# Executive Summary

During the past decade, the U.S. has experienced a surplus gas supply. Future prospects are brightening because of increased estimates of the potential size of undiscovered gas reserves. At the same time, U.S. oil reserves and production have steadily declined, while oil imports have steadily increased.

Reducing volume growth of crude oil imports was a key objective of the Energy Policy Act of 1992. Natural gas could be an important alternative energy source to liquid products derived from crude oil to help meet market demand. The purpose of this study was to (1) analyze three energy markets to determine whether greater use could be made of natural gas or its derivatives and (2) determine whether those products could be provided on an economically competitive basis. The following three markets were targeted for possible increases in gas use: transportation fuels, power generation, and chemical feedstock.

Gas-derived products that could potentially compete in these three markets were identified, and the economics of the processes for producing those products were evaluated. The processes considered covered the range from commercial to those in early stages of process development. The analysis also evaluated the use of both high-quality natural gas and lower-quality gases containing $CO_2$ and $N_2$ levels above normal pipeline quality standards.

## Gas Supply and Utilization

The U.S's gas-supply surplus of the past decade is slowly disappearing as the new reserve addition rate has almost kept pace with the annual depletion rate caused by consumption. The strong reserve addition rate that has maintained the supply surplus has occurred in a weak gas-price market. Future gas supply and pricing have significant implications for where energy research and development (R&D) dollars should be allocated. Current and future relative prices of natural gas, crude oil, and coal are important for today's energy use decisions and tomorrow's considerations of substituting coal- and gas-derived liquid products in applications that currently use products derived from crude oil.

This report's economic analyses are based on price forecasts developed by the U.S. Department of Energy/Energy Information Administration (DOE/EIA); they predict that U.S. gas prices will rise faster than oil prices from now until the year 2010 (Exhibit ES-1). A forecast of higher price growth for natural gas versus crude oil means that, for a gas-to-liquid conversion process, the feedstock cost would increase more rapidly than the price of the product.

An alternative scenario with high crude-oil prices in the future would be an environment in which processes for converting gas or coal to liquids begin to look attractive. Most of the energy forecasting community has been lowering their estimates of long-range crude prices in recent

**Exhibit ES-1. Price Forecasts for U.S. Oil and Natural Gas**

| Forecast | Price (in 1994 US$) | | | Growth Rate (%) |
|---|---|---|---|---|
| | 1993 | 2000 | 2010 | 1993-2010 |
| 1994 DOE Outlook | | | | |
| Gas ($/MCF) | 1.79 | 2.48 | 3.56 | 4.1 |
| Oil ($/bbl) | 18.65 | 21.25 | 28.88 | 2.6 |
| 1995 DOE Outlook | | | | |
| Gas ($/MCF) | 2.02 | 2.29 | 3.37 | 3.1 |
| Oil ($/bbl) | 16.12 | 19.13 | 24.12 | 2.4 |
| 1995 GRI Forecast | | | | |
| Gas ($/MCF) | 2.06 | 2.53 | 2.71 | 1.6 |
| Oil ($/bbl) | 16.42 | 18.58 | 20.54 | 1.3 |

years. Forecasts, however, contain much uncertainty. Government-funded R&D is not directed solely at preparing for the most likely future; the Government must also commit resources to preparing for the less likely outcomes that may occur. In this case, the need is to prepare for a possible significant increase in crude oil price and a larger price differential versus U.S. gas. The probability of a high crude-price scenario should affect the level of resource commitment to gas-to-liquids R&D. Clearly, the probability of high crude prices has diminished.

The U.S. gas supply outlook is optimistic. In its 1995 U.S. Energy Supply and Demand analysis, the Gas Research Institute (GRI) estimates that the volume of reserve needed to meet consumption through the year 2010 can be added with little price increase. Previous GRI assessments showed significant price increases would be required. GRI bases its outlook on improvements in technology expected in the coming decade.

## Analysis of Gas-Derived Products in Transportation Fuels Markets

Three types of products derived from natural gas can be used in the transportation fuels market (Exhibit ES-2). Natural gas is currently used in the production of MTBE, an ether and oxygenate, used as a blend component in producing gasoline because of its high octane properties and ability to meet the Clean Air Act Amendments of 1990 (CAAA) oxygen-content standard for gasoline that about one-third of the U.S. market requires. Other ethers and alcohols could potentially be produced from natural gas and compete in the gasoline market. While oxygenates command a price premium compared with other gasoline components, the volumes required are limited by octane need and oxygen-content requirements as specified by environmental regulations.

Natural gas can also be used to produce synthetic gasoline and diesel for which there is obviously a large market. In this case, the issue is the price competitiveness of gas-derived gasoline and diesel versus products derived from crude oil. The final avenue of access is production of alternative transportation fuels, primarily methanol and CNG.

**Exhibit ES-2. Assessment of Increased Gas Use in the Transportation Fuels Market**

| Fuel Type | Gas-Derived Products | Market Penetration | Market Size |
|---|---|---|---|
| Gasoline blend components | MTBE, Other ethers, Alcohols | Easy | Limited by need for oxygenates |
| Gasoline and diesel | Synthesized gasoline and diesel | Easy if price is competitive | Large |
| Alternative transportation fuels | Methanol, Compressed natural gas (CNG) | Difficult | Large but difficult to penetrate |

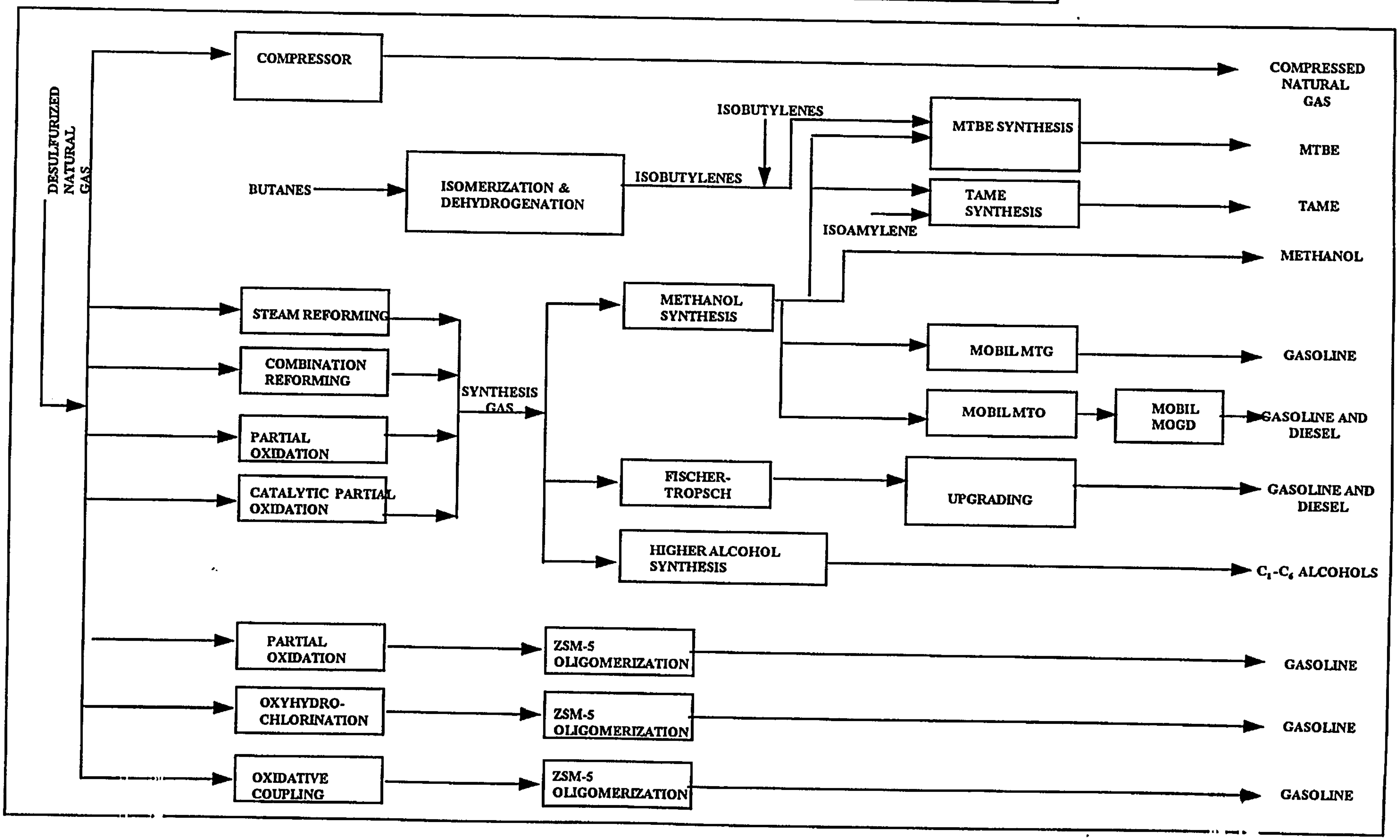
Even if the alternative transportation fuels can be produced at prices competitive with gasoline and diesel fuel, they face major hurdles in gaining entry and acceptance in that market.

Ideally, an alternative-fueled vehicle would be an original equipment vehicle/engine system optimized to use the specific fuel. During the transition period of establishing use of the fuel, existing gasoline or diesel vehicles can sometimes be converted to using the alternative fuel, such as methanol or CNG. Vehicles can also be designed to use either of two fuels (bi-fueled) or a combination (flexible-fueled). These types of vehicles are designed to help consumers cope with the problem of finding fuel while the distribution and fueling station infrastructure is growing. Finally, a new fuel must gain acceptance, which depends on how consumers compare the alternatively-fueled vehicle's economics, convenience, performance, and safety with conventionally-fueled vehicles.

## Economic Evaluation of Gas to Transportation Fuel Conversion Process

Process routes for natural gas to transportation fuel processes are shown in Exhibit ES-3. The economic evaluation for these processes was done using data taken from various economic studies. Only Fischer-Tropsch (FT) and oxidative coupling economic data were available from a common source. Since each data source used somewhat different factors to determine total capital and total operating and maintenance costs, it was decided to accept certain basic data from the economic sources and calculate the remaining economics using a consistent methodology. All costs were escalated to December 1993 using Nelson-Farrar Indexes reported in the *Oil and Gas Journal*. Estimates of future gas prices were based on the 1994 EIA outlook (see Exhibit ES-1). The GRI forecast, which estimates a lower price-growth rate, was used in sensitivity analysis studies.

## EXHIBIT ES-3
## CONVERSION OF NATURAL GAS TO TRANSPORTATION FUELS



A summary of the economic analysis of converting natural gas to transportation fuels is shown in Exhibit ES-4. Converting natural gas to methanol and MTBE involves commercial processes, and various facilities have been built where products are being produced and marketed at competitive prices. The cost of producing MTBE from natural gas and n-butane was evaluated and estimated at 86 cents per gallon (cpg). Analysis of the gasoline market shows that MTBE can command a price premium of 30-40 cpg over refinery gasoline gate prices. Thus, MTBE is clearly commercially viable at current gasoline prices, and its competitiveness should continue in the future.

**Exhibit ES-4. Comparative Economics of Gas to Transportation Fuel Processes**

| Process | Liquid phase methanol | UOP - MTBE | IFP higher alcohol | Fischer-Tropsch | Oxidative coupling | Delivered CNG |
|---|---|---|---|---|---|---|
| Product | Methanol | MTBE | C1-C6 alcohol | Gasoline or diesel | Gasoline | CNG |
| Costs (cpg) | | | | | | |
| Feed | 24 | 51 | 36 | 52 | 52 | 48 |
| Other operating | 7 | 17 | 22 | 28 | 43 | 11 |
| Capital | 12 | 14 | 43 | 58 | 67 | 7 |
| Total | 44 | 86 | 120 | 137 | 169 | 73 |
| Equivalent gasoline (cpg) | 74 | NA | NA | 137 | 169 | 73 |
| Competing fuels | Gasoline | Octane blend compnts. | Gasoline blend compnts. | Gasoline | Gasoline | Delivered gasoline |
| Competing fuel price (cpg) | 68 | 98 | 68-98 | 68 | 68 | 84 |

The economic analysis estimated that methanol can be produced from continental U.S. gas at 44 cpg. Viewing methanol as an alternative transportation fuel, the 44 cpg must be translated to an equivalent gasoline basis, accounting for energy density and efficiency differences. On a gasoline-equivalent basis, methanol would be 74 cpg at the plant gate versus 68 cpg for gasoline. Although not a large differential, an even slightly higher price, combined with the formidable hurdles of developing distribution and refueling infrastructure and gaining consumer acceptance, is a major obstacle on the path to commercial success for methanol.

The demonstrated processes are those that have been built at commercial scale and for which cost and technical feasibility have been demonstrated. Conversion of natural gas to liquids using FT is placed in this category. While there are no operating FT gas-to-liquid plants, there are commercial FT units for converting syngas from coal gasification and commercial units for generating syngas from natural gas. The estimated cost of producing liquid fuels from natural gas using a FT process is 1.37 $/gal. (double the current price of gasoline). If gas prices rise faster than crude, the gap between the cost of producing FT liquids and gasoline would only widen. The economic hope for a FT process using natural gas may lie with utilizing remote gas resources. The processes analyzed in this study that are in the R&D phase include producing higher alcohols from natural gas and oxidative coupling, a direct methane to gasoline process. Using conversion and selectivity assumptions for oxidative coupling previously used in a Bechtel analysis, the cost of producing a gasoline product would be 1.69 $/gal. This cost far exceeds current gasoline prices. Moreover, review of various oxidative coupling research results indicates that the conversion and selectivity assumed in the Bechtel economic analysis are beyond those that have practically been achieved.

Several processes continue to be studied to convert natural gas to $C_1$-$C_6$ alcohols. In this study, economics were developed for the IFP process and the estimated cost of the product was 1.20 $/gal. While the higher alcohols merit a market price premium over gasoline, the IFP alcohol product consists of 50-70% methanol and 16-23% ethanol. Because of such poor selectivity to higher alcohols, the process appears economically unattractive. In this process, as in the case of oxidative coupling, the question is whether there is sufficient reason to believe that a *major* process improvement is achievable that can justify further R&D expenditures.

The most cost competitive of the alternative transportation fuels is CNG. As shown in Exhibit ES-4, CNG can be supplied to the motoring public in many parts of the U.S. at a price less than gasoline on a gasoline equivalent basis. CNG has good engine performance and substantial elements of a delivery infrastructure. The problems with gas is that it is a *gas*. Compared to gasoline, CNG fuel to drive an equivalent distance occupies four-to-five times the space needed by gasoline. Thus, larger fuel tanks are required. Perceptions about safety may also pose a problem because a gas seems inherently more dangerous to many people than does a liquid fuel, particularly when the gas is under considerable pressure.

Recently, considerable interest has been generated about the possible use of DME (dimethyl ether) as an alternative diesel fuel. In contrast to MTBE and TAME, DME has a high cetane number rather than a high octane number; hence, it is a compression ignition fuel. The cost of producing DME was not evaluated in this study but the process developer has claimed costs similar to methanol. The most interesting aspect of DME is its attractive emissions performance attributes. In sharp contrast to diesel, which has a particulate emissions problem, combustion of DME produces virtually no particulates.

## Economics and Use of Gas in Chemical Feedstock and Power Generation Markets

Use of natural gas in chemical feedstock and power generation applications is established. This study analyzed the market for chemical products to assess demand growth and the potential for increased gas usage. Likewise, the issue of increased natural gas use in the power sector was addressed. For each application, use of low-quality natural gas (LQNG) was also compared with use of high-quality natural gas (HQNG).

Principal uses of natural gas in the chemical feedstocks market are in the production of ammonia, methanol and hydrogen (Exhibit ES-5). The most promising growth area for increased gas usage is in methanol production. U.S. methanol consumption in 1991 was 1.68 billion gallons; in 1995, it is expected to reach 2.75 billion gallons. This growth is primarily attributable to the increased use of methanol to produce MTBE for use in making oxygenated and reformulated gasoline. The high rate of methanol demand growth will diminish after 1995. Use of methanol as a direct transportation fuel is an uncertain factor in assessing long- term demand prospects.

**Exhibit ES-5. Use of Natural Gas as a Chemical Feedstock**

| % of Total Natural Gas Consumed as Feedstock | Material Produced | Product Use | U.S. Market Growth |
|---|---|---|---|
| 60 | Ammonia | Fertilizer | Very Low |
| 22 | Hydrogen and other | Oil refining | Moderate |
| 18 | Methanol | Transportation fuels and chemicals | High |

Ammonia production currently accounts for 60% of natural gas used as chemical feedstock. U.S. demand, however, has been stagnant, along with the continued threat of foreign competition from low gas-price regions throughout the world. Because of the small chance for ammonia production capacity growth in the U.S., little opportunity for increased use of natural gas is apparent.

The process conversion routes from natural gas to chemical and power market inputs are shown in Exhibit ES-6 and the economics are summarized in Exhibit ES-7. As can be seen, using high-quality gas as process feed, methanol can be produced at a cost well below current market price, but the market is currently tight and prices are at the height of a short-term spike. More importantly, future prices are expected to support an acceptable return on investment. On the other hand, ammonia prices, which are currently high, still do not cover the return to capital. Market growth and U.S. facility economics provide a consistently bleak outlook for increasing use of natural gas for ammonia production.

Use of gas is increasing as a fuel for power generation due to favorable economics, a 3.7 cent per kilowatt hour cost, supports that growth.

## Economics of Using Low-Quality Natural Gas

In all of these cases, LQNG and HQNG were compared for use as a feed. The LQNG considered contained 13% $N_2$. A high nitrogen gas was analyzed because it is most costly to upgrade a low-quality gas with high nitrogen content. In the methanol case, assuming the methanol product would sell at the same price whether using the LQNG or HQNG feed, comparative values of the LQNG and HQNG would be 2.27 $/MMBTU and 2.43 $/MMBTU, respectively. In the ammonia

## EXHIBIT ES-6
## CONVERSION OF NATURAL GAS TO CHEMICALS AND POWER

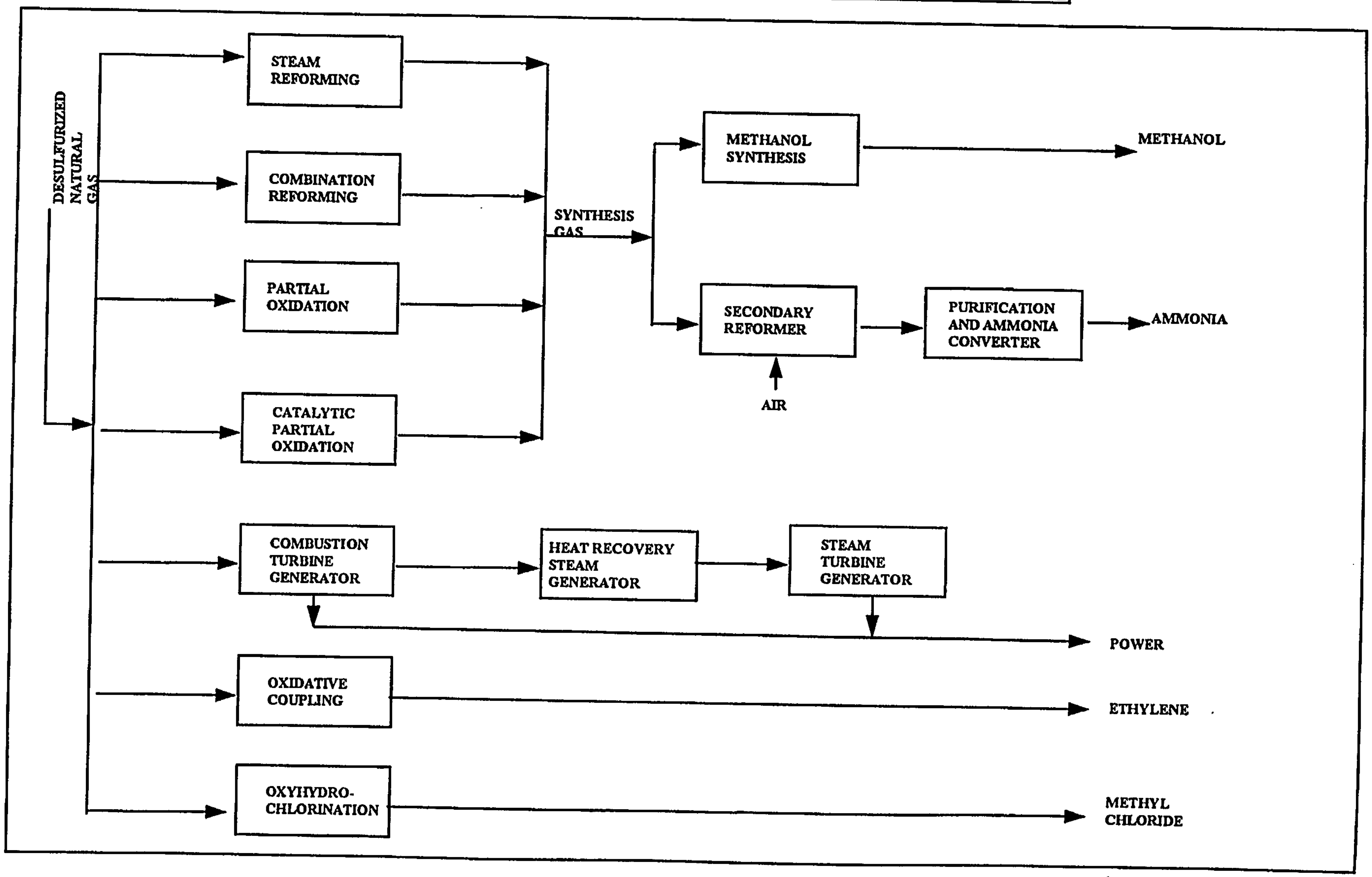


**Exhibit ES-7. Economic Comparison of Natural Gas in Chemical and Power Processes**

| Process | Liquid-phase Methanol | | Ammonia | | Combined cycle | | Cryogenic nitrogen production |
|---|---|---|---|---|---|---|---|
| Product | Methanol | | Ammonia | | Electric Power | | HQNG |
| Type of natural gas feed | High quality | Low quality | High quality | Low quality | High quality | Low quality | Low quality |
| Costs ($/unit product) | | | | | | | |
| Unit name | Gallon | Gallon | Short ton | Short ton | kWh | kWh | $10^6$ Btu |
| Feed | 0.24 | 0.24 | 50 | 46 | 0.019 | 0.018 | 1.58 |
| Other operating | 0.07 | 0.07 | 80 | 83 | 0.005 | 0.006 | 0.31 |
| Capital | 0.12 | 0.12 | 57 | 59 | 0.011 | 0.012 | 0.24 |
| Total | 0.44 | 0.44 | 240 | 240 | 0.037 | 0.037 | 2.43 |
| Value of natural gas feed ($/$10^6$ Btu) | 2.43 | 2.27* | 2.43 | 2.24* | 2.43 | 2.32* | 1.71* |
| Product's market price range, 10/93-10/94 ($/unit) | 0.46-1.40 | | 104-232 | | 0.046-0.052 | | 2.43 |

* Assumes product will have same price it would if produced from HQNG.

case, the values are 2.24 $/MMBTU and 2.43 $/MMBTU, respectively. In the combined-cycle case, the LQNG value is 2.32 $/MMBTU, a range of 0.11 $/MMBTU-0.19 $/MMBTU lower than the HQNG value. These values compare favorably to the cost of upgrading the LQNG via nitrogen rejection, which would place a value of only 1.71 $/MMBTU on the LQNG. Results that make direct use of LQNG appear to be the path to pursue. However, an important element of the economics not considered is LQNG transport to the production facility and product transport to customers. In the case of power, it is expensive to transport if it cannot be marketed locally. In the case of ammonia, no new production facilities are needed. In the case of methanol, the product is needed in the Gulf Coast region, where high $N_2$ gas production is low.

Thus, the economics of LQNG look favorable, but location of market and production facilities limits opportunities.

## Improving Process Economics and Market Potential

The economic analysis serves two purposes. First, it shows the relative cost of providing products using competing process options. Second, it establishes the sensitivity of the production costs to changes in the cost of feed, reductions in capital cost, or improvements in conversion rates or selectivity.

Selected sensitivity analysis cases for FT are displayed in Exhibit ES-8. The exhibit shows that use of a slurry reactor reduces product cost 2 $/bbl. GRI price growth versus DOE price forecast would reduce the initial product cost by 4.60 $/bbl. Large differences are achieved if the technology is used in a remote gas area where facility construction costs are comparable to those of the U.S. With gas prices at 0.50 $/MMBTU, production cost would be 36 $/bbl; if plant size were scaled up four times, price could be reduced to 25 $/bbl.

Such indirect conversion processes as FT and methanol production involved high capital cost; the syngas generation step represents 70% of the facility cost for methanol and 56% for FT. Thus, if improvement could be found in this step, the impact would be significant. While syngas production is viewed as an established process, such new approaches as membrane reactor systems could still provide opportunities for further improvement.

In the case of the direct conversion processes, poor conversion and selectivity have been the barrier to achieving competitive process schemes. For these processes, marginal improvement will not suffice. New concepts with the *potential* to break through the yield barriers are needed for eventual success.

Achieving greater use of natural gas as an alternative transportation fuel is an uncertain prospect. The U.S. Government has set a target of displacing 30% of the crude derived fuels for light-duty vehicle with non-crude-derived by 2010. CNG has attractive economics, but the potential growth on new motor vehicles to 30% faces both political uncertainty in terms of long-term commitment, as well as the obstacles of developing a delivery system infrastructure, refueling technology, refueling outlets, and consumer acceptance.

Exhibit ES-8. Fischer-Tropsch Process Economics Sensitivity Analysis

| Case | Syngas Process | Type FT Reactor | Plant Location | Capacity (B/D) | Gas Price ($/MMBTU) | | Unit Cost of Product ($/bbl) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Initial | Growth Rate | Feed | O&M | Cap. Charge | Plt. Gat |
| 1 | Partial Oxidation | Arge Fixed-Bed | Gulf Coast | 14,500 | 2.43 | 3.1 | 21.68 | 11.91 | 24.53 | 59.6 |
| 2 | Partial Oxidation | FT Slurry | Gulf Coast | 14,500 | 2.43 | 3.1 | 20.92 | 11.88 | 22.56 | 56.8 |
| 3 | Partial Oxidation | FT Slurry | Gulf Coast | 14,500 | 2.43 | 1.6 | 20.92 | 11.88 | 22.56 | 54.0 |
| 4 | Partial Oxidation | Four RX Slurry | Gulf Coast | 58,000 | 2.43 | 3.1 | 20.92 | 7.47 | 15.05 | 45.6 |
| 5 | Partial Oxidation | FT Slurry | Asia | 14,500 | 0.50 | 0 | 4.30 | 11.88 | 22.07 | 35.9 |
| 6 | Partial Oxidation | FT Slurry | Asia | 14,500 | 0.00 | 0 | 0.00 | 11.88 | 21.94 | 31.8 |
| 7 | Partial Oxidation | FT Slurry | Asia | 58,000 | 0.50 | 0 | 4.30 | 7.47 | 14.86 | 25.0 |

# 1. Introduction

The U.S. has substantial uncommitted reserves of natural gas and large quantities of undiscovered conventional resources, as well as such unconventional gas resources as coal bed methane and tight sands. Conversion of gas to liquid fuels and other forms of energy could unlock these resources, reduce the need for imported fuels, and provide a secure supply of liquid fuels.

The three market segments for natural gas utilization are (1) motor fuels, (2) power generation, and (3) chemical feedstock markets. Major routes for converting natural gas to transportation fuels, chemicals, and power are described and process economics for converting natural gas to these products are presented. Use of both HQNG and LQNG have been analyzed in these market applications and economics for them are presented. A sensitivity analysis has also been presented for Fischer-Tropsch economics.

Prior to determining the economics, a literature search was carried out for a wide variety of processes for converting natural gas to fuels for transportation, power and chemical markets. The transportation fuels considered included methanol, MTBE, $C_1$-$C_6$ alcohols, FT liquids, gasoline by direct conversion, and compressed and liquefied natural gas. Production of methanol, ammonia, and ethylene for chemical markets was analyzed; gas use in the power sector was evaluated. A particular process was chosen for detailed studies for each of these products, but alternative ways of making the same product were also discussed.

This report provides the results of these studies, whose objectives included the following:

- Identifying best possible use of domestic resources and ways to decrease dependency on foreign energy sources.
- Determining which processes for converting natural gas are most likely to have a future payout in the form of economical processes that can be commercialized.
- Providing a better understanding of natural gas supplies, current and future utilization and pricing, and applying this knowledge to making decisions about transportation fuels.
- Determining which processes to emphasize in future research, development, and demonstration projects to benefit our country most.

# 2. U.S. Natural Gas Supply and Market Analysis

## 2.1. Supply

Interest in "gas-to-liquids" has been tied strongly to the supply/demand picture for both natural gas and crude oil. In the 1970s, the price of international crude oil rose rapidly. During that same period, gas supplies in the U.S. were shrinking and, while prices were regulated, increases were being allowed for "new" gas supplies. In the U.S. crude-oil and natural-gas price and supply environment of the 1970s, the interest in gas-to-liquids focused on converting remote gas, which had a low market value, to liquids and transporting the liquids to U.S. markets. The potential sources of remote gas considered were Alaska, the Middle East, and Southeast Asia. However, during the 1980s, the U.S. supply/demand and price paths for crude oil and natural gas followed directions that differed from what had been forecast; consequently, the gas-to-liquid focus changed.

Increasing crude oil and gas prices of the late 1970s and early 1980s resulted in a response of falling demand and surplus supply. However, the oil and gas supply surpluses differed greatly for oil and gas. In the case of oil, the supply surplus was international and resulted in falling international and domestic crude oil prices. The U.S. oil supply from domestic sources has, as a consequence of the crude oil price decline, steadily declined since 1985. Increases in oil imports have been required to meet demand. By contrast, the gas supply surplus has been within the U.S., and, while gas prices declined when crude prices declined, additions of new gas supply and production capability have maintained a surplus.

U.S. natural gas production and productive capacity are shown in Exhibit 2-1. Surplus productive capacity has existed since 1980. Since 1986, the gap between capacity and production has been slowly closing as capacity has been declining slightly and demand increasing.

Since the U.S. produces about 10% of its proven natural gas reserves each year, new reserves have had to be added annually to maintain the productive capacity for the past decade. Much of these reserves has been added in a relatively weak gas market, i.e., low prices. This has occurred for several reasons [1, 2].

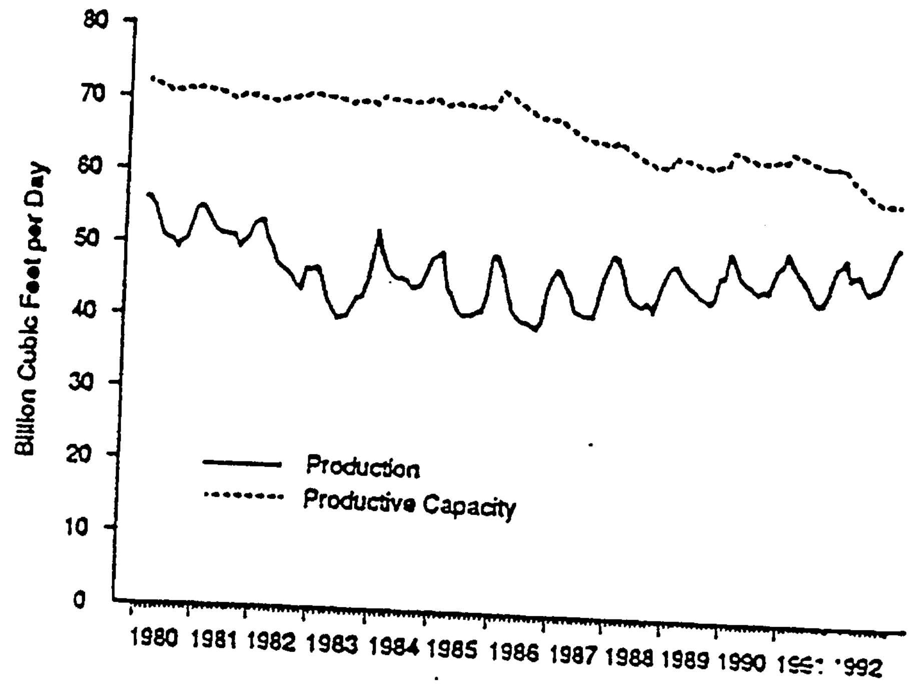
- Infield drilling and new drilling technology have resulted in significant revisions to the reserve estimates of known fields.

- As gas market prices have fallen, so have finding costs. This has resulted from a combination of declining drilling costs and increases in reserves added per well drilled.

- Tax incentives have encouraged the development of non-conventional gas reserves, such as coal bed methane and gas from tight formations. In 1992 about 10% of production came from non-conventional sources (approximately 2/3 from tight gas and 1/3 from coal bed methane).

**Exhibit 2-1**

**Natural Gas Production and Productive Capacity by Month, 1980-1992**




Source: Energy Information Administration, *Natural Gas Productive Capacity for the Lower 48 States: 1982 through 1993.*

Prospects for being able to sustain future U.S. supply to meet gas market requirements by continuing to add the reserves needed is now viewed with much greater optimism than in the 1970s. Exhibit 2-2 shows the current estimates of undiscovered natural gas resources in North America [3].

## 2.2. Demand

Natural gas is now being consumed in five market sectors in the United States, as shown in Exhibit 2-3. The historical consumption in these markets is shown in Exhibit 2-4. The largest consuming market sector is the industrial sector. The historical plot of industrial gas consumption reveals some of the significant changes that have affected U.S. gas markets. In the price-regulated environments of the early 1970s, demand was rising rapidly, but new supplies were being added at too slow a rate to keep pace with increased demand. This led to supply shortages and curtailment of gas supplies to consumers and priorities of services, which brought about declines in demand in the industrial and utility sectors. Again in the early 1980s, increasing energy prices for oil and gas, conservation measures, and a shift away from heavy industry led to further declines in industrial and utility demands.

In the past five years, there has been an increase in industrial demand. The largest element of this increase has been the demand originating in cogenerators and non-utility generators (NUGs) of electricity. Thus, while the electric utility sector appears to be falling slightly, the actual overall use of gas for electricity generation has been rising.

About 92% of the gas used in the industrial sector is for fuel and power; the remaining 8% of the gas consumption is used for process feedstocks. That means that about 3.5% of total natural gas consumption is used as feedstock. Natural gas is used as a feedstock to produce the following three materials [4]: ammonia, hydrogen, and methanol. The percent of total natural gas consumed as process feedstock for each of the three materials is 60, 23, and 18, respectively.

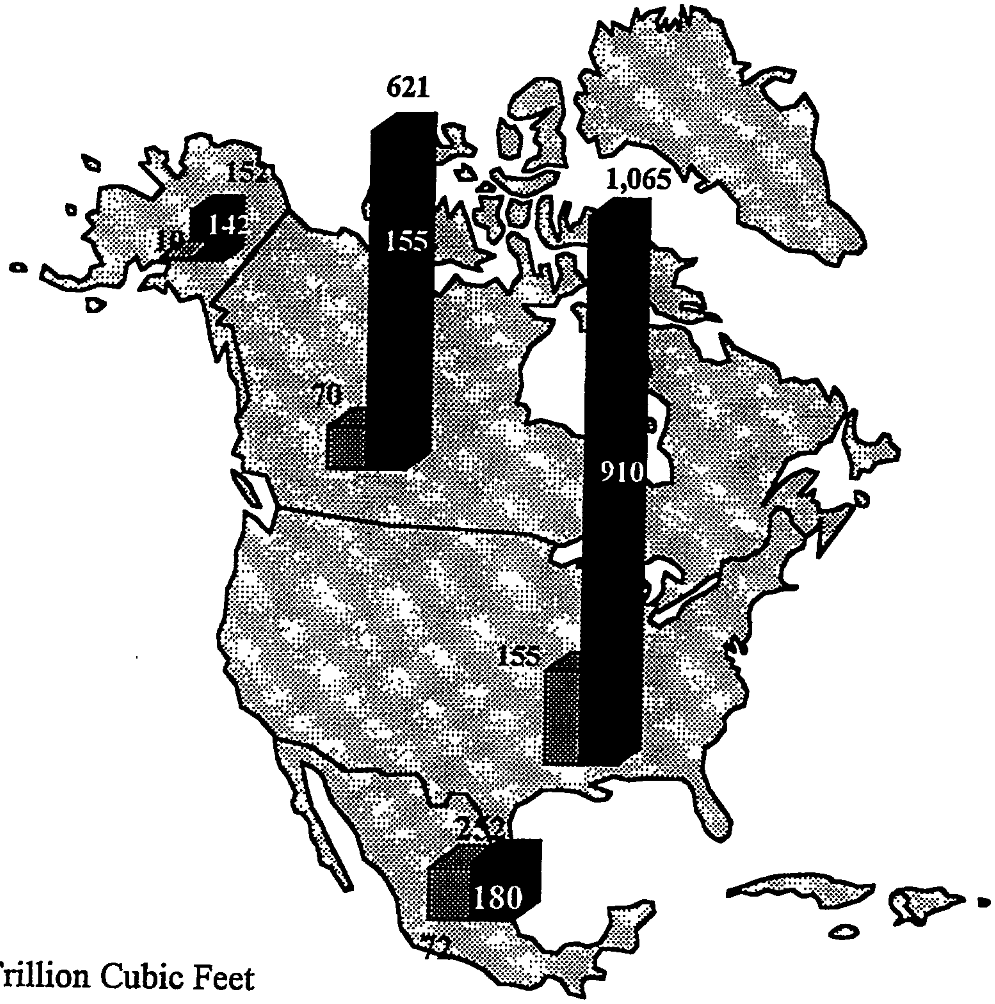
## 2.3. Gas Markets of the 1980s and Search for New Markets

The surplus gas availabilities and lower prices in the late 1980s prompted gas producers and marketers to seek new market opportunities, especially where attractive prices might be achieved. There has been interest in three market areas: power generation, chemical feedstocks, and transportation fuels. The most significant growth to date has been in the power generation area. Natural gas has been an attractive fuel for new cogeneration and non-utility generators because:

- Relatively high-generation efficiencies of natural gas-fired combined-cycle plants, along with lower gas prices, yield attractive generation economics.

- Gas-based generation systems are smaller in scale than other fossil-generation systems and are often more compatible with cogeneration and NUG market needs. The smaller-scale systems have also been attractive to utilities that have become fearful of having large-capacity expansions judged as being investments that were not "prudent."

## EXHIBIT 2-2
### Current Estimate of Undiscovered Natural Gas Resources



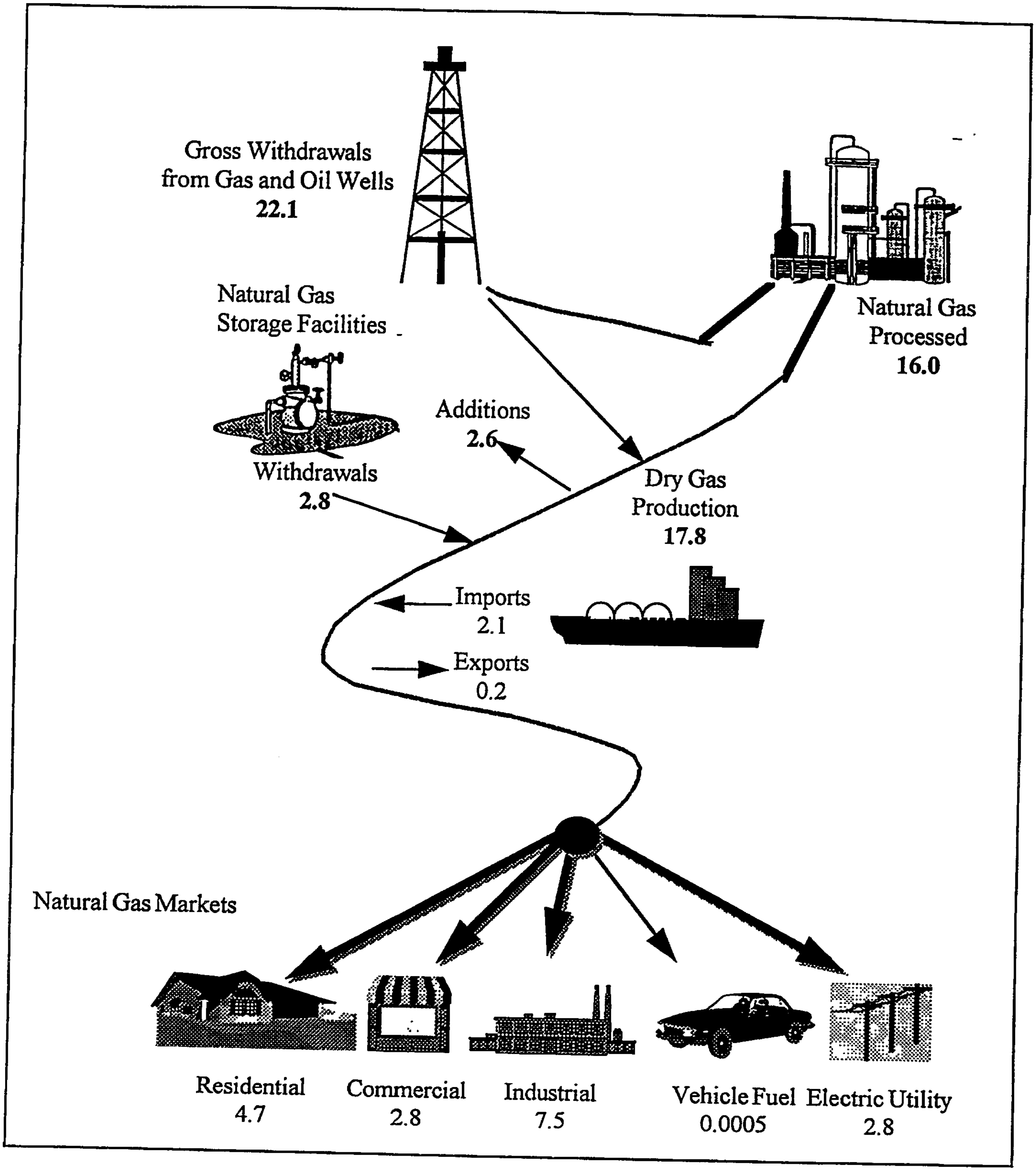

Volumes in Trillion Cubic Feet

- Undiscovered Resources
- Proved Resources

Note: Resource base estimates include resources in areas currently off limits to exploration and development. Resource and Mexico reserve data are estimates as of December 31, 1990, using current technology. Other proved reserve data are estimates as of December 31, 1992, using current technology.

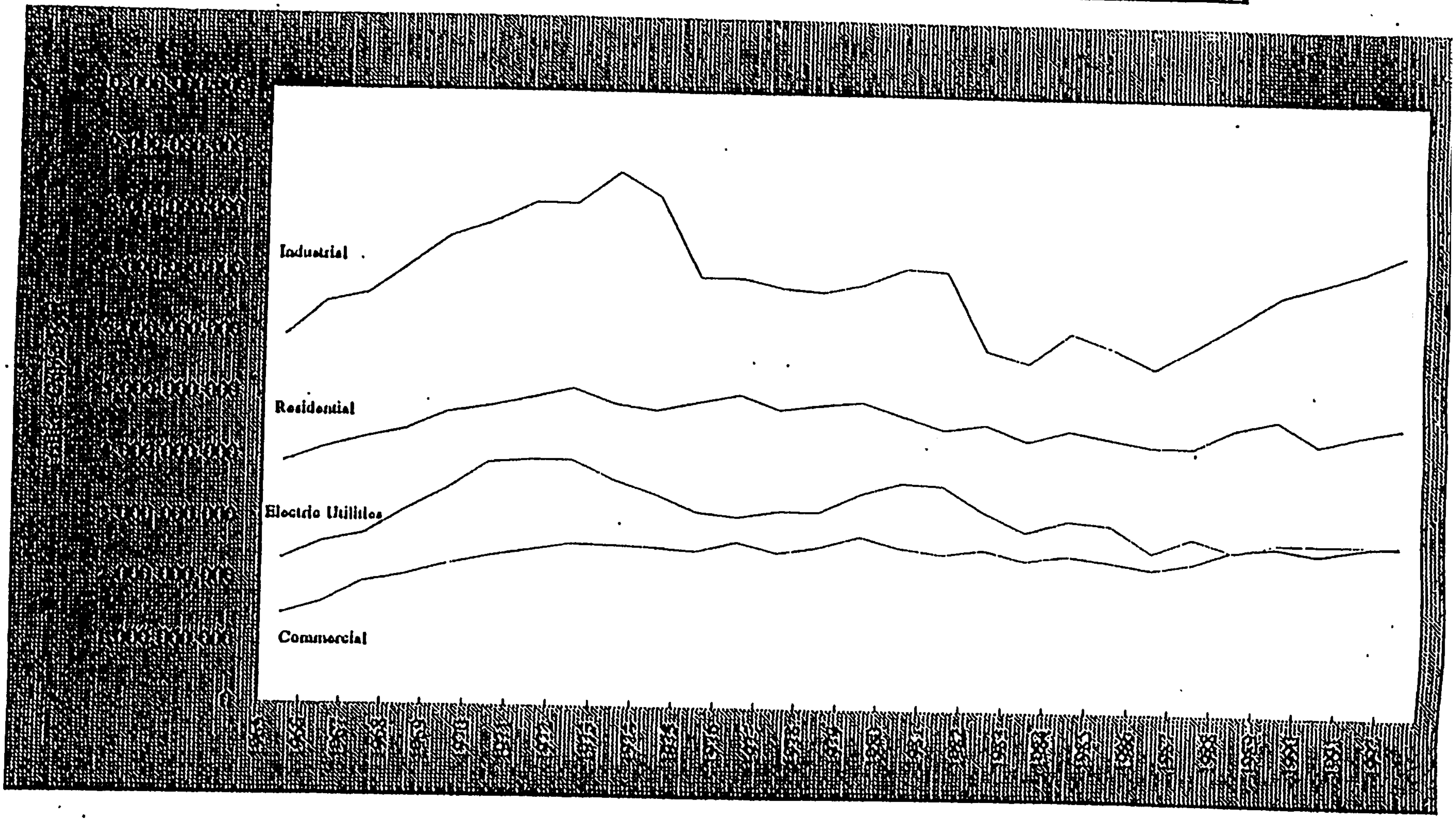
Sources: Reproduced from "*Natural Gas 1994, Issues and Trends,*" DOE/EIA 8520, July 1994.

## EXHIBIT 2-3
### NATURAL GAS SUPPLY AND DISPOSITION IN THE UNITED STATES, 1992 (TRILLION CUBIC FEET)



## EXHIBIT 2-4

### Natural Gas Delivered to Consumers in the United States, 1965-1992




Sources 1965-1975: *Bureau of Mines, Minerals Yearbook, "Natural Gas"* chapter.

1976-1978: *Energy Information Administrator Production and Consumption,* 1979.

1980-1992: *Form EIA-176, "Annual Report of Natural and Supplemental Gas Supply and Distribution."*

- Natural gas has excellent environmental characteristics.

Opportunities in the chemical feedstock market may, in fact, be indirectly tied to the transportation market. Two of the three products that use natural gas as a feedstock are tied to the transportation fuel market to a significant degree. Natural gas is used for production of hydrogen. The greatest demand for hydrogen is in the crude-oil refining process to improve yields and reduce the sulfur content of transportation fuels. Methanol has a number of chemical market uses, but growth in methanol demand is tied to expanding use in the production of MTBE (for which methanol is required) and direct use of methanol as a transportation fuel.

Of the three market opportunities, this interim report focuses primarily on the transportation fuel market, which is discussed in detail in Section 3.

## 2.4. Gas Supply and Demand Issues–Low Quality Gas

The quality of natural gas in the U.S. resource base was described in a previously published report [5]. In that report, a portion of the current proven reserves was defined as LQNG because the gas produced from some reservoirs contains sufficient amounts of non-hydrocarbon gases to lower the heating value or other properties of the natural gas to levels below commercial pipeline standards. LQNG is a natural gas that contains more than 2% carbon dioxide, more than 4% nitrogen, or more than 4% combined carbon dioxide and nitrogen. The analysis of the quality profile of U.S. natural gas resource is based on a detailed study [6] of the chemical composition of current resources and estimated composition of undiscovered gas.

Analysis of the data base of natural gas resources provides the breakdown shown in Exhibit 2-5 for each of the LQNG reserve categories. Four columns are shown in the table to clearly identify the part of the resource that contains high amounts of both $CO_2$ (>2%) and $N_2$ (>4%).

**Exhibit 2-5. Reserves of Natural Gas Classified According to Contaminant Level**

| | Low Quality Natural Gas, % of Reserves | | | | |
|---|---|---|---|---|---|
| Category | >2% $CO_2$ but ≤4% $N_2$ | ≤2% $CO_2$ but >4% $N_2$ | ≤2% $CO_2$ and ≤4% $N_2$ but >4% $CO_2$+$N_2$ | >2% $CO_2$ and >4% $N_2$ | Total LQNG |
| Proven | 18.6 | 13.1 | 1.0 | 1.6 | 34.3 |
| Probable | 33.7 | 8.0 | 0.7 | 1.8 | 44.3 |
| Undiscovered | 31.4 | 7.2 | 0.4 | 3.1 | 42.0 |
| Total | 29.4 | 8.6 | 0.6 | 2.5 | 41.1 |

While Exhibit 2-5 indicates that 34% of proven reserves are low quality and 41% of the total resource base is potentially low quality, additional analysis of the data base showed that the low quality gas resources contained only moderate amounts of impurities. The $CO_2$ plus $N_2$ content of proven reserves are shown in Exhibit 2.6. As can be seen, approximately 88% of the proven reserves have less than 10% $CO_2 + N_2$ and about 98% of the proven resources have less than 20% $CO_2 + N_2$.

Exhibit 2-5 indicates that, of the LQNG resources, only 1.6% has both high $N_2$ and high $CO_2$. Consequently, upgrading LQNG is a matter of removing either $CO_2$ or $N_2$ from most LQNG gas streams. In Section 9, conversion of LQNG directly to liquids options is compared with upgrading it to pipeline quality.

## 2.5. Gas Supply and Demand Issues--Use of Remote Gas

There are large supplies of natural gas in regions of the world with small demand markets. In the U.S., natural gas reserves are 165 trillion cubic feet and annual production is about 10% of reserves. By contrast, reserves in the Middle East are about 1,500 trillion cubic feet and annual production is only about 1/2 of a percent of the reserves.

Because natural gas is expensive to transport when pipeline links are not available and ocean vessels are the only option, there is large variation in gas prices between developed gas market areas (Europe or continental U.S.) and remote regions, such as the Persian Gulf. The attraction of the vast resources and lower gas prices in some regions, such as the Persian Gulf, continues to generate interest in utilizing the gas resources in these regions for gas-to-liquid projects and shipment of the liquid products to market areas.

The lower gas prices in remote regions must offset the added higher facility investment and transportation costs that occur when building gas-to-liquid plant facilities in remote locations and transporting the liquid products to market areas. Exhibit 2-7 illustrates this point by comparing the production and transportation costs for conversion of natural gas to methanol at different locations [7].

Exhib. 5

# PROVEN RESERVES VS. $CO_2$ PLUS $N_2$ CONTENT

Lower 48 States

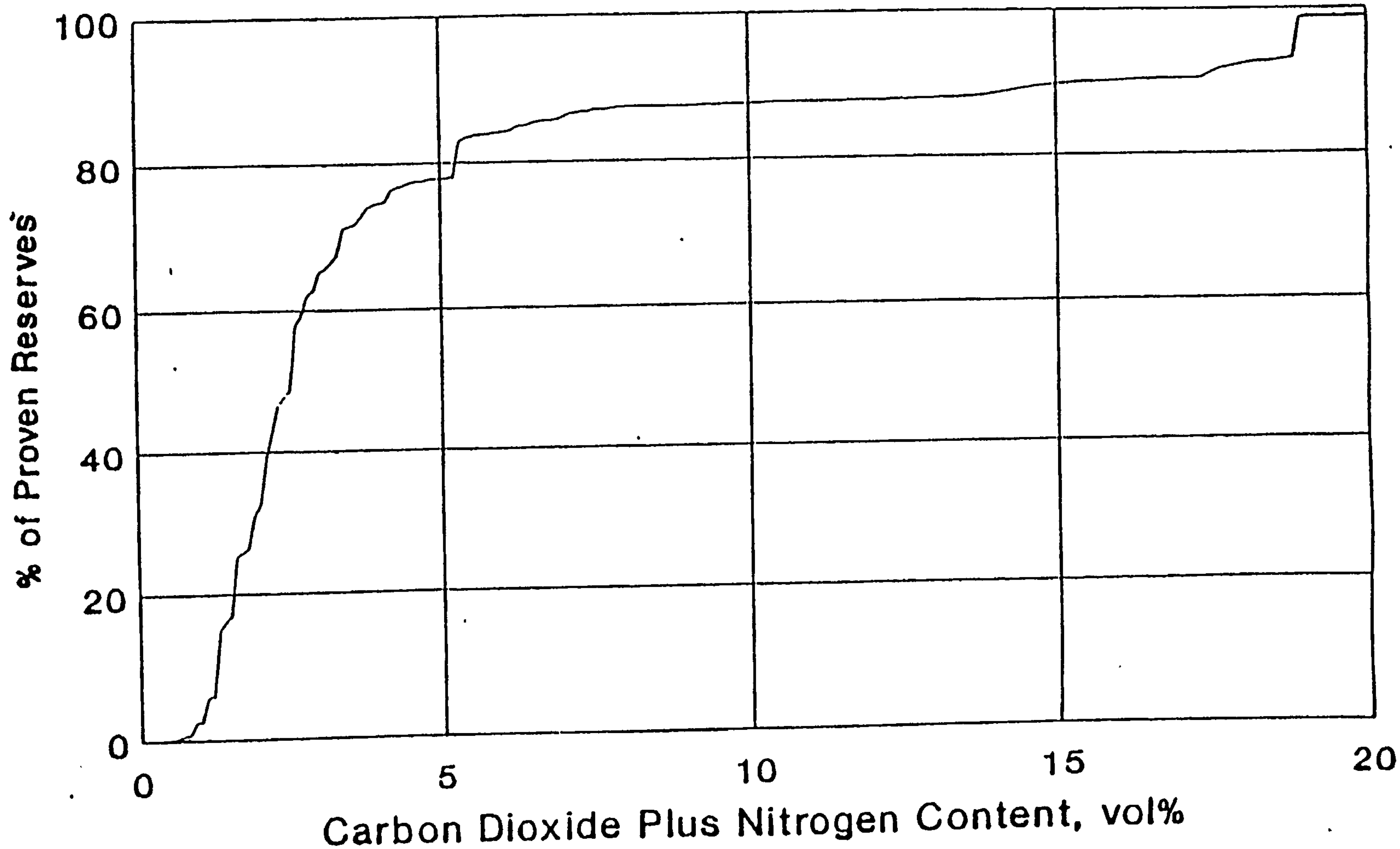


**Exhibit 2-7. Methanol Production Cost (¢/Gallon)**

| Production | Plant Locations | | |
|---|---|---|---|
| | U.S. Gulf Coast | Persian Gulf | Alaska |
| Gas Feedstock | 22 | 6 | 4 |
| Other Operating | 7 | 7 | 10 |
| Capital Charges | 12 | 14 | 26 |
| Total Production | 41 | 27 | 40 |
| Transportation to U.S. | 0 | 9-27 | 3-6 |

## 2.6. Price Outlook

The price of natural gas and future price growth are important to the economics of gas-to-liquid conversion processes. Since gas-derived products primarily compete against crude-oil derived products, the future prices of natural gas versus crude oil are also important.

This study used the natural gas and crude oil price projections contained in the 1994 Annual Energy Outlook [7] developed by DOE/EIA. The oil and gas price forecast is given in Exhibit 2-8. In EIA's 1994 forecast, future gas prices were projected to grow at a faster rate than crude oil. In recent years, virtually all energy forecasters have projected gas price growth at a higher rate than crude oil prices. The assumption of higher future gas price growth rate relative to crude oil makes it more difficult for a process using a gas feed to be economically attractive versus a process using a crude oil feed.

A new set of energy price forecasts have recently become available [8, 9], and Exhibit 2-8 shows the 1995 EIA Outlook and the latest GRI forecasts. As can be seen again, gas price growth is projected to exceed crude oil price growth. The growth rate is somewhat closer. The drawing together of oil and gas price growth, however, is not sufficient to change the outcome of the economic analysis done using the 1994 forecast, based on sensitivity analysis studies.

**Exhibit 2-8. Forecasts of U.S. Oil and Natural Gas Prices (US$ 1994 prices)**

| | Price in | | | Growth Rate (%) |
|---|---|---|---|---|
| Forecast | 1993 | 2000 | 2010 | 1993-2010 |
| 1994 DOE Outlook<br>Gas ($/MCF)<br>Oil ($/bbl) | <br>1.79<br>18.65 | <br>2.48<br>21.25 | <br>3.56<br>28.88 | <br>4.1<br>2.6 |
| 1995 DOE Outlook<br>Gas ($/MCF)<br>Oil ($/bbl) | <br>2.02<br>16.12 | <br>2.29<br>19.13 | <br>3.37<br>24.12 | <br>3.1<br>2.4 |
| 1995 GRI Forecast<br>Gas ($/MCF)<br>Oil ($/bbl) | <br>2.06<br>16.42 | <br>2.53<br>18.58 | <br>2.71<br>20.54 | <br>1.6<br>1.3 |

## 2.7. Summary

Availability of natural gas for the next 20 years to meet U.S. needs is projected to be adequate. Needs can be supplied from North American gas resources. The U.S. gas supply surplus, which has existed for the past decade, is disappearing; this will induce a higher rate of price growth. Gas use will continue in the present markets. The growth in use of gas for power generation may decline with rising prices. The transportation market appears to be a potential growth market but development is in an early stage and long-term prospects can only be judged as uncertain at this stage.