected.**
-

RD&D

There are numerous RD&D opportunities to address key objectives for natural gas supply, delivery and end use:

- improve the long-term economics of resource development as an important contributor to the public good;
- reduce the environmental footprint of natural gas production, delivery and use;
- expand current use and create alternative applications for public policy purposes, such as emissions reductions and diminished oil dependence;
- improve safety and operation of natural gas infrastructure;
- improve the efficiency of natural gas conversion and end-use so as to use the resource most effectively.

Historically, RD&D funding in the natural gas industry has come from a variety of sources, including private industry, the DOE, and private/public partnerships. In tandem with limited tax credits, this combination of support played a major role in development of unconventional gas. It has also contributed to more efficient end-use, for example in the development of high-efficiency gas turbines.

Today government funded RD&D for natural gas is at very low levels. The elimination of rate-payer funded RD&D has not been compensated by increased DOE appropriations or by a commensurate new revenue stream outside the appropriations process. The total public and public-private funding for natural gas research is down substantially from its peak and is more limited in scope, even as natural gas takes a more prominent role in a carbon-constrained world.

While natural gas can provide a cost-effective bridge to a low carbon future, it is vital that efforts continue to improve the cost and efficiency of low or zero carbon technologies for the longer term. This will require sustained RD&D and subsidies of limited duration to encourage early deployment.

MAJOR RECOMMENDATIONS

The Administration and Congress should support RD&D focused on environmentally responsible domestic natural gas supply. This should entail both a renewed DOE program, weighted towards basic research, and a complementary industry-led program, weighted towards applied research, development and demonstration, that is funded through an assured funding stream tied to energy production, delivery and use. The scope of the program should be broad, from supply to end-use.

Support should be provided through RD&D, and targeted subsidies of limited duration, for low-emission technologies that have the prospect of competing in the long run. This would include renewables, carbon capture and sequestration for both coal and gas generation, and nuclear power.

CONCLUSION

Over the past few years, the U.S. has developed an important new natural gas resource that fundamentally enhances the nation's long-term gas supply outlook. Given an appropriate regulatory environment, which seeks to place all lower carbon energy sources on a level competitive playing field, domestic supplies of natural gas can play a very significant role in reducing U.S. CO₂ emissions, particularly in the electric power sector. This lowest cost strategy of CO₂ reduction allows time for the continued development of more cost-effective low or zero carbon energy technology for the longer term, when gas itself is no longer sufficiently low carbon to meet more stringent CO₂ reduction targets. The newly realized abundance of low cost gas provides an enormous potential benefit to the nation, providing a cost effective bridge to a secure and low carbon future. It is critical that the additional time created by this new resource is spent wisely, in creating lower cost technology options for the longer term, and thereby ensuring that the natural gas bridge has a safe landing place in a low carbon future.

NOTES

¹One quadrillion Btu (or “quad”) is 10¹⁵ or 1,000,000,000,000,000 British thermal units. Since one standard cubic foot of gas is approximately 1,000 Btu, then 1 quad is approximately 1 Tcf of gas.

²EIA 2009 Annual Energy Review, Figure 45.

³Global-warming potential (GWP) is a relative measure of how much heat a given greenhouse gas traps in the atmosphere.