Clean Energy Technologies

5. Fossil Resource Development

5.1 Energy Efficiency for Crude Oil Refining

5.2 Natural Gas to Liquids

5.3 Increased Natural Gas Production

5.4 Co-Production with Integrated Gasification Combined Cycle

5.5 Carbon Dioxide for Improved Oil and Gas Recovery

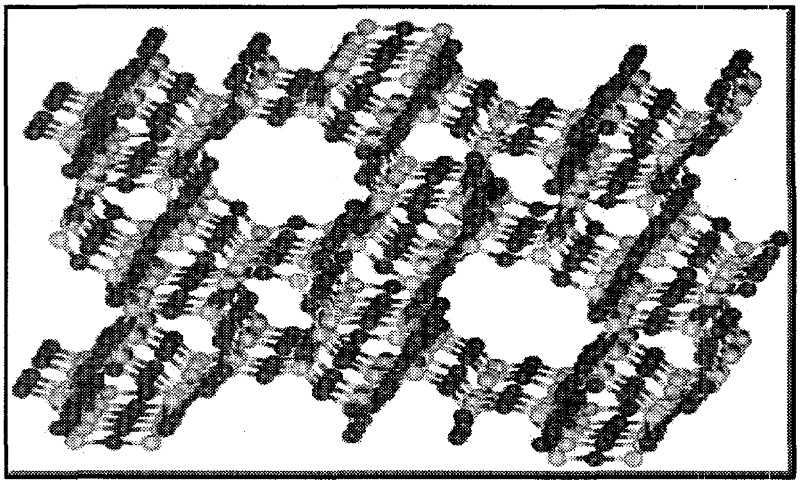
5.1 ENERGY EFFICIENCY FOR CRUDE OIL REFINING

Technology Description

Refining of petroleum crude oil remains a dominant and strategic industry for the U.S. economy. Refining involves separating and converting crude oil hydrocarbon stocks to produce transportation fuels such as gasoline, kerosene, and jet fuel and by-product fuels such as petroleum coke. Separation and conversion processes used in refineries are energy intensive; the source of energy is often the combustion of light hydrocarbon gases that produce CO_2. Fugitive emissions of light hydrocarbon gases from refining operations are another source of GHGs.

System Concepts

- Hydrocarbon use can be made more efficient by increasing the efficiency of converting crude oil to transportation fuels and/or separating and using valuable components of refining off-gases (light hydrocarbons). The former leads to higher yields, and the latter prevents useful off-gases from entering a combustion stream.
- — Reducing the amount of low-value product (such as fuel grade coke) increases the efficiency of the refining process.
- — Several refining processes produce off-gases that have value if they can be separated.



Zeolite ZSM-5 catalyst structure

Representative Technologies

- Catalysis improvements
- Advanced separation methods (membranes)
- Mild pretreatment processes
- Refinery process optimization and advanced sensors

Technology Status/Applications

- Energy-intensive distillation and other conventional separation processes are still the workhorses of the refinery. However, these suffer in separation efficiency and downtime.
- Energy-intensive steam reforming of methane to synthesis gas followed by methanol synthesis is still uneconomical.
- Heavy oil upgrading process efficiency has plateaued.
- Optimization modeling technology for refining systems is moving toward technologies such as reactive multiphase flow simulations.

Current Research, Development, and Demonstration

RD&D Goals

For the near term:

- Demonstrate new refinery catalysts with improved efficiencies and selectivities.
- Test fugitive gas emission identification techniques (tracers and backscatter imaging equipment) in refinery settings.

By 2003:

- Demonstrate on a pilot scale that advanced inorganic membranes can be used to separate and use refinery off-gases.
- Demonstrate on a pilot scale that heavy oil processing can be improved by pretreating to remove impurities before catalytic upgrading.
- Laboratory test short-contact-time reactors with higher methane conversion and greater carbon selectivity.

By 2008:

- Demonstrate through simulations how a combination of advanced sensors, detailed modeling, and process optimization could lower emissions and improve energy efficiency.

RD&D Challenges

- To effectively use off-gases, advanced separation methods must be developed. Inorganic membranes offer promise in this area. Membranes made from zeolites, sol-gels, aerogels and combined zeolites–sol-gels offer the potential of tailor-made separation materials (i.e., hydrogen from nitrogen or isolation of methane). With the proper inclusion of different types of metals in these porous materials, olefins from alkanes could also be separated.
- Specific target catalysis areas are alkylation processes, catalytic cracking, heavy oil cracking, and hydrocracking.
- Up to 50% of heavy oil is of little value to refiners because the nondistillable portion is of poor quality and is difficult to convert to transportation fuels. This material is often converted to low-grade coke. Pretreatment conversion technologies would allow more of the heavy oil to be converted to high-value, more efficiently burning transportation fuels.
- In the case of methane, for full utilization, separation must be followed by a conversion process. This conversion process would serve the same purpose as with natural gas, which is to make liquids that can be handled in a similar manner as refinery distillates.

RD&D Activities

- Supporting efforts are sponsored primarily by DOE/FE with some assistance from EE and ER. Funding is typically less than $10M/year.
- Newer technology for methane liquifaction involves partial oxidation of methane to synthesis gas that removes the thermodynamic limitations of steam reforming. Partial oxidation followed by methanol synthesis represents a potential solution that is being researched.
- It is estimated that a methane conversion efficiency of greater than 30% with a carbon selectivity of greater than 85% is needed. These schemes will require short-contact-time reactors at elevated temperatures, some with novel methods of heating and quenching. These short-contact-time reactors will involve bed configurations in which the energy to initiate the reactions is supplied to the catalyst by chemical, radio frequency, or microwave energy.

Recent Success

- The feasibility of nitrogen-methane separation with tailored zeolite materials on glass substrates derived through the sol-gel manufacturing process has been demonstrated in the laboratory.
- The application of barrier membrane technology to separate hydrogen in several different refinery streams is being investigated. The benefit of this technology is a very-high-throughput membrane that can operate at process temperature and pressure with high separation factors.

Commercialization and Deployment

- Catalysis technology is at various levels of development, from experimental to commercial.
- With modern simulation and analysis technology, better knowledge of unit operations and integrated processes offers the opportunity for true process optimization. The scales run the gamut from molecular level simulations to continuum level analysis to systems level analysis. With improved process sensors and controls, lower emissions and more efficient energy usage can be achieved.
- Tracers can be developed to identify fugitive emissions of methane from refineries and pipelines. Backscatter absorption gas imaging and light detection and ranging (LIDAR) technologies have proved effective in imaging methane plumes at remote distances and ppm concentrations. Recent improvements in LIDAR systems for national security missions should be applicable to fugitive gases as well.

Potential Benefits and Costs

Carbon Reductions

- The petroleum refining industry consumes 5.9 quads per year, 80% of which results from burning fuels in refinery heaters and boilers.
- Improved off-gas separations, more selective catalysts, and effective methane capture could cut GHG emissions 10 to 20% in a decade. This represents a potential carbon reduction range of 8.5 to 17 MtC/year.
- Carbon reduction estimates from this pathway are 2–4 MtC in 2010, 3–6 MtC in 2020, and 4–8 MtC in 2030.

R&D Expenditures

- Current DOE RD&D funding for this pathway is approximately $10M/year.
- Annual DOE RD&D budget required to generate the estimated carbon reductions is $15M/year, 2000–2030.

Market

- This technology pathway is applicable to the entire refining industry.

Nonenergy Benefits and Costs

- The United States is steadily losing refining capacity. Only new technology that addresses all environmental concerns will stabilize this trend.
- The United States produces much heavy oil. An improved refining process could add $1 to $2/bbl to the value of this oil.

Risk Factors

Technical Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low — High

- Technologies have been demonstrated at small scale. The scale-up challenge cannot be minimized.

Commercial Risk

1 2 3 4 5 6 ⑦ 8 9 10

Low — High

- Refineries have been leaving the United States because of environmental cleanup costs.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- The technology could be developed and implemented to make crude oil refining and processing facilities consistent with environmental regulations.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- The refinery of the future will be a vast improvement over current technology.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

Regulatory Risk

1 2 3 ④ 5 6 7 8 9 10

Low — High

Key Federal Actions

- The federal government could work with the petroleum industry to allow the refining of crude oil to rebound as a high-technology, clean, strategic industry for the U.S. economy.
- Collaborative industry/government/university research efforts on catalysis, membrane separations, heavy crude upgrading, and process efficiency improvements could be increased.

5.2 NATURAL GAS TO LIQUIDS

Technology Description

Conversion of natural gas to liquids (GTL) has shown considerable advancement in the past 5 years. Novel processes for the physical conversion of gas to liquefied natural gas (LNG) in remote areas have been identified and show good potential at a demonstration level. In addition, recent studies have indicated that diesel fuels produced from natural gas are significantly less polluting than petroleum derived diesel. Economical conversion of gas streams to liquid products such as fuels and commodity chemicals will allow full use of domestic natural gas supplies while addressing the issue of GHGs.

System Concepts

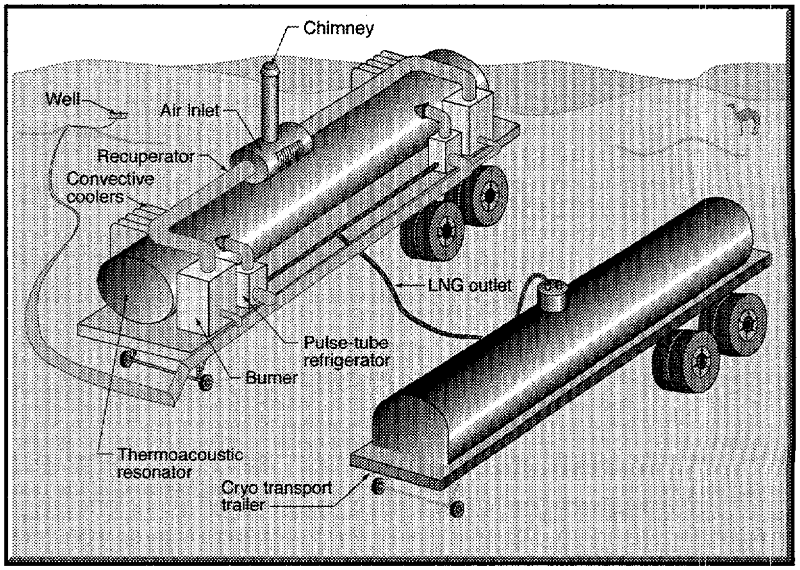
- LNG production: Thermoacoustic natural gas liquefaction produces LNG at lower costs than conventional technology.
- Natural gas diesel fuels: Diesel fuel derived from natural gas far exceeds conventional diesel fuels in reducing emissions including hydrocarbons, carbon oxides, NO_x, and particulates.

Representative Technologies

- Diesel fuels produced via Fischer-Tropsch conversion of synthesis gas have shown low emissions and good efficiency in engine tests.
- In the case of LNG production, process uses direct gas burning to generate sound waves to drive an orifice pulse tube refrigerator. Does not require the use of electricity.

Technology Status/Applications

- Production of LNG from natural gas employing thermoacoustics has been demonstrated at 100 gal/day.
- Diesel fuels produced via conventional synthesis gas technology presently have low yields.



Natural gas liquifier

Current Research, Development, and Demonstration

RD&D Goals

By 2000:

- Demonstrate 500 gal/day production of LNG from natural gas using thermoacoustic processes.
- Identify new catalyst compositions to effectively promote natural gas diesel fuel production.

By 2004:

- Scale up technologies to commercial levels.
- Demonstrate natural gas diesel fuel production at a commercial size.
- Optimize an integrated process using ion transport membranes for conversion of natural gas to synthesis gas, followed by synthesis gas conversion to transportation fuels, and demonstrate natural gas diesel fuel production at a commercial size.

By 2011:

- Produce 200,000–500,000 bbl/day of diesel fuel from remote natural gas sources.

RD&D Challenges

- Research and technology for process improvements are needed to
  - — improve modeling of the complex fluid dynamics and nonequilibrium chemistry of the processes to improve process control and process optimization for a variety of input natural gas compositions
  - — develop relevant process sensors for automated process control and optimization
  - — provide scale design for commercial implementation
- Catalyst development: Identifying catalytic materials that selectively promote high-cetane paraffin formation from synthesis gas is a key for producing diesel fuel from natural gas.

RD&D Activities

- DOE is actively promoting and funding materials, catalyst, and process development for the direct and indirect conversion of methane.
- Industry has targeted natural gas conversion, to both liquid fuels and LNG, as a major research area.
- Significant government/industry research efforts are under way to more effectively convert natural gas to synthesis gas.

Recent Success

- Research over the past 10 years has shown significant improvements in all areas of methane conversion.
- Recent reports indicate that improved yields of high-quality diesel fuels from natural gas can be obtained.

Commercialization and Deployment

- Examples of commercial GTL processes include Mobil's process of converting synthesis gas to methanol followed by conversion to gasoline (1985), Sasol's slurry phase distillate (Fischer-Tropsch) process (1992), Shell's middle distillate synthesis process (1993). Recently, Sasol signed a memorandum of understanding with Qatar General Petroleum Corp. and Phillips Petroleum to build a 20,000 bbl/day plant (Fischer-Tropsch) in Qatar.
- A team headed by Air Products was selected by DOE to head an $84M research program to develop membrane technology for synthesis gas production.

Potential Benefits and Costs

Carbon Reductions

- GTL provides an effective way to use methane, a GHG.
- Estimates have placed the GHG reduction potential of eliminated leaks at 12 MtC/year in the United States and approximately 300 MtC/year if applied to stop leaks from pipelines in Russia.
- Carbon reduction estimates are 2–4 MtC in 2010, 5–10 MtC in 2020, and 10–15 MtC in 2030.

RD&D Expenditures

- Current DOE RD&D funding for this pathway is approximately $5M/year.
- Required federal funding: 1.5 times the current level, or $8M/year through 2030.

Market

- About 2,000–5,000 Mcf per day of natural gas is used to produce 200,000–500,000 bbl/day of high-quality diesel fuel.
- Approximately 80,000 new jobs are created for each 1 million bbl/day of diesel fuel.
- Existing liquid pipeline infrastructure can be used for transportation and distribution.
- Spinoff for LNG includes use by gas utilities for peak demand spikes and natural gas vehicle gas stations.

Nonenergy Benefits and Costs

- Costs: Thermoacoustic LNG production—additional $500K/year, 5 years, total = $2.5M; diesel fuel production (catalyst development)—additional $1M/year, 6 years, total = $6M; fuel testing in pilot-scale facility, emission impact analysis and optimization, additional $1M/year, 8 years = $8M.
- Both natural gas to fuels and LNG will reduce dependence on imported oil.

Risk Factors

Technical Risk

1 2 3 ④ 5 6 7 8 9 10

Low — High

- Technologies have been demonstrated at small scale; however, the challenge of scale-design cannot be minimized.

Commercial Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Liquid hydrocarbon fuels have existing markets, facilities, and infrastructure for transportation and utilization; however, high capital cost facilities may be required.

Ecological Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Technologies for construction and operation of oil and gas facilities are well developed. Fuels produced by these processes are clean burning with very low sulfur and nitrogen compound emissions.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Most of the technology for producing and handling natural gas and liquid hydrocarbon products is available, is well understood, and presents no major new risks.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- None currently identified.

Regulatory Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

Key Federal Actions

- Collaborative industry/government research efforts could be developed to identify catalysts and processes to economically convert natural gas to liquid diesel fuels.
- More federal funding is needed to begin to address the broad range of technical issues related to commercial scale up, remote construction, and operations.
- A federal mandate to reduce emissions through fuel switches would accelerate this pathway.
- Significant U.S. and international activity is expected in both the GTL and LNG areas through the year 2010 and beyond. There is opportunity for the United States to be the leader in GTL and LNG technologies and market the technology abroad.

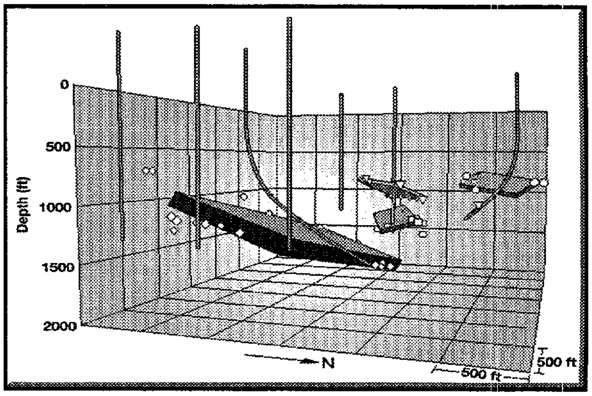
5.3 INCREASED NATURAL GAS PRODUCTION

Technology Description

Natural gas as a fuel has a fundamental advantage over oil and coal in terms of reducing carbon emissions because of its lower carbon-to-hydrogen ratio. The United States has an abundant natural gas supply and needs only the development of technology to make it available to displace oil and coal from the power generation and transportation markets. This can be accomplished in the near term through secondary gas recovery (230 Tcf); in the mid-term through low-permeability formation development (500 Tcf), offshore (100 Tcf), and coalbed methane(400 Tcf); and in the long term by exploiting currently untapped methane hydrates (2700 Tcf) and deep source gas (3000 Tcf). Only a small success rate would be needed to effectively meet the expected demand of 28 Tcf in 2010.

System Concepts

- Improved knowledge of resources to understand the characteristics of gas-in-place and to quantify what is recoverable.
- Increased production efficiency via drilling, completion, and stimulation.
- Effective deployment of technologies in conventional and unconventional resources.
- Advanced storage concepts in areas of demand to minimize service curtailments.
- Development of technology to recover gas from hydrates and deep gas sources.



Fracture mapping technology

Representative Technologies

- Advancements in 3-D seismic could reduce risks by 10% for all exploration wells and by 5% for development wells in 2010 (cumulative reserves of 37 Tcf are possible).
- Advancements in drilling, completion, and stimulation are expected to reduce costs associated with recovery (cumulative reserves of 6 Tcf are possible in 2010).
- New technology in gas storage could eliminate a 5% annual loss (cumulative savings of 5 Tcf in 2010).
- Detecting and preventing leaks from natural gas pipelines using backscatter absorption gas imaging and optical methane detectors can detect and prevent leaks from natural gas pipelines (cumulative savings of 5 Tcf in 2010).

Technology Status/Applications

- Industry focuses on drilling and fracturing with fluids; this technology is not applicable to low-permeability formations.
- Available seismic technology is helpful in locating productive strata but needs improved resolution to locate natural fracture systems that are the "sweet spots."
- Interest in gas hydrates and deep gas is evolving with detection and characterization in both onshore and offshore environments; coalbed methane development remains stagnant.

Current Research, Development, and Demonstration

RD&D Goals

- The goal of the gas supply program is to expand the national reserve base.
- Low-permeability formations and marginally economic reservoirs are the targets for half of the future gas supply.
- Production tests in coalbeds are needed to fully develop this resource.
- Gas hydrates and deep gas sources are targets for the long-term supply.

RD&D Challenges

- Developing innovative drilling and subsurface diagnostics to eliminate damage to formations while drilling, to improve recovery efficiency from them, and to reduce costs.
- Developing advanced technologies that increase resolution in naturally fractured formations to reduce risks in locating favorable places to drill.
- Improving diagnostics to detect gas hydrates and deep gas resources.

RD&D Activities

• Resource and reserve assessments	FY 1997 ($3.3M)
• Drilling, completion and stimulation	FY 1997 ($5.4M)
• Low permeability formations	FY 1997 ($4.4M)
• Natural gas storage	FY 1997 ($1.0M)

Note: In the early 1980s, hydrates, deep gas, and coalbed methane characterization work was conducted, but it ended with the passing of the energy crisis. Data remain archived at FETC.

Recent Success

- Maps and databases for use in exploration were published and distributed to industry.
- An air hammer was developed with industry to double the drilling rate in horizontal wells.
- A "dry stimulation" process was introduced to industry to avoid formation damage in wells.
- Vast improvements were made in processing complex 3-D data sets.
- Fundamental understanding of hydrates, deep gas, and coalbed methane has been documented.

Commercialization and Deployment

- Advanced stimulations that avoid formation damage are currently being used in select applications; more customers must be exposed to their merits.
- Improved drilling tools and diagnostics have reached a market plateau over the past 5 years and account for the better recovery efficiency to date with fewer wells.
- Only a limited volume (5%) of available coalbed methane is being produced.
- Widespread deployment of technologies is expected by collaborating service companies.

Potential Benefits and Costs

Carbon Reductions
- This pathway would expand production of natural gas, which could be expected to decrease gas prices, making gas more competitive for electricity production.
- Reductions of 150–200 MtC/year would be achieved if 25% of coal-fired power plants were displaced by natural gas–fueled plants in 2030.
- Carbon reduction estimates for this pathway are 10–20 MtC (2010), 75–100 MtC (2020), 100–200 MtC (2030).

RD&D Expenditures
- Current DOE RD&D funding for this pathway is $14M/year.
- 1.5 times this current level is required to achieve the estimated carbon emission reductions, or $21M/year through 2030.

Market
- An assured gas supply could displace 2 million bbl oil /day from switchable stationary markets (25% of *imported oil*).

Nonenergy Benefits and Costs
- Energy security at non-disruptible prices in the market.

Risk Factors

Technical Risk

1 2 ③ 4 5 6 7 8 9 10

Low High

- New technology development is considered a low to medium risk. Widespread acceptance may require demonstrations in every basin for quantification. Support for industry's offshore production problems may be required.

Commercial Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low High

- Drilling and stimulation advances may be hindered by industry's manner of doing business; if patents are not owned by the vendors, new advances may not find their way into the marketplace.

Ecological Risk

① 2 3 4 5 6 7 8 9 10

Low High

- Not significant.

Human Health Risk

① 2 3 4 5 6 7 8 9 10

Low High

- Not significant.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low High

- Not likely.

Regulatory Risk

① 2 3 4 5 6 7 8 9 10

Low High

Key Federal Actions

- An optimum funding level ($300M to 2010 plus $450M from 2010 to 2030.
- Federal codes to attain emission reductions may be required to influence fuel switching.
- A federal partnership program may be required to instill confidence in new technology.

5.4 CO-PRODUCTION WITH INTEGRATED GASIFICATION COMBINED CYCLE

Technology Description

The IGCC process offers industry low-cost, highly efficient options for meeting market requirements. One of the most efficient and environmentally friendly technologies for producing low-cost electricity, IGCC can process many feedstocks including coal, petroleum coke, biomass, and municipal wastes. In combination with synthesis gas conversion technologies, it is the only technology that can coproduce a variety of commodity and premium products in addition to power to meet future market requirements.

System Concepts

- IGCC for electricity production converts carbonaceous feedstocks in a gasifier into synthesis gas, a mixture of CO_2 and hydrogen. The gas is cleaned of particulates, sulfur, and other contaminates to permit further processing and combusted in a high-efficiency gas turbine/generator. The heat from the turbine exhaust gas is extracted to produce steam to drive a steam turbine/generator.
- In coproduction mode, feedstocks can be processed before gasification to extract valuable components, or the synthesis gas can be converted to products. Valuable precursors from feedstocks such as coal can be extracted to manufacture high-strength, lightweight carbon fibers and anode coke. Clean synthesis gas can be catalytically converted into environmentally superior transportation fuels, high-value chemicals, or hydrogen.

Representative Technologies

- Sasol in South Africa has been converting coal to transportation fuels and chemicals for more than 40 years, but the technologies used are not efficient. Shell has built a plant to convert natural gas to fuels in Malaysia using a combination of new and older technologies. The transportation fuel product is environmentally superior to conventional petroleum products and has commanded a premium price.
- Liquid-phase methanol synthesis is being demonstrated at an Eastman Chemical coal gasification facility. Its design capacity is 80,000 gal/day. The project is demonstrating a new cost-effective route for producing liquid fuels and chemicals in a mode that could be readily integrated with an IGCC plant to coproduce power and fuels/chemicals.

Technology Status/Applications

- IGCC demonstration projects using coal, petroleum coke, or other petroleum refinery wastes are operating or under construction in the United States and worldwide. Many are designed for coproduction to allow improved thermal efficiencies.
- Conversion of synthesis gas to transportation fuels has been investigated for several decades. Significant advances in catalysis and reactor design are generating interest from industry. The environmental superiority of the resulting transportation fuels—which substantially reduce emissions of hydrocarbons, CO_2, and particulates—has been recognized as a key ingredient for meeting future environmental regulations.
- IGCC and IGCC coproduction technologies can be readily integrated into existing refineries and chemical plants to convert waste materials to end products or used to repower inefficient existing plants. The pulp and paper industry produces much biomass waste, most of which is used internally to generate power and steam. Most boilers used in this industry are old and must be replaced, a potential market of 20,000 MW of capacity. Because of the large steam usage in these plants relative to power consumption, IGCC operating in the coproduction mode offers a unique opportunity for steam and power production while simultaneously destroying hazardous chemicals and generating synthesis gas fuel for kiln operation.

Current Research, Development, and Demonstration

RD&D Goals

By 2004:

- Identify low-cost feedstocks (e.g., biomass, municipal waste, black liquor) available in sufficient quantities for commercial applications.
- Evaluate the gasification of low-cost feedstocks in advanced gasifiers either separately or via co-feeding with other carbonaceous materials.
- Reduce consumption of sorbents, catalysts, and filter elements by 40% from today's levels.

By 2006:

- Reduce the cost of IGCC and IGCC coproduction technologies through the use of advanced air separation technologies, advanced gasifiers, high-efficiency gas turbines, and improved synthesis gas cleanup and CO-to-H_2 shift technologies.
- Begin pioneer plant demonstration of IGCC coproduction concept.

By 2010:

- Reduce the installed capital cost of gasifier-based technologies by at least 10% of current designs.
- Demonstrate the reliability, availability, and maintainability of IGCC and coproduction technologies to secure financing of future facilities.

By 2015:

- Demonstrate the modularity for reducing plant cost and demonstrate near-zero discharge of wastes, emissions, and CO_2.

RD&D Challenges

- Reduce the cost of synthesis gas for both power and fuels production.
- Develop catalysts and sorbents that are mechanically strong and have high activity.
- Optimize the design of process facilities to obtain the lowest total installed cost without sacrificing performance and safety.
- Improve materials for high-temperature gas turbines.
- Identify and develop innovative, cost-effective ideas for sequestering or using CO_2.

RD&D Activities

- Develop and demonstrate ceramic membranes for high-efficiency, low-cost oxygen production.
- Optimize the process design and engineering, procurement, and construction activities of IGCC and coproduction facilities.
- Develop advanced gasifier technologies for achieving higher throughput and using a variety of low-cost opportunity fuels such as petroleum coke and biomass.
- Develop and demonstrate advanced, high-efficiency gas cleanup technologies for removing impurities from the gasifier product.
- Develop and demonstrate 2600°F inlet gas turbines, advanced power cycles and fuel cells, and low-temperature catalysts and processes for conversion of synthesis gas.

Recent Success

- Two advanced IGCC Clean Coal demonstration projects have been successfully operated using coal.
- An advanced sorbent for removing sulfur from synthesis gas has been developed with sufficient mechanical strength for use in moving bed and transport reactors. Large scale testing is scheduled.
- Operation of the liquid-phase methanol facility is being demonstrated. The design production rate of 260 tons of methanol per day was achieved on the first day of operation.
- Preliminary diesel engine tests on Fischer-Tropsch fuels from indirect liquefaction show exceptional performance. Combustion efficiency is high and emissions tests show no sulfur oxides, lower NO_x, and significantly lower hydrocarbons than in conventional diesel fuels.

Commercialization and Deployment

- Industry is using slurry reactor and catalyst technology to convert natural gas to methanol, chemicals, and liquid fuels.
- Engine testing done in DOE programs is helping demonstrate the environmental benefits of these advanced fuels.
- Conceptual designs are improving industry's understanding of these processes and reducing the risk of deployment.
- In situ or underground coal gasification can produce high-quality synthesis gas as a feedstock for combined cycle power plants or advanced Fischer-Tropsch processes. The technology has been commercially developed in the former Soviet Union and limited commercial scale testing performed in the United States.

Potential Benefits and Costs

Carbon Reductions

- In the cofeed, coproduction mode, carbon emissions are expected to be a third lower than from separate facilities producing the same amount of power and fuel.
- Transportation fuels produced from synthesis gas contain no sulfur and aromatics and reduce hydrocarbon, CO, and particulates emissions by 25–40% compared with low-sulfur, low-aromatic petroleum diesel.
- If all existing coal-based power plants were replaced with IGCC coproduction technologies, they could produce about 2 million bbl/day of transportation fuels while producing the same power output, but with 15% lower CO_2 emissions (16 MtC/year).
- Coal that is transformed into a liquid using these technologies can sequester excess CO_2 at the point of production. Depending on the type of coal, 30–35% of the carbon from coal could be captured during synthesis gas and liquid fuels production.
- Potential carbon reductions are 245 MtC/year @ 50% efficiency by 2020 and 325 MtC/year @ 60% efficiency by 2030.
- Portions of this potential are estimated in those years: 5–10 MtC in 2010; 50–100 MtC in 2020; and 65–130 MtC in 2030. Carbon reduction estimates are already counted in other pathways (3.3 and 6.1). They should not be added again to these pathways because that would involve double counting.

RD&D Expenditures

- The IGCC program has been funded at about $50M annually. An annual DOE RD&D budget of $75M/year through 2030 is required to generate this pathway's estimated carbon reductions.

Market

- This energyplex approach presents opportunities to replace a petroleum-based fuel with more abundant coal-based fuels. Currently, 300 GW coal electrical capacity is available in the United States.

Nonenergy Benefits and Costs

- Improve U.S. industrial competitiveness in new technologies.
- Enhance energy security and reduce the trade deficit through use of domestic resources instead of foreign oil.

Risk Factors

Technical Risk

1 2 3 ④ 5 6 7 8 9 10

Low — High

- Advanced materials and technologies for producing them are needed for membranes, catalysts, filters and sorbents.

Commercial Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Operational experience needs to be developed through pilot and demonstration projects.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Fuel testing is needed to demonstrate the performance of these fuels with existing and future engine designs.

Human Health Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- Life cycle assessments are needed to eliminate or minimize risks.

Economic Risk

1 2 3 4 ⑤ 6 7 8 9 10

Low — High

- Thermophysical property data and models are needed to improve the accuracy of process designs to reduce financial risks.

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

Key Federal Actions

- Accelerate the deployment of both IGCC and liquid fuels technologies in the United States.
- Maintain the current level of support in the near term and increase it as the need for advanced demonstration projects materializes.

5.5 CARBON DIOXIDE FOR IMPROVED OIL AND GAS RECOVERY

Technology Description

Each day 50 trillion scf of CO_2 is vented from power plant stock gases in the United States. Also each day, the United States extracts more than 1.1 billion scf of CO_2 from underground deposits and pumps it into oil reservoirs to enhance the recovery of petroleum. Instead, the CO_2 that would otherwise be emitted to the atmosphere (from fossil-fueled combustors) could be captured and used. In the future, CO_2 contained within powerplant stack gases could also be pumped into coal seams to recover methane economically or to replace base gas in storage wells.

System Concepts

- Separate CO_2 from the stack gas of power plants and other combustors and use it in a number of improved oil and gas recovery methods. The CO_2 would have multiple uses for enhanced oil recovery, gas cap maintenance, well stimulation, inert gas replacement in storage, and methane recovery from coalbeds.
- Reject the nitrogen from the air before combustion so that the flue gas is principally CO_2 and water vapor, from which the CO_2 is either separated for food-grade applications or injected as CO_2-rich flue gas to be used in improved oil and gas recovery operations.
- Remove some of the carbon from the fuel (and add hydrogen to fuel) before the fuel is sent to the end user. The removed carbon is available as a concentrated CO_2 stream.
- Capture CO_2 from low-quality natural gas for injection.
- Combine energy recovery and GHG reduction by either capturing the flue gases or removing the CO_2 from stack gases in a setting where a dual fuel (natural gas and coal) power plant is located close to an *in situ* gassy unmineable coalbed. CO_2 from stack gases would be injected into the coalbeds to produce methane, which would be used to fuel or co-fire the power plant. The CO_2 emissions from the plant would then be continuously re-injected into the coalbeds to recover methane.

Representative Technologies

- Passage of flue gas through a solution of monoethanolamine (MEA) (or related compounds.
- The use of an air separation plant in front of an existing power plant.
- Recovery of CO_2 from coal gasification and subsequent use for enhanced energy recovery.
- Upgrade low-quality gas into pipeline methane and use the CO_2 from higher efficiency membrane separation for other applications.
- Co-produce methane and electricity by using CO_2 to produce methane from unmineable coal seams, using the methane to fire a power plant, injecting the CO_2 from the plant's stack gases into the coal seams in a continuing cycle.

Technology Status/Applications

- MEA technology is commercial for applications limited to certain gas streams found at certain chemical plants.
- O_2-CO_2 recycling has been pioneered at the pilot scale in the United States and the results have been duplicated in the United Kingdom, Europe, and Japan. It appears technically suitable for electric power plants but has not been applied because natural CO_2 deposits are less expensive.
- CO_2 recovery from coal gasification produces ~240 million scf per day of CO_2. A project is under way to recover CO_2 at the Great Plains Coal Gasification Plant and pipeline ~100 million scf/per day to the Weyburn oil field in Canada. Additional CO_2 from the pipeline could be used in North Dakota, Montana and Wyoming.
- CO_2 from stack gases or exhaust gases could be used to recover additional enhanced oil and sequester GHGs. There is an increasing industry awareness of the benefits of well stimulation with CO_2 and demand for both low-quality and food-grade CO_2 is expected to gain momentum. The potential use of direct flue gas or exhaust gas needs to be further investigated.
- CO_2 could be used for base gas replacement in gas storage reservoirs. Natural gas itself or nitrogen is currently used, ~4.3 trillion scf.
- Several companies have proprietary data and technology for CO_2 injection into coal for higher yields of methane recovery. Unofficial information from private sources indicates that the process is technically and potentially economically feasible.

Current Research, Development, and Demonstration

RD&D Goals

For the near term, validate the CO_2/CH_4 concepts that will

- Reduce the cost of recovering CO_2 from combustors and lead to a reduction of CO_2 emissions at targeted power plants.
- Demonstrate the stability and permanence of CO_2 storage in coalbeds and gas storage reservoirs and increased production of methane from coalbeds by CO_2 injection.

By 2002, develop and validate the CO_2/CH_4 concepts that will

- Reduce the cost of recovering CO_2 from combustors by 30–50%.
- Demonstrate improved oil recovery from CO_2 well stimulation treatments.
- Demonstrate that methane production from unmineable coalbeds in selected coal power plant regions will permit 10% co-firing, which will further reduce emissions.

By 2005, develop and validate advanced CO_2/CH_4 concepts that will

- Demonstrate the use of stack gas CO_2 as direct flue gas for improved oil recovery.
- Exhibit the performance, reliability, and efficiency to store CO_2 and optimize CH_4 recovery in coals with varying thickness, maturity, and depth.
- Determine the feasibility of directly injecting power plant flue gas to remove stored SO_2 and NO_x as well as CO_2.

RD&D Challenges

- Improve gas-gas separations, particularly the separation of air into oxygen and nitrogen and the separation of CO_2 from nitrogen.
- Conduct research to determine (1) where CO_2 goes upon injection, (2) how it interacts geochemically with the reservoir rock and fluid, and (3) how these interactions affect the recovery of gas and oil.
- Determine influence of water-saturated coalbeds on CO_2 injection and adsorption
- Adapt existing oil and gas well methodologies to CO_2 injection requirements.
- Determine the extent to which the concepts can be applied to the full range of unmineable coals.
- Determine the feasibility of direct flue gas injection.

Current Research, Development, and Demonstration (continued)

RD&D Activities
- RD&D on O_2/CO_2 recycling systems has been carried out (international funding probably equivalent to several million dollars in recent years). DOE funded pioneering work in this area in the mid 1980s; funding was approximately \$2M.
- Analytic and laboratory process studies are ongoing.
- Commercial recovery and use of coalbed methane demonstrated by industry.
- Laboratory and field tests are needed to confirm the fundamental relationships supporting CO_2 injection and methane recovery in a variety of coals and reservoir environments.

Recent Success

- The practice of CO_2 injection has grown significantly. Petroleum production rose from 30,000 bbl/day in 1986 to 171,000 bbl/day in 1996. In 1996, there were 61 CO_2 injection projects in the United States. CO_2 usage associated with well stimulation is increasing as well operators begin to appreciate the benefits, and the service industry begins to capitalize the equipment needed to provide a stimulation service.
- Industry has privately demonstrated the concept of injecting CO_2 into coals for enhanced methane production (proprietary data).
- DOE-sponsored laboratory testing on bituminous coal samples shows the affinity factor of CO_2 to coal surface is 2:1 over CH_4.

Commercialization and Deployment

- A CO_2 pipeline will be constructed in 1999 from the Great Plains Coal Gasification Plant to Canadian oil fields.
- Co-firing and reburn technologies in several U.S. power plants have been demonstrated in joint DOE-GRI-industry partnerships.
- CO_2 is used commercially in enhanced oil recovery, well stimulation, and well remediation applications.
- Industrial R&D on CO_2 displacement of CH_4 in coal seams.

Potential Benefits and Costs

Carbon Reductions
- CO_2 storage capacity in coals and enhanced production of methane from gassy coals is potentially large. Estimates have placed the sequestration potential of this approach at 50 MtC/year. But it is unclear how much of this potential might be realized.

RD&D Expenditures
- Present DOE R&D budget for effort is \$0.
- An annual DOE RD&D budget of \$8–10M/year is required through 2005.

Market
- Increased natural gas production from conventional and tight gas formations with emphasis on coalbeds (coalbed gas now furnishes 5% of U.S. supply at more than 1 Tcf/year and increased reserves and production of domestic petroleum.

Nonenergy Benefits and Costs
- Avoided need and cost for SO_x/NO_x control on power plants whose flue gas is recovered and sequestered in oil wells and coal seams; reduced NO_x and particulate matter through methane use with coal for power; and substantial international market opportunities for the United States.

Risk Factors

Technical Risk

1 2 3 ④ 5 6 7 8 9 10

Low — High

- Improved gas-gas separations are challenging but not infeasible.

Commercial Risk

1 2 3 ④ 5 6 7 8 9 10

Low — High

- Little commercial risk after technical risk is removed. Only commercial risk comes from the potential discovery of now unknown deposits of inexpensive CO_2.

Ecological Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- Properly capped oil fields are known to sequester CO_2. The presence of coal-bed methane suggests that coal beds can sequester gases over geologic time periods.

Human Health Risk

1 2 ③ 4 5 6 7 8 9 10

Low — High

- No increase over present practice.

Economic Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

Regulatory Risk

1 ② 3 4 5 6 7 8 9 10

Low — High

- None foreseen.

Key Federal Actions

- Characterization of potential coal resource base geographically with respect to power plant location and regional/local coal properties.
- Economic analysis.
- Pilot demonstrations in United States.
- Government—industry—academia partnerships.