CHAPTER 4
FOSSIL ENERGY

…everything comes back to energy: our global environmental strategies, our national economy, local and regional air pollution, the notion of moving toward a more resource-efficient society, national security in terms of the Middle East, the burgeoning requirements of the Third World, especially the Asian Rim—everything comes back to energy.

John H. Gibbons, Assistant to the President for Science and Technology[1]

Fossil fuels will likely remain the principal energy sources for most of the world, including the United States, well into the middle of the next century. They are plentiful, widely dispersed, and easy to transform, transport, and use. Technologies for extracting and converting fossil fuels continue to improve. In fact, the promise of DOE/industry supported R&D is technology that can lead to continued affordable use of fossil fuels (including coal) even in a greenhouse-constrained society and moderation of oil imports and the cost to the economy of future oil price shocks[2].

MOTIVATION AND CONTEXT

Energy systems of the world are largely (75 percent) based on fossil fuels, and the fossil share of the U.S. energy market is projected by the Energy Information Administration (EIA) to increase from 85 percent in 1996 to 88 percent in 2015.[3] The fossil energy industry is huge and represents more than 5 percent of the U. S. gross national product. It provides a mature, well-developed, and very efficient supply, conversion, and distribution system. Although the resources of fossil fuels are finite, continuously advancing technologies maintain them as the principal resources of commercial energy. Fossil energy technologies also continue to improve dramatically with respect to efficiency and environmental performance. Compared to conventional pulverized coal-fired power plants, for example, advanced integrated gasification combined-cycle systems produce almost 30 percent more electricity per unit of CO_2 emitted[4] (or the same amount of electricity with 30 percent less CO_2 emitted), with very low emissions of SO_x, NO_x, and particulates.

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[1] Gibbons (1996).
[2] Oil price shocks are rapid increases in world oil prices resulting from supply curtailment as from the oil embargo from 1973 to 1974 or interruptions as from the Iran-Iraq war in 1979.
[3] EIA (1997); findings from this document, the 1997 edition of the EIA's "Annual Energy Outlook", are denoted AEO 97 throughout this chapter.
[4] These are also described interchangeably as carbon emissions.

Notwithstanding these attractive attributes and progress, major challenges to society are associated with increasing use of fossil fuels—principally environmental ones, particularly CO_2 emissions, and the vulnerability of the U. S. economy to oil price shocks.[5] These major challenges to society indicate a need for Federal government involvement in R&D, because their mitigation represents public good outcomes only partially addressed by private sector activities. There is simply not sufficient incentive or profit motive for private industry to address such challenges alone, many of which are wholly or partially external to the market. Also, the Federal government is the largest single holder of oil, gas, and coal reserves in the United States, and significant royalties, fees, and taxes are paid by the companies developing, producing, and using these resources. Thus, there is considerable incentive via these monies for doing R&D that leads to the efficient utilization of these resources.

Another major factor influencing the different roles of government and industry in R&D is the changing situation in the private sector. Specifically, industry R&D is driven by an ever-intensifying and single-minded focus on increasing returns on high-risk investments through satisfying the needs of the customer. Although the private sector invests much more than the government in fossil R&D (in the range of $1.5 billion per year by the oil and gas industry alone as compared to $365 million in FY 1997 by the DOE Office of Fossil Energy (FE), the private sector R&D is increasingly applied and must compete with other investments. Technologies are as likely to be externally acquired as they are to be developed internally. In the oil and gas industry, R&D is directed at frontier areas such as the deep Gulf of Mexico, the Arctic, and at other parts of the world where returns are high. Domestic mature resources are left to the independent producers who cannot generally afford R&D. For electricity generation, deregulation and restructuring have tended to shift R&D investments from utilities to their vendors. The Electric Power Research Institute (EPRI) has "unbundled" (separated) services to be much more directed at each investor, and the Gas Research Institute (GRI) is moving in a similar direction. With these changes, government investment can ensure that the necessary "public good" R&D is done to address societal issues.

The current fossil R&D programs of the Federal government[6] are addressing both the environmental and oil-price-shock challenges—more or less. The principal R&D objectives of FE were described to the Fossil Task Force and to the Panel as follows:

- Eliminate environmental impacts as barriers to fossil fuel production and use, while maintaining the availability and affordability of these fuels. This objective includes reducing carbon emissions.

- Ensure the availability of secure and affordable transportation fuels.

A third general objective of DOE is as follows:

- Maintain U.S. science and technology leadership in energy.

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[5] Fossil fuel use is still a major contributor to air pollution from both stationary sources, including power plants and industrial processes, as well as mobile sources, i.e., motor vehicles. Regulations proposed recently by the Environmental Protection Agency (EPA) would tighten NO_x emission standards to reduce tropospheric ozone from photochemical reaction between NO_x and hydrocarbons and would impose emission standards on fine particulates. In addition, other hazardous air pollutants (HAP), such as mercury from coal burning, are a growing concern.

[6] The fossil energy area as defined by the Fossil Task Force includes fossil fuel supply and conversion to electricity and fuels for end uses such as transportation, industrial production, and buildings. The Fossil Task Force's "stovepipe" does not include end use of fossil fuels or electricity, which is covered by the Efficiency Task Force, but it does include the transmission and distribution infrastructure of oil and gas pipelines. [The infrastructure of the electric transmission and distribution system was covered by the Renewables Task Force (see Chapter 6).] The Fossil Task Force did not, however, evaluate R&D on this infrastructure. Pipeline safety falls under the purview of the Department of Transportation, and the Presidential Commission on Critical Infrastructure Protection is evaluating the energy infrastructure, including both pipes and wires, relative to accidental or malicious damage.

These objectives are being pursued under conditions of declining budgets, and it is imperative to improve the productivity of R&D both from government and the private sector. FE's response is to put increased emphasis on leveraging its R&D investment with GRI, EPRI, and with industry consortia, and to begin to look for ways to get more for less. This will mean a more science-based technology development, with emphasis on computer simulation and design and with emphasis on testing of components rather than whole-system demonstrations.

Obviously, all three objectives have important international consequences. Improved coal and gas power technologies can significantly reduce CO_2 emissions globally. Oil and gas production technologies that diversify sources outside of the Middle East can help reduce the probability of a future oil price shock, and sustained domestic production reduces the cost of oil imports to the U.S. economy. Maintaining science and technology leadership improves our chances of being competitive and of providing better choices in the world markets.

The objectives seem properly drawn relative to the challenges to society, and many of the changes beginning to take place in DOE programs seem appropriate. In the Findings, Evaluations, Initiatives, and Recommendations section, these programs are evaluated against the objectives, and recommendations are discussed for new initiatives, phasing out programs, and budget changes. Clearly, R&D is necessary, but not sufficient, to advance new technologies to the point of commercialization, which is the ultimate extension of R&D. Commercialization issues are discussed in the Demonstration and Commercialization Issues section. In the Relevant Policy Issues section, some management issues are identified. In the Energy and Environmental Impact section, estimates of the potential impacts of advanced fossil technologies on CO_2 emissions and on oil and gas production are discussed. Finally, in the Crosscuts section, projects and issues that crosscut DOE and the government are enumerated. Appendix D is a somewhat more detailed working version of this chapter.

FINDINGS, EVALUATIONS, INITIATIVES, AND RECOMMENDATIONS

In this section, programs are described and findings, evaluations, initiatives, and recommendations are discussed.

Description of DOE FE R&D Program Areas[7] and Principal Findings and Evaluations

FE's R&D programs may be divided into three categories: coal and gas power, coal fuels, and oil and gas production and processing. In FY 1997, these programs were funded at $184 million, $16 million, and $70 million, respectively, for a total of $270 million. A more detailed listing of this budget is given in Table 4.1; the "Other" category in Table 4.1, amounting to a total of $95 million in FY 1997, includes predominantly the cost of program management. It also includes environmental restoration, regulatory reviews, plant and equipment, and small amounts for university research and the remnants of the Bureau of Mines. An additional $15 million was obligated in FY 1997 for the Clean Coal Program, a $2.4 billion 20-year effort cost-shared with industry to demonstrate advanced coal technologies that reduce emissions.[8]

[7] The government fossil-related R&D is concentrated in DOE. Important R&D programs also operate in the Department of the Interior (DOI), namely, the U.S. Geological Survey (USGS), which is concerned with understanding fossil resources, and the Minerals Management Service (MMS), which is concerned with the safety of offshore exploration and production. The combined budgets of these agencies for fossil-related R&D are about $35 million per year or one-tenth of the DOE budget. In this discussion, the focus is on DOE programs, but the roles of USGS and MMS, particularly as they may relate to new initiatives, are included.
[8] FE (1997a).

Table 4.1: **PCAST ProposedFive-Year (1999-2003) Fossil Energy R&D Budget (Millions of Budget Year or As-Spent Dollars)** [Note a]

				Proposed Budgets					
		1997 Actual	**1998 Request**	**1999**	**2000**	**2001**	**2002**	**2003**	**Comments**
COAL POWER		**86**	**84**	**79**	**90**	**88**	**88**	**82**	
	Advanced Integrated Gasification Combined Cycle (leading to Vision 21)	22	22	26	32	39	46	47	Vision 21
	Advanced Fluidized Bed Combustion	18	18	16	16	11	6	0	Vision 21?
	High-Performance Power Systems	10	11	8	9	4	2	0	Vision 21?
	Low-Emission Boiler Systems	10	5	0	0	0	0	0	
	Advanced Research (except for sequestration)	26	28	28	32	33	34	35	Vision 21
GAS POWER		**97**	**78**	**92**	**92**	**83**	**74**	**70**	
	Advanced Turbine and Engine Systems (such as hydrogen-fueled turbines)	47	31	33	32	28	28	29	Vision 21
	Molten Carbonate Fuel Cells	36	33	35	32	22	6	0	
	Solid Oxide & Other Advanced High-Temperature Fuel Cells	12	12	21	22	28	34	35	Vision 21
	Advanced Research	1	1	3	5	6	6	6	Vision 21
COAL FUELS		**16**	**16**	**9**	**12**	**16**	**16**	**16**	
	Direct Liquefaction	5	6	0	0	0	0	0	
	Indirect Liquefaction (includes funds for biomass & waste)	4	4	4	4	4	5	5	Vision 21
	Solid Fuels and Feedstocks	5	5	0	0	0	0	0	
	Advanced Research and Environmental Technologies	2	1	5	8	11	11	12	Note b
OIL AND GAS PRODUCTION AND PROCESSING		**70**	**77**	**86**	**94**	**107**	**110**	**113**	Oil & Gas
	Oil Production	41	46	42	43	44	45	47	
	Oil Processing	5	6	5	5	6	6	6	
	Gas Production	17	20	25	29	35	36	37	
	Gas Processing	7	6	8	11	11	11	12	
	Advanced Research	0	0	5	5	11	11	12	Note c
INITIATIVES		**1**	**2**	**18**	**21**	**40**	**46**	**47**	
	Sequestration [collaboration with USGS]	1	2	10	11	17	23	23	Vision 21
	Methane Hydrates [collaboration with USGS, MMS, and Navy]	0	0	5	5	11	11	12	Oil & Gas
	Hydrogen Manufacture and Infrastructure [joint with EE]	0	0	1	2	6	6	6	Vision 21
	Technology and Oil PriceElasticities	0	0	1	1	1	1	0	Oil & Gas
	Developing Country Technologies	0	0	1	2	6	6	6	Note d
OTHER	Program Direction & Management Support; Equipment; Environmental Restoration; Regulatory Activities, and Miscellaneous R&D	**95**	**89**	**95**	**97**	**100**	**102**	**105**	
TOTAL R&D		**365**	**346**	**379**	**406**	**433**	**437**	**433**	

[a] Totals may not be consistent with summation of entries due to rounding; uniform rounding practice was used.
[b] Retrofit environmental research for hazardous air pollutants.
[c] Advanced research with universities and national laboratories.
[d] Country-specific low-carbon technologies.

The Coal Power Program is aimed at increasing efficiency and reducing emissions. In particular, the FE R&D objective for coal is to reduce environmental impacts to such a degree they are no longer a constraint to coal use. This is a necessary condition for coal to remain a strategic resource for the country in the longer term. Coal is certainly strategic (that is, it is necessary) to the economy today because it is used to generate about 56 percent of U.S. electricity (see Box 4.1). As is the case for oil and gas, a significant fraction, about one-third of the total and two-thirds of western coal, is mined from Federal lands. Furthermore, great progress has been made in reducing the environmental impact of coal production and use through a combination of policies, ranging from regulations to R&D (funded by the Federal government and by the private sector, principally through EPRI) and demonstrations including the Clean Coal Program.

The principal remaining environmental challenge is CO_2 emissions, and it is formidable. Recently, FE has proclaimed a new initiative called Vision 21.[9] The goal of Vision 21 is to develop a power system (which might also produce clean transportation fuels) that is highly efficient (about 65 percent), produces no appreciable air pollutants, and has no net carbon dioxide emissions. In addition, the goal is a system that produces power at less cost than the best pulverized coal plants today and, in fact, at costs competitive with natural gas. This is a most ambitious vision, but it has some chance of being realized (see Figure 4.1), and it is an appropriate target for DOE.

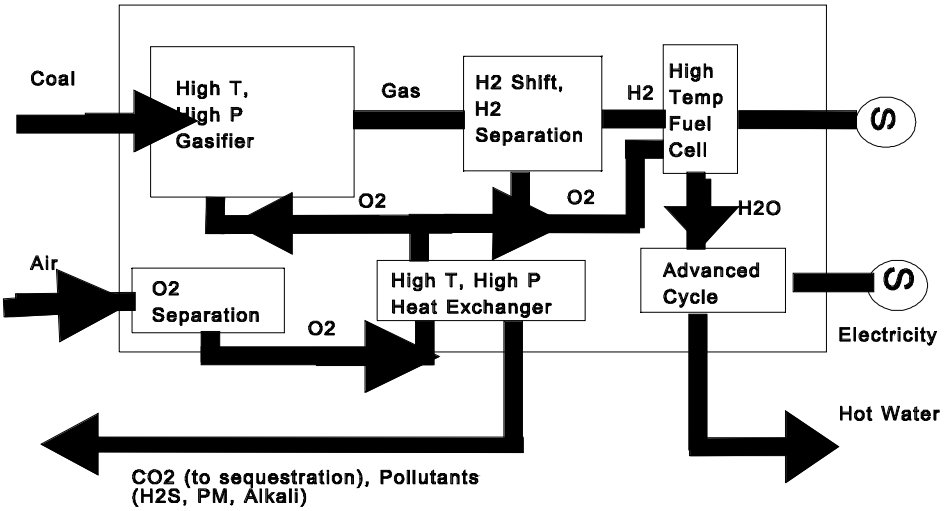

Figure 4.1: The Vision 21 Plant. Vision 21 is the DOE Office of Fossil Energy's idea for freeing coal power from environmental constraints. For this scheme, coal and/or other feedstock fuels such as biomass and some waste materials are gasified in an oxygen blown gasifier, and the product is cleaned of sulfur and reacted with steam to form hydrogen and CO_2. After heat extraction from the CO_2, it is sequestered from the atmosphere. The hydrogen can eventually be used as a transportation fuel or it could be oxidized in a high-temperature fuel cell and the reactant hot gases could drive a gas turbine and a steam generator to make electricity. This system could have an efficiency of 60 to 65 percent, which is the goal. Air pollutants are negligible and net CO_2 emissions are zero or nearly so. The overall cost goal is 10 percent less than that of a state-of-the-art pulverized coal plant. Additionally, the vision is to use producer gas in a Fischer-Tropsch process to make clean transportation liquids.

[9] FE (1997b).

Box 4.1: Coal as a Strategic Resource

Today coal is used to generate the bulk of U.S. electricity (56 percent in 1995); hence coal is certainly a strategic (i.e. necessary) resource. Reserves are enormous, equal to several hundred years of supply at the current rate of use. Similarly, large deposits are found around the world. For coal to remain strategic depends, however, on how two interrelated issues play out, cost, and carbon emissions.

For new electric generation capacity coal can not compete with natural gas environmentally or economically at this time in the United States. Gas power technologies are less expensive and they emit far less CO_2 per unit of electricity produced than the best coal technologies. However, the cost of coal is likely to remain low and the cost of gas may rise as demand for it increases. So, at some time in the future advanced coal technologies may be less expensive to use if CO_2 emissions can also be controlled economically, assuming control will be required. The same CO_2 requirement would pertain to gas, of course, although emissions are less intense.

Results of a recent DOE sponsored conference suggest that there are no very serious technical barriers to CO_2 sequestration although uncertainties about costs, environmental impacts, and the long term integrity of storage schemes remain to be resolved satisfactorily.[a] See the Initiatives Section.) Technologies for CO_2 capture and sequestration are being deployed today. In Norway, for example, Statoil, the Norwegian gas and oil company, is using state-of-the-art technology to sequester CO_2 from production of natural gas in saline aquifers under the North Sea. If these and more economical methods can be applied to coal systems, carbon emissions may be removed as an issue.

In the meantime the use of low cost coal is a practical necessity in many parts of the world including China and India where inexpensive natural gas is not likely to be found. The technology choices made by these countries will have global as well as regional and local environmental consequences and are, therefore, of importance to the United States. Consequently, the Panel endorsed two essential and interacting elements of a coal R&D strategy to be carried out in partnership with the private sector: (1) developing cost effective technologies that are attractive to coal-intensive developing countries and are much better environmentally with significantly reduced CO_2 emission rates; and (2) inventing and developing advanced components and systems leading to DOE's Vision 21 with investigation of CO_2 sequestration schemes and approaches to lower-cost clean transportation fuels including hydrogen manufacture and distribution for transportation and electric power.[b] If successful, this R&D could lead to coal's retaining a strategic part of the U. S. energy future.

[a] Socolow (1997).
[b] Hileman (1997).

Vision 21 is not a reality yet and, in most circumstances today, coal cannot compete economically or environmentally with natural gas as the fuel for new power plants in the United States with current price scenarios. This situation is likely to persist for the next decade or two, primarily because gas is relatively inexpensive and is forecast to remain so; advances in the technology of the gas turbine (and other conversion technologies) will continue to favor gas; and deregulation of the generation portion of the electric system will likely make gas the preferred fuel for new sources and for repowering.

On the other hand, coal power will likely grow rapidly in some parts of the world, notably in China and India, where indigenous premium fuels are scarce and expensive. This trend will exacerbate the CO_2 emissions of those countries, which will be major sources of atmospheric emissions worldwide. One way to moderate this impact is to develop attractive coal power technologies that have lower CO_2 emissions (see Box 4.2). Because most activity will be in developing-nation markets, the FE program should focus on them.

Vision 21 must be compatible with this reality; it needs to be a technology for the global market, or it may fill no market at all. R&D should be tailored to produce versions that are attractive to specific developing-country situations. This global focus of R&D represents a major paradigm shift for DOE and for Congress. It requires a substantial overhaul of the DOE coal power program.

Box 4.2: The Cool Water Integrated Coal Gasifier Combined-Cycle Plant
A Model For Government/Industry Collaboration

The goal of the Cool Water Coal Gasification Project, located at the Southern California Edison (SCE) Mojave Desert site, was to design, construct, test, and operate the world's first commercial-scale integrated coal gasification combined-cycle (IGCC) plant. The IGCC design included a new 120 megawatt electrical generating unit. The project's industrial sponsors viewed coal gasification as a way to use the world's vast coal resources in a way that would meet or surpass environmental performance requirements without add-on pollution controls. By taking advantage of rapidly improving gas turbine technology, a significant increase in conversion efficiencies could be achieved, thus reducing CO_2 emissions as well. Cool Water provided a commercial-scale process to better understand operational dynamics, coal suitability, and environmental performance. Construction of the project began in December 1981 and was completed in April 1984.

In addition to financial support from SCE ($40million), the project was funded at $45million by Texaco, and $30 million each by GE, Bechtel Power, and the Japan Cool Water Program Partnership. The Electric Power Research Institute (EPRI), representing the U.S. utility industry, contributed $75 million and additional funding of $5 million each was provided by the Empire State Electric Energy Research Corporation, and the Sohio Alternate Energy Development Company. The U.S. Synthetic Fuels Corporation agreed to provide price differential payments up to $120 million for syngas produced after commercial production began in June 1984. The facility was to operate under price guarantees for an initial 5 years and then to be acquired by SCE for a total operational life of 20 years. The plant ran until 1989 when the essential objectives of the program had been met and after a period of low and stabilized oil prices. A total of $105 million price differential payments was made out of the $120 million originally authorized.

Completed ahead of schedule and under budget, the Cool Water Project demonstrated that a commercial-scale synthetic fuels facility involving first-of-a-kind technology could be successfully planned, organized, designed, constructed, and operated. It also demonstrated that, notwithstanding technical success, start-up financial assistance for such projects might still be necessary for survival in today's energy market. Nevertheless, commercial interest in the technology continues to increase as combined-cycle efficiencies continue to approach 60 percent with significant reductions in capital costs and CO_2 emissions. Fluidized bed combustion (FBC) has provided only modest environmental and cost advantages in recent years. Although capital costs still remain slightly above FBC options, the imposition of CO_2 limits would increase IGCC's attractiveness substantially. The Cool Water experience has been broadly shared with other IGCC projects in Europe, Asia, and the United States.

Lessons Learned

1. Demonstration-scale projects should require industry to provide the capital costs for the facility. Participation should be as broad as possible across the designer, constructor, owner/operator or user communities to ensure a competitive supply capability and widespread experience. EPRI's funding, for example, provided a means by which all U.S. utilities could participate—from design input to data output.

2. Government support for technology deployment and commercialization should focus on market stimulation, environmental issues, and plant or product testing, rather than on plant costs. Government support in dollars and time should be capped.

3. A well-defined test program to demonstrate all expected benefits is essential.

The Coal Power Program consists of the following project areas: the low-emission boiler systems (LEBS); advanced pressurized fluidized bed combustion systems (PFBC); the high performance power systems (HIPPS); advanced integrated coal gasification combined-cycle systems (IGCC); and advanced research that is crosscutting and includes environmental technology. LEBS is needed to develop the next generation of pulverized coal plants with greater than 42 percent efficiency and very low NO_x and SO_x

emissions. It is evolutionary near-term technology. Advanced PFBC involves a fluidized-bed carbonizer to produce a fuel gas and char, which is burned in a fluidized-bed combustor. Both the carbonizer and combustor include a limestone sorbent for sulfur removal. The hot flue gases after particulate cleaning are fed to a gas turbine combined cycle powered with the fuel gas. HIPPS uses a coal-fired high-temperature furnace to heat compressed air, which is the working fluid for a gas turbine combined cycle. Heat input may be boosted by burning pyrolysis fuel gas or natural gas. The goal is efficiency in excess of 50 percent on a higher heating value basis.[10] IGCC involves the gasification of coal to produce a gas that is burned in a gas turbine combined cycle; efficiencies in excess of 50 percent are the goals.[11] Alternatively, hydrogen or liquid fuels can be produced as in Fischer-Tropsch indirect liquefaction; if the gasifier is oxygen blown, the products can be CO_2 and hydrogen, with the former being separated for sequestering relatively inexpensively. IGCC fits Vision 21 well; others may have components or variations that fit to a degree or aid the transition to Vision 21, but CO_2 separation will be more difficult for LEBS, PFBC, and HIPPS.

Finally, the advanced research program contributes to all the projects with technologies for solving difficult problems such as corrosion or of making gaseous separations at low cost. Success for Vision 21 depends on significant innovations in the areas of separations, catalysis, corrosion, combustion, materials, computational science and design, and electrochemical processes. Contaminant removal for environmental or process (to prevent degradation of equipment) reasons is critical to the emerging technologies and is thus a crosscutting issue, although specifics of the methods will likely vary from technology to technology. To obtain maximum efficiencies, it is necessary that this contaminant removal, which may be accomplished by physical or chemical methods, be performed at or near the temperature of operation of the process system. Among the most important contaminant removal processes are particulate removal using hot-gas filtration and sulfur removal using high-temperature sulfur getters. Hot-gas cleaning for removal of corrosive and/or noxious contaminants and for removal of particulates is an integral part of the development of the various high-performance technologies.

The Gas Power Program will extend the competitive advantage of gas over coal, but it will also provide essential elements of Vision 21 (see Box 4.3). The program includes both advanced gas turbines and two high- temperature fuel cells: solid oxide and molten carbonate. Natural gas combined-cycle systems are revolutionizing the power industry and plants with efficiencies of 52 to 55 percent are being achieved. Further advances being pursued have diminishing returns compared to the very significant efficiency improvements already made for combined-cycle systems. Nevertheless, the further improvement of gas turbine and other heat engine technologies, particularly with the innovation of the high-temperature fuel cell combined-cycle systems, development of smaller scale but more efficient gas turbines, and the development of hydrogen turbines, will lead not only to further productivity of natural gas in power generation, but to the improvement of coal, biomass, and waste systems as well.

The Advanced Turbine Systems (ATS) Program seeks to develop a greater than 60 percent thermal efficiency (lower heating value or LHV) system in combined-cycle applications, with very low NO_x emissions. The ATS is a collaborative program with the Office of Energy Efficiency and Renewable Energy (EE), which is developing smaller scale industrial turbines, and it is an excellent example of joint planning and execution of a crosscutting program.

The molten carbonate fuel cell (MCFC) and the solid-oxide fuel cell seek 50 to 60 percent stand-alone efficiencies for distributed or centralized applications. The fuel cells may also be used with turbines in

[10] Higher heating value refers to the heat of combustion of a fuel, including the heat of vaporization of water formed during the combustion process, whereas lower heating value does not include the heat of vaporization of water. The difference becomes more important as the hydrogen content in the fuel increases.
[11] FE (1997b).

a combined cycle arrangement with an efficiency goal of about 70 percent. These technologies are compatible with Vision 21. However, the lower temperatures of the MCFC make it less efficient in a combined cycle, and the movement of CO_2 across the electrolyte may make carbon management more difficult. Both fuel cells have important potential in properly managed biomass systems where net CO_2 emissions are zero, by definition (Chapter 6). The sensitivity of fuel cell performance to impurities in the fuel stream is an important research topic for applications with coal, biomass, or waste primary fuels.

Advanced research, including that directed to innovations in electrochemistry, catalysis, and materials, that contributes to all power systems, but particularly focuses on gas power systems, may lead to innovations crucial to achieving the very high efficiency goals of this program. Electrochemical processes are crucial to fuel cell (as well as battery) advances, and additional support for electrochemical R&D seems warranted. One difficulty is that electrochemistry seems to be a neglected topic in the curricula of the best engineering schools in the United States. Additional effort and funding for advanced research for gas power systems are warranted.

Box 4.3: Natural Gas as the Transition Fuel

Because of the forces of competition loosed by deregulation and advances in the technology of finding and producing gas from ever more difficult formations, the price of natural gas at the well head is at less than $2/million Btu and is expected by EIA projections to remain at such levels for the next 20 years even with a one-third increase in consumption during that period.[a]

Because of its highly competitive cost, its cleanliness and efficiency in conversion, and because the combustion turbine with or without combined cycle technology is relatively inexpensive and can be put in place quickly, gas is the fuel of choice for new electricity capacity additions. Its direct utilization in many other end-use applications in industry, buildings, and even in transportation is growing. To the extent that gas is used instead of coal or oil, carbon dioxide emissions are reduced both because of the higher hydrogen content of natural gas compared to other fossil fuels and because it can often be used more efficiently so the yield of useful services per unit of chemical energy expended is greater.

For the United States, gas is providing a low cost means to slow the rate of growth of CO_2 emissions. It has been called a bridge to a renewable energy future,[b] but the irony is that the low cost of gas makes it difficult for renewables to compete economically. Nevertheless, gas will be a significant strategic energy source for moderating carbon emissions well into the middle of the next century.

The R&D strategy is to continue to develop technologies that will expand domestic reserves and keep the cost of production down. It may be that gas can be produced economically from the methane hydrates on the continental shelf, and this may prove to be a very large new source globally, particularly for some developing countries such as India as well as for the United States. (See Initiatives section.)

Natural gas may be the transition fuel in another sense. It may become a transportation fuel itself or a competitive source of transportation liquid fuels (see Figure 4.3.) and ultimately the least cost source of hydrogen for transportation should fuel cells become the power sources of choice for advanced ultra efficient vehicles. In a real sense, gas will be the first test bed for technologies which may ultimately be used with coal in a greenhouse-constrained society where hydrogen manufacture and or power production is accompanied by carbon sequestration.

[a] EIA (1997).
[b] Serchuk and Means (1997).

The Coal Fuels Program is aimed at production of transportation fuels from coal through direct or indirect liquefaction. It also includes a program on coal preparation R&D that is now called Solid Fuels and Feedstocks in the new program plan[12] and a program called Advanced Fuels Research that supports the other three components.

Neither direct nor indirect liquefaction is likely to be important in the U.S. fuels market in the foreseeable future, and both produce copious quantities of CO_2, about twice as much as is produced from petroleum-derived fuels. Furthermore, the gas-to-liquid fuels technology is much closer to producing clean diesel fuel at near competitive costs, and it yields much less CO_2 emissions (0 to 15 percent more than petroleum derived diesel fuels).

Indirect liquefaction involves first the gasification of coal to produce synthesis gas, followed by purification to remove CO_2 and other contaminants, and then conversion of the synthesis gas to liquid products using the highly flexible Fischer-Tropsch processes. Thus, indirect liquefaction is compatible with Vision 21 (coal gasification) and with gas-to-liquids (Fischer-Tropsch) technology. Furthermore, coproduction of liquid fuels and electricity provides process efficiencies in the indirect process that reduce the amount of carbon dioxide emissions.[13] This flexibility may prove to be attractive for developing countries. Indirect liquefaction may also be applied to biomass and certain waste materials. The R&D experience and expertise of FE and its industrial contractors should be applied to such renewable resources in collaboration with EE. As with coal, these feedstocks cannot compete economically with petroleum, let alone natural gas, in the United States, but this may not be the case globally, and certain niche markets may serve to accelerate the technology on a productive learning curve.

Direct liquefaction of coal involves the catalytic reaction of hydrogen directly with coal in process derived solvents. Tremendous advances (product yields, purity, ease of upgrading, etc.) in direct liquefaction technology have been made since the era of large pilot plants in 1979-1982. However, there is a considerable cost (and CO_2) burden associated with the hydrogen production necessary for direct liquefaction processing. Thus, direct liquefaction does not appear to offer any advantages over indirect liquefaction; it is not competitive with direct liquid hydrocarbon supplies; and it is not compatible with Vision 21.

The Solid Fuels and Feedstocks Program may lead to better methods for cohandling a variety of solid fuels with coal, such as biomass and some waste materials, and it may lead to methods for reducing mercury and other hazardous air pollutants (HAP) via coal cleaning; if the latter is the principal objective, the R&D seems much too narrowly focused. Rather, a comprehensive science-based effort on HAP should be initiated as an accelerated environmental retrofit program that includes the front end of the cycle.

Oil and Gas Production and Processing R&D is directed at the margins of the resource base. These margins include (l) high-risk but potentially high-impact research investments at the front end of the resource cycle (e.g., deepwater methane hydrates R&D discussed in the Initiatives section below), which are generally not yet pursued by the established industry, and (2) investments in stimulating technology transfer through demonstrations and other means to maintain production from lower margin resources characterized by significant though small increments of production, e.g., stripper well production, which are pursued by independent operators without internal capability. (See Box 4.4 and Figure 4.2.)

The former investments contribute to U.S. science and technology leadership in industry as well as to resource diversification in frontier provinces such as the deep Gulf of Mexico and around the globe outside the Middle East. The latter investments contribute to three objectives. First, they help sustain domestic

[12] FE (1997b).
[13] Gray and Tomlinson (1997).

production from mature resources, which reduces the balance of payments accounts from oil imports. This is beneficial as long as these resources are cost competitive, and may be particularly important during an oil price shock. Second, they prevent premature abandonment, and therefore loss, of some resources. Third, they help maintain revenue streams to Federal and State treasuries from taxes and royalties, which may amount to more than $6 billion per year for all U. S. domestic production.

Box 4.4: Secondary Gas Recovery: A Government/Industry Success Story

In 1988, DOE produced a landmark study that assessed the unrecovered natural gas in the nation's old natural gas fields at 288 trillion cubic feet (Tcf), an estimate more than three times greater than the then-current estimate by the Interior Department. Some oil and gas industry experts knew that geologically complex oil reservoirs did not drain easily, but it was not recognized that natural gas could be blocked by these complexities from reaching wells – even in very old fields. With gas price projections to the year 2000 declining with each new assessment, DOE was motivated to propose a partnership to prove the existence of this potentially huge additional resource for satisfying the nation's demand for low-cost gas.

DOE teamed with GRI, the State of Texas, and private industry, creating the Secondary Gas Recovery (SGR) Project to exploit powerful new technologies to prove the "gas reserve growth" potential. DOE leveraged $8.5 million in federal funding with $6.5 million from GRI, $1 million from Texas, and $6.3 million from industry to support a 5-year proof-of-concept project. The new technologies to be developed and applied included 3-D seismic and vertical seismic profiling. The Bureau of Economic Geology at the University of Texas led the SGR team and coordinated the research, first in the onshore Texas Gulf Coast Basin and then in the Ft. Worth Basin.

The most important measures of the SGR Project's success are the substantial increase in the assessed secondary natural gas resources and the increased production of the gas in the targeted districts of the Texas Gulf Coast. Knowledge of the technologies applied by the project was transferred to industry through a program of 14 short courses and workshops conducted by the SGR team and attended by more than 600 individuals, of whom two-thirds are independent producers and consultants. Compared to the period from 1990 to 1992, the increased national secondary gas production ascribable to the knowledge disseminated and the technologies developed and applied by the SGR Project may have reached 30 percent by 1996. Extrapolating from the 1993 drilling rate to 2000 and ascribing only 20 to 30 percent of the incremental production to the SGR Project, gross incremental production revenue by 2000 would range from $916 million to $1,374 million, at prices no more than $2.51 (1994 dollars) per thousand cubic feet for the Gulf Coast alone. These revenues are as much as 60 times the SGR team's investment. Moreover, the 1996 GRI estimate of the secondary gas resource is now 508 Tcf for onshore and waters of the lower 48 states.

Lessons Learned

1. Federal R&D partnership with industry is appropriate to motivate development and application of technology with potentially large energy, economic, environmental, and strategic returns to the nation.

2. Equitable and stable cost-sharing and existence of mutual benefits are essential for commitment of project partners over the project period.

3. Clear technical objectives and feasible performance, cost, and schedule goals must be stated and agreed upon before project initiation.

4. Project risks and potential excess of costs over benefits must be frequently assessed.

5. Projects should be led by individuals with proven technical and managerial competence and experience.

6. Projects with a steep learning curve should be favored for Federal support.

The R&D areas include advanced drilling, completion, and stimulation systems; advanced diagnostics and imaging systems; reservoir life extension; oil and gas processing; and environmental and crosscutting research.[14] The gas processing area focuses on the important question of converting natural gas to liquid fuels, particularly clean diesel fuels, and it features advanced ceramic membrane separation (Figure 4.3) and catalysis devices to reduce the costs. This area is very compatible with Vision 21.

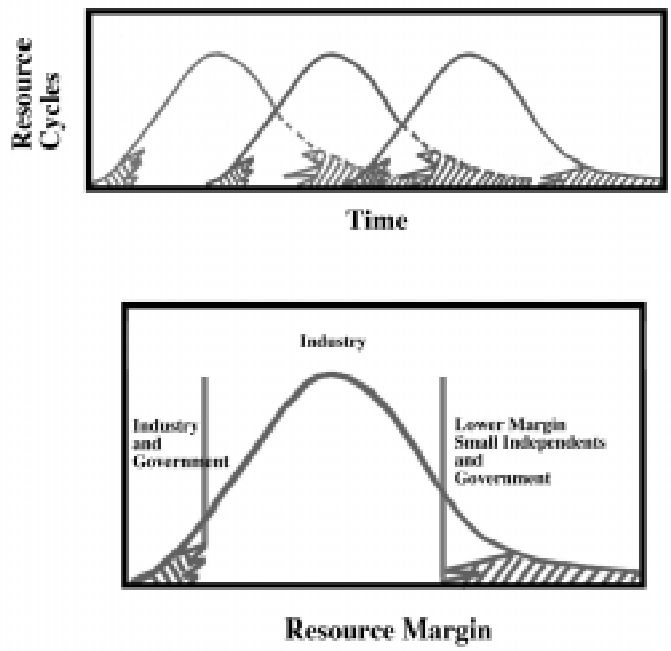

Figure 4.2: The oil and gas resource cycle and public/private roles. Government involvement in oil and gas R&D is appropriate at the front end of the resource cycle, where risks are high but impact potential is great, and for the strategically important lower margin resources at the back end of the resource cycle, where the principal activities of government involve technology and information transfer and demonstration of advanced technology. With time, the resource base changes, e.g., from mature onshore to shallow offshore to deep offshore; the industry segments may change as well.

Also, DOE has the opportunity to create and maintain a National Geosciences Data Repository System to archive well logs and other data currently at risk of being discarded or destroyed by industry. This effort, through the American Geological Institute and the geosciences societies, to preserve important scientific data and complementary efforts to archive core specimens will contribute significantly to increased understanding from and use of a very large base of well-drilling experience.

The oil and gas R&D investment seems about right based on several benchmarks. In fact, increased gas production efforts in collaboration with GRI and other parts of the industry are warranted given increasing demands projected by GRI and EIA (about 30 Tcf by 2015), perhaps stimulated further by the need to control CO_2. R&D directed at marginal and frontier resources may produce technologies necessary to stabilize costs of increased production. Further, such technologies may help expand the global gas availability (e.g., gas hydrates or coal seam methane) and use in some countries where development is currently unattractive. R&D planning should be in the context of the strategic significance of gas for

[14] FE (1997c).

reducing CO_2 emissions globally. The R&D investment is a kind of insurance policy against an uncertain and unwanted future.

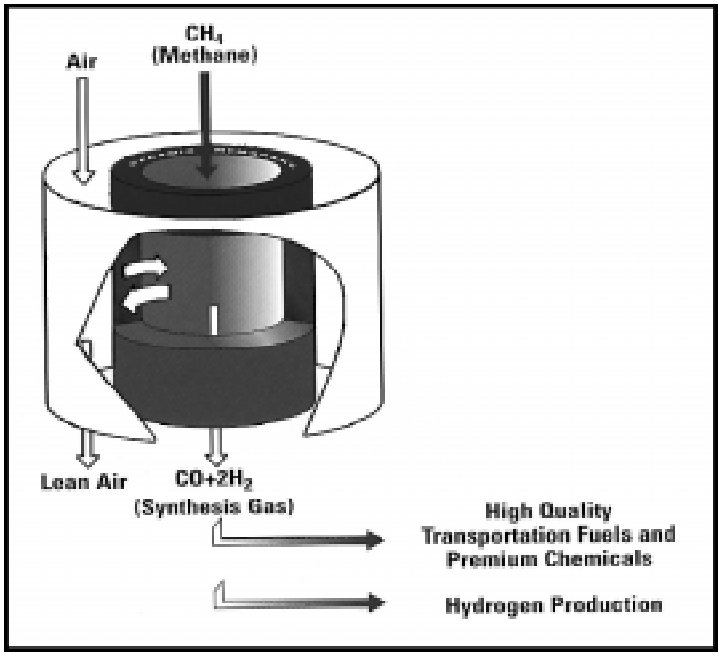

Figure 4.3: The natural gas to liquids process. Natural gas to liquids may be the process most nearly economical for making clean synthetic transportation liquids from fossil fuels other than oil. The cost can be reduced if oxygen can be extracted from air more efficiently than by cryogenic processing. DOE FE is supporting R&D on one promising method. It uses a high-temperature ceramic membrane to pass the oxygen as ions from the air side to the methane side.

Recommendations

Below are summarized the Panel's recommendations for modifying and enhancing FE programs to better accommodate potentially changing circumstances and to better leverage and encourage private sector investments.

Coal and Gas Power

The recommendations for coal and gas power are the following:

- **FE's coal power strategy should be the introduction, to specific coal-intensive countries, of attractive power technologies that reduce carbon dioxide and other emissions. (See developing countries technologies discussion in Initiatives section.)**

- **FE should invest more aggressively in a focused advanced-research program, leveraging fundamental research in the Office of Energy Research (ER), Office of Defense Programs, Department of Defense (DOD), and the National Science Foundation (NSF), and encouraging innovative ideas from industry.** Vision 21 will become a reality only with significant breakthroughs.

Maximum use of computational science for enhanced simulation and design—aided by science of materials, separations, combustion, electrochemistry, and catalysis and with emphasis on component testing rather than large demonstrations—will reduce costs while helping to ensure science and technology leadership in pursuit of Vision 21.

- **A much larger science-based CO_2 sequestration program should be developed, with the budget increasing from the current $1 million per year to the vicinity of tens of millions. It should involve the USGS as well as the upstream oil and gas scientific and technical community and ER.** (See CO_2 sequestration in Initiatives section below).

- **A program should be built with EE to develop technologies to reduce the cost of manufacturing hydrogen from carbonaceous materials and to develop a strategy and technology for evolving a hydrogen supply infrastructure.** (See hydrogen manufacture and infrastructure discussion in Initiatives section below.)

- **A joint program with EE should be developed to bring FE's experience and expertise to bear on applying IGCC, PFBC, and other concepts to biomass and waste**. (See Chapter 6.)

- **LEBS should be ended, and the budget should be directed to Vision 21 and to reducing hazardous air emissions from existing and future coal-fired plants.**

Coal Fuels

The recommendations for coal fuels are the following:

- **The Direct Liquefaction Program should be terminated and the resources applied to Vision 21.**

- **The Solid Fuels and Feedstocks Program should be ended, and the budget redirected toward a comprehensive science-based program aimed at technologies to reduce hazardous air emissions, including fine particulates, from existing and future coal-fired plants.**

Oil and Gas Production and Processing

The recommendations for oil and gas production and processing are the following:

- **FE should develop with industry, including industry associations such as GRI, a strategic R&D plan for natural gas as the transition fuel of the twenty-first century. (See Natural Gas Box.)**

  Collaborative planning with industry has been ongoing for several years and the Panel recommends renewed R&D emphasis on natural gas for the transition to lower CO_2 emissions and decreased oil imports.[15]

[15] FE (1995).

- **FE should increase the R&D investment for gas production and processing technologies. With anticipated increasing demand (perhaps in the range of 30 to 40 Tcf), the cost of domestic production from frontier and marginal resources will rise significantly unless better technologies are developed and applied.**

- **FE should continue supporting technology transfer and cost-effective demonstrations to help maintain production from mature and marginal regions of domestic production.**

- **An advanced research component should be added to the budget. It would provide support for foundation-building R&D in universities and the national laboratories to help maintain the leadership of the United States in oil and gas technologies**

- **FE should develop a science-based program with industry, the USGS, MMS, EPA, and the Department of the Navy to understand the potential of methane hydrates worldwide. (See Initiatives section below.)**

- **FE and EE, with the analytical support of the EIA, should examine the potential impact of better technologies on the long- and short-term price elasticity of oil supply and demand, including the impact of substitutes, to develop a more effective R&D portfolio to reduce the cost of future oil shocks. This examination will help DOE develop a Comprehensive Transportation Fuels R&D Strategy. (See Technology To Reduce the Cost of Oil Price Shocks discussion in Initiatives section below.)**

- **FE, with the American Geological Institute, the geosciences societies, and the USGS, should ensure adequate archiving of drilling records and core samples, which are at risk of being discarded or destroyed.**

Initiatives

Initiatives include CO_2 sequestration, methane hydrates, hydrogen manufacture and infrastructure, technology to reduce the cost of oil price shocks, and developing-country technologies.

CO_2 Sequestration

Carbon dioxide emissions from the use of fossil fuels may prove to be the greatest vulnerability of these energy sources. Emissions per unit of energy service provided can be reduced by improving the efficiency of conversion and by capturing and permanently sequestering CO_2 emissions. Doing the latter on a scale necessary to make a difference is an enormous undertaking, at least as difficult as extracting fossil fuels in the first place. The capture and sequestering of emissions from coal-fueled power plants have been estimated to increase the cost of electricity delivered to the bus bar by at least 30 percent.

On the other hand, Williams has argued that if hydrogen becomes the principal transportation fuel, the cheapest method of manufacture will be by carbothermic reduction of water using fossil fuels or biomass.[16] If this manufacture is done centrally near places where CO_2 can be sequestered, the estimated cost of hydrogen delivered to market still will be less than that by any other method of production. A principal reason is that CO_2 is a pure by-product of the process, so the separation is done and the added cost is for sequestration only. For hydrogen to become a principal transportation fuel, the fuel cell must become the

[16] Williams (1996).

power source of choice for highway vehicles. This scenario represents a long-time-horizon, i.e., the middle of the twenty-first century viewpoint. (See also the Hydrogen Manufacture and Infrastructure initiative below.)

The many approaches to CO_2 sequestration have been analyzed recently by Herzog et al.[17] This work and the results of a recent workshop indicate a need for R&D in the following areas: estimating the size and location of sequestration sinks, e.g., deep saline aquifers and depleted oil and gas reservoirs; evaluating potential environmental impacts, e.g., with deep ocean disposal; evaluating better techniques for separating CO_2 and novel ideas for transforming it, e.g., to clathrates for ocean disposal perhaps synergistically with production of methane from methane hydrates; evaluating ideas for using CO_2 in the process of sequestration, e.g., to help recover coal seam methane through substitution of adsorbed CO_2 for adsorbed methane; and evaluating the permanence of various sinks.[18]

The R&D should be supported and managed by FE in collaboration with ER and the USGS. It should also collaborate strongly with international efforts, notably those in Japan and Europe. The aim should be to provide a science-based assessment of the prospects and costs of CO_2 sequestration. This is very-high-risk long-term R&D that will not be undertaken by industry alone without strong incentives or regulations, although industry experience and capabilities will be very useful. It is important to recognize the risks associated with any R&D program that will not have an impact for more than 20 years.

The current annual funding level of $1.0 million in FE is insufficient. It should be increased to a level in the range of several tens of millions (following the agenda recommended by the DOE workshop mentioned above), but care should be taken to establish specific objectives for each part of the program and criteria for judging when R&D should be terminated.

Methane Hydrates

Methane hydrates are a potentially enormous natural gas resource. Estimates range from 100,000 to 700,000 quads (Tcf) worldwide in ocean sediments, many times the entire estimated conventional resources of natural gas and oil.[19] Methane hydrates are solid icelike materials containing molecules of methane bound in a lattice of water molecules. The stability of these materials is such that they are formed on ocean shelves at several hundred to several thousand feet depth, with the release of methane from decay of biological materials deposited there. Methane hydrates are also found under permafrost in arctic regions, and in fact gas has been produced from deposits in Siberia.[20] Because of the wide geographical distribution of these deposits, they may provide a source of natural gas for some otherwise gas-poor regions. For example, India has recently begun to offer leases for methane hydrates off its southeastern shore.

Major deposits for the United States lie off the Carolina coasts and the deep-water portions of the Gulf of Mexico shelf. Some exploratory drilling sponsored by NSF has been done as a part of the Ocean Drilling Program, and industry expects to encounter deposits in the process of drilling for conventional oil and gas in the Gulf of Mexico. In fact, DOE sponsored a hydrate program from 1983 to 1992, and invested about $8 million in that effort. Given the growing desirability and demand for natural gas, the termination of that activity was probably premature. Many questions remain to be researched, including fundamental thermodynamic and kinetic properties, safety and environmental impact of production schemes, the economics of production, and even disposal of CO_2 emissions as hydrates in the same vicinity where the methane is produced. Industry R&D is likely to focus on drilling hazard mitigation. One issue that has

[17] Herzog et al. (1997).
[18] Socolow (1997).
[19] Kvenvolden (1993).
[20] Collett (1993).

received considerable attention is the possibility that climate change can produce some positive feedback, which could cause release of large quantities of methane to the atmosphere. The DOE research program should contribute to better understanding of this possibility.

The research agenda should be formulated with FE leadership, and ER, USGS, MMS, EPA, and the Department of the Navy (Naval Research Laboratory), at least, should be involved in the formulation. The program should be developed jointly with the oil and gas industry. It should also seek strategic ties with key countries. The budget for this program can start at a few million dollars a year to develop a comprehensive R&D agenda. Carrying out the program should be leveraged by the private sector, other agencies, and the international community.

Hydrogen Manufacture and Infrastructure

FE should work with EE to develop a comprehensive program on hydrogen manufacture. EE has the lead on hydrogen, but FE should help with the R&D agenda for the manufacture of hydrogen from fossil fuels, biomass, and wastes (Chapter 6). FE should bring to bear the experience from IGCC, other coal technologies, and from the gas-to-liquids processing technology and should use its close association with the coal and the oil and gas industries. In collaboration with ER, emphasis should be on fundamental research to improve separations, catalytic processes, and materials. The objective should be to lower manufacturing costs.

The other issue is the evolution of an infrastructure for the safe distribution of hydrogen. The experience of the oil and gas industry should be invaluable with respect to operating hydrogen systems, including materials for pipelines, compression and storage technology, safety systems, and cost estimates, to name a few.

Technology To Reduce the Cost of Oil Price Shocks—A Comprehensive Transportation Fuels R&D Strategy

A key objective of the FE R&D program is to develop technologies that can reduce the cost of the next oil price shock, not to mention the cost of paying a premium for oil because of cartel power in the market. Meeting this objective will also increase world security by decreasing oil imports. This objective includes technologies that can diversify petroleum sources worldwide, create substitutes, and decrease dependence on oil (see Box 4.5). The FE contribution involves R&D relevant to increased oil and gas production from domestic resources and to substitutes including transportation fuels from natural gas and coal. How effective are these activities given the fact that price shocks are short-term phenomena? What else can be done with R&D policy? What about the demand side of the response, which is the responsibility of EE? Do these two parts of DOE need to collaborate and coordinate their R&D more aggressively? Should oil dependence be managed as a cross-cutting opportunity?

FE and EE, with the help of EIA, should develop an analytical framework for assessing the impact of advances in technology on the long- and short-run elasticities of oil supply and demand. Such a framework will provide DOE with a tool for evaluating R&D choices and other policies for moderating the cost of potential future oil price shocks caused by large but short-duration—several years—supply reductions, such as those that occurred between 1973 and 1974 and between 1979 and 1980. The modeling effort should be reviewed by the National Academy of Sciences and industry groups representing oil, gas, coal and transportation.

This analysis will help DOE formulate a comprehensive transportation fuels R&D strategy (see Chapter 6). Currently, work in EE is in progress on alcohol fuels from biomass, alternative fuels vehicles,

and hydrogen, and in FE on enhanced oil and gas production and processing, including gas to liquids. All of these disparate activities have not been brought into a coherent comprehensive strategy focused on the oil dependence, price volatility, and security issues. The *Comprehensive Transportation Fuels R&D Strategy* must be supportive of environmental objectives as well.

Box 4.5: Oil Security Requires a Transportation Fuels R&D Strategy

Almost all—97 percent for the United States—of the world's transportation fuels derive from petroleum, but 65 percent of the world's proven reserves are in the Middle East. Fifty percent of world exports of petroleum come from this notoriously unstable region, and they are growing.

Two major oil price shocks over the past quarter century due to interruptions of Middle East oil supply and cartel pricing have been estimated to have cost the U.S. economy almost four trillion dollars from 1972 to 1991.[a] One fourth of the loss was transfer of wealth[b] and the rest was loss of GDP. This does not include the cost of the Gulf War which itself caused a third supply interruption from Iraq and Kuwait that was made up by Saudi Arabia. Oil prices did rise appreciably during that disruption, but only briefly prior to the Saudi Arabian action.

No one knows the probability of another disruption, but it is not zero, and it may grow as OPEC market share and hence market power grow. If an interruption of the size of those of the seventies were to occur sometime in the next decade followed by a gradual return of supply, the cost to the U.S. economy has been estimated to be about half a trillion dollars with an equivalent gain by oil exporters.[c] Selling from the Strategic Petroleum Reserve (SPR) would help moderate costs, but not by much because the SPR is too small to offset such a large and sustained shortfall..

Reducing imports will decrease the cost to the economy of an oil price shock. Perhaps more importantly, reducing imports lessens stress on the world market that can create instabilities and threaten world security. Imports are not the whole problem, however. Even if the U.S. imported no oil and the entire U.S. oil demand were produced domestically, the price of transportation fuels would rise due to a curtailment in world supply since oil is an internationally traded commodity.

There are several promising R&D strategies for reducing the cost of a future disruption and for increasing national security by reducing oil imports. Included are improving transportation fuel efficiency, attractive alternative fuels, enhanced domestic production of petroleum and increased diversification of supply outside the Middle East, and to increased price responsiveness (elasticity) of supply and demand both short and longer term. The effectiveness of each R&D target will vary; for example, efficiency improvement that reduces demand overall will have a different impact than enhanced domestic production. Furthermore, each of the alternative fuels: compressed natural gas, liquid fuels produced from heavy crude, gas, coal, biomass or waste, electricity; and ultimately hydrogen produced from fossil fuels or biomass or even from electricity will have a different impact depending on R&D success. The evolution of transportation fuels given concerns about oil security and the environment (e.g., climate change) and the difficulty with infrastructure change can be influenced enormously by the results of R&D.

Because the issues are complex, the implications of technology trade-offs and opportunities are not easily understood, and they change with time. For this reason the Panel calls for DOE to develop a comprehensive Transportation Fuels R&D Strategy that exposes and evaluates the options and opportunities and helps to inform R&D investment by government and industry. Success could be worth a lot of money and improved security.

[a] Greene and Leiby (1993).
[b] Transfer of wealth refers to the increased cost of oil imports beyond what would have been paid had oil pricing been competitive. The wealth transfer calculations of Reference 23 were found to be in error recently. The value is about one trillion dollars rather than 1.5 trillion (Paul Leiby, personal communication, October 1997.)
[c] Greene, Jones, and Leiby (1995).

Developing Country Technologies

The attractiveness to various developing countries of advanced technologies that emit less CO_2 will depend on how well the technologies fit the specific situation in each country. A developing-country initiative would be in support of joint research programs with in-country organizations, resulting in technology adapted to or developed for specific coal-intensive countries. An example might be coal bed methane in China. The potential resource is of the order of 1200 Tcf, and its production could reduce CO_2 emissions to the extent that gas substitutes for coal. The R&D would focus on using CO_2 or coal-power-plant flue gas to enhance recovery of methane from coal seams while simultaneously sequestering CO_2 as well as other pollutants. This initiative would augment and focus FE's existing international program toward joint R&D. This initiative should be pursued jointly with the U. S. Agency for International Development (AID) and various international R&D and financial organizations.

Budget Recommendations

The Panel concludes that the overall FE R&D budget level is about right., but it recommends significant redirection of resources. For this redirection to be productive, however, it is essential that FE continue effective cost sharing and leveraging against private sector R&D investments. With only modest (less than 15 percent) budget increases, funding for the five initiatives and for Vision 21 can be derived from budget rearrangements involving the ending of certain programs, such as LEBS, direct liquefaction, and solid fuels and feedstocks, and the gradual phasing out of others, such as PFBC, HIPPS, and MCFC, as they are completed, commercialized, abandoned, or transitioned into Vision 21.

This suggested redirection is shown in Table 4.1 for the 5 years of FY 1999 through FY 2003. The budget is in budget year or as-spent dollars adjusted for assumed inflation. It should be noted that the funding recommendations for initiatives, which include some elements of Vision 21, are strictly suggestions and are not meant to be prescriptive. Each will evolve to more or less than the targets suggested in Table 4.1. This suggested budget also accommodates the development of a comprehensive research program aimed at the cost-effective reduction of hazardous air pollutants from existing and future coal-fired electric plants. It includes an advanced research component to the Oil and Gas Production and Processing Program, as well as an increase in funding in the gas production and processing areas. A larger advanced research budget relative to gas power in the areas of fuel cells and advanced turbine systems is also recommended. It should be noted that FE is in the process of restructuring and rethinking its R&D agenda. Many ideas are being explored, and they may justify additional budget increases. Vision 21 is such an idea, and it entails a moderate- to long-term R&D program which, if successful, will likely lead to significant budget increases within several years as the need for demonstration of the concepts develops.

DEMONSTRATION AND COMMERCIALIZATION ISSUES

As has been noted, the principal markets for advanced coal technologies are in developing nations. The U.S. market will be dominated, at least through 2015, by gas for new electricity capacity as indicated by the AEO 97. The ratio may be 10 to 1. In the period to 2015, 30 gigawatts of new coal capacity may be built. Although this still gives an adequate market for some demonstrations of advanced coal technologies; the great bulk of the activity will be abroad, and that is where the impact of advanced coal technologies on reducing CO_2 emissions can be important.

To provide attractive choices, two conditions must be met. First, the technology must be demonstrated in the countries that will use them and shown to be reliable, safe, environmentally superior, and efficient. The R&D process itself should be tailored to the particular country in question. In other words, the demonstrations need to show high performance in the market where the technologies will be sold. Second,

the cost must be competitive. For this latter condition to apply to demonstrations, excess cost will likely need to be bought down with U.S. funding. Also, the lower cost of production in developing countries will need to be used to lower capital expenditures. The developing nations need to become real partners in supplying the hardware as well as the bricks and mortar. One possibility is to use remaining Clean Coal Program funding to provide buy down capital for demonstrating less carbon intensive technology as it is developed. The Clean Coal Program has several hundred million dollars remaining. Why not use these funds on an advanced IGCC in India or China? Could such a proposition be approved by Congress and the Administration? There is some evidence that it might.

The Senate Interior Appropriations Subcommittee language for the FY 1998 DOE FE budget is noteworthy:

> *At the same time, fossil fuel use in developing countries is expected to increase dramatically, and will wipe out domestic gains in emissions reduction unless advanced technologies are developed to the point where they are reasonably priced and sufficiently reliable to meet the needs of those countries.*[21]

DOE needs to put forward some exciting proposals in concert with industry, involving a stream of ever-improving gas and coal technologies that emit less CO_2. The costs should be shared so that the risk is shared. Everyone has a stake in making the initiative successful, including the developing countries. But, this effort should not be made just to sell advanced coal technologies. It should be part of an overall strategy to provide attractive choices of low-CO_2-emitting and cleaner energy technologies that are cost-effective in the global market.

DOE's oil and gas R&D programs are very actively and effectively coupled with all parts of the industry. This collaboration ranges from technology transfer and demonstrations with the independents to very sophisticated work with the service companies and majors on computational science, instrumentation, and materials research. The primary issue is for DOE to walk a careful line as an impartial facilitator and R&D partner without being accused of favoritism or being a competitor. The program needs to be coordinated more closely with DOE ER to effectively support the objective of science and technology leadership, and an advanced research component in the budget has been recommended.

Relevant Policy Issues

There are two policy issues that the Panel recommends FE address.

Portfolio Analysis Recommendation

FE has developed a reasonable strategic plan based on its three primary objectives: reducing CO_2 emissions and other environmental impacts, reducing oil dependence, and science and technology leadership. Comprehensive portfolio analysis has not kept pace, nor has there been any portfolio analysis across the DOE on these objectives, although one on CO_2 is in progress.

The Change, Resource, Implementation, and Probability (CRIP) data system and associated models provide useful beginning tools for evaluating the oil portfolio. CRIP is a bottom-up project-by-project evaluation of the expected outcomes. It could be easily extended to gas and, with some difficulty, to coal and gas power, and to coal fuels. Ultimately, performance metrics, if chosen wisely, should be comparable to actual results. Validation of these tools is needed. Expectations about R&D success should be fed into the

[21] Senate (1997).

EIA National Energy Modeling System to obtain estimates of impacts of better technologies on the energy system as a whole. These estimates should provide some indication of the relative importance of R&D investments, or at least it might provide a vehicle for sensitivity analysis.

Ultimately portfolio analysis should be given public scrutiny. GRI accomplishes this through a very elaborate slate of advisory committees that scrutinize the portfolio from many points of view. This could be a useful model. Some means of facilitating public comment and feedback, over and above the budgetary process in Congress, needs to be provided.

Whatever the difficulties, **portfolio analysis against the social objectives of FE programs should be carried out periodically, and it should be integrated into an overall analysis across the DOE.**

Management Costs– Benchmark Against Other Organizations

FE management costs are running at 20 percent or about $69 million in FY 1997. These costs seem high, and, furthermore, the cost per dollar spent on R&D has been increasing over time. FE needs to benchmark its R&D management costs against comparable organizations in DOE, the rest of the Federal government, and certain other organizations, such as EPRI and GRI. Such benchmarking should provide specific ideas for reducing costs. Also, it will permit open discussion of management cost issues across DOE.

ENERGY AND ENVIRONMENTAL IMPACT

The potential energy and environmental consequences on the United States and the world from successful fossil energy R&D are discussed below.

U.S. Impact

In this section, estimates are made of the potential impact of successful R&D on two public good challenges to society: reducing CO_2 emissions and mitigating downside economic risks from oil dependence.

Table 4.2 is a spreadsheet for 14 aggregated R&D areas of FE. The information derives from the Panel Portfolio Analysis Questionnaire answered by the DOE staff. The FE staff worked very diligently to provide these answers. Table 4.2 gives summary estimates for the two objectives of CO_2 emission reductions and domestic oil and gas production increases estimated for the period from 2010 to 2015; these results are due to better technologies from current and planned DOE R&D programs. They indicate 0.7 million barrels per day (MMbpd) of increased production of oil and 2.6 trillion cu ft (Tcf) of increased gas production per year overall by 2010. These increases are very substantial, although the probability of achieving them is not clear.

Calculating the potential carbon emission rate reductions is more complex. Changes in emission rates from better technologies are estimated in Table 4.2. The problem becomes one of estimating the market size and its penetration. To do this, the AEO-97 Reference Case projections for new coal- and gas-generating capacity were used. Then, some heroic guesses were made about technology penetration rates. It was assumed that all new gas power facilities to 2005 were combined cycles with 55 percent efficiency, that the efficiency rose to 60 percent by 2006, and that this improved technology captured 100 percent of the gas electric market until 2010, when 70 percent efficient fuel cell combined cycles begin to penetrate. It was assumed that 25 percent of new capacity between 2011 and 2015 was at 70 percent efficiency and the rest at 60 percent.

For coal, it was assumed that advanced pulverized coal technology with 42 percent efficiency would be built exclusively until 2005 when 50 percent efficient technology (advanced IGCC, advanced PFBC, or HIPPS) would be built and would capture 100 percent of new coal between 2006 and 2010. From 2011 to 2015, a 60 percent efficiency Vision 21-type technology would capture 50 percent of the market allotted by EIA to coal. The results are given in Table 4.3. They indicate that the emission reductions could be 167 million metric tons of carbon per year by 2015, with some 86 percent (144 million tons) of this reduction being due to gas technologies and only 14 percent (23 million tons) to coal. The reason is that gas is the favored fuel. Coal does not capture much of the market, and, in fact, the EIA reference scenario may be optimistic relative to coal. Gas could be used to substitute more aggressively for coal in power generation if CO_2 emissions need to be curtailed. For example, if an additional 10 Tcf of gas were used to repower existing coal plants with 55 percent efficiency combined-cycle gas systems, CO_2 emissions could be reduced another 300 million metric tons per year. Such a substitution would depend, in part, on the ability to increase the efficiency of gas use in the economy and to produce it inexpensively from domestic resources.[22]

Global Impact

Using the reference case scenario of the *EIA International Energy Outlook 1996* (Table 21) for electricity, and applying the same comparable efficiency improvements for worldwide applications as were used for the United States, reductions in CO_2 emissions from improved coal technologies of about 240 million tpy by 2015 and reductions from improved gas technologies of 150 million tpy were estimated.[23] In addition, the increase in renewables use in the Reference Case could account for a CO_2 emissions reduction of about 500 million tpy, if renewables were assumed to have substituted for coal. The results indicate that improved coal and gas technologies can make a significant difference.

CROSSCUTS

Collaborations within DOE and between DOE and other agencies are discussed.

Crosscutting DOE

DOE energy R&D is organized around energy sources, end-use efficiency, and fundamental research. On the other hand, the energy challenges of the nation and the world do not easily fit in these boxes or stovepipes. FE is immersed in two public-good grand challenges: developing technologies that reduce the cost of climate stabilization and that reduce the cost of future oil price shocks. But these challenges are much broader than FE, and, in fact, they crosscut DOE and beyond. Response to these challenges should be managed comprehensively by DOE, both with respect to portfolio and to technology and science overlap and reinforcement. Currently, they are not.

Collaborations across DOE are required and crucial to accomplish the objectives described above in the initiatives on sequestering, methane hydrates, hydrogen, and oil elasticity. In addition, several technology overlaps provide an opportunity for more effective R&D progress, including collaborations with EE on biomass gasification and indirect liquefaction, and on fuel cells. In addition, advanced drilling technologies developed for oil and gas may be useful for other resources, such as geothermal, and, of course, in sequestering. (See Box 6.3.)

[22] It should be noted that CO_2 savings for gas and coal are calculated relative to the average emission rate (0.246 kgC/kWh) from fossil electric generation in 1995. Thus, calculated savings for gas are due mostly to comparing very efficient gas with very much less efficient systems based mostly on coal. In a sense, this overestimates the impact resulting from technology advances. (See notes to Table 4.3 giving a range of results.)
[23] EIA (1996).

Efforts are being made to study fuel cell R&D more cooperatively across the country. These efforts involve the National Fuel Cell Program with DOD, the National Aeronautics and Space Administration, EPRI, and GRI. DOE participates with GRI and EPRI on a Fuel Cell Steering Committee to coordinate funding and planning. Still, a more intense interaction between FE, ER, and EE is needed.

One of the most important collaborations across DOE is between the energy technology programs and ER. It is essential to the objective of maintaining the science and technology leadership in the global energy markets. What is required is a creative give-and-take between people doing fundamental R&D and those doing applied R&D on the energy technologies themselves. This linkage between ER and the energy technology offices is not as strong as many believe it should be.

FE has a mechanism for improving the interaction, and it is being applied for Vision 21. Advanced research money is being used to develop a comprehensive strategy of fundamental and applied R&D to address each component of Vision 21. Such a strategy is the basis for joint planning with ER managers. The ER money is leveraged and vice versa. This example may be a model for the energy technology and ER offices to use. A similar mechanism seems necessary to change the ad hoc interactions to more strategic interactions. Continuous cooperation is time consuming and often frustrating. Managers need incentives to invest the effort, and various schemes might work. (See Chapter 7.)

Interagency Collaboration

No regular coordination occurs between FE and DOI, particularly between USGS and MMS. Although committees have operated in the past, they seem to have become very inactive. Now there are reasons for FE to reactivate them. The first is CO_2 sequestration and the second is gas production from methane hydrates. The Department of the Navy is an important part of the hydrates issue, and the EPA will be important in both. (See sections above on CO_2 sequestration and methane hydrates.). Collaboration with U. S. Agency for International Development is needed to pursue joint R&D on Vision 21 technologies with developing coal-intensive countries.

Table 4.2: DOE Fossil Energy R&D Program: Costs and Impacts on Carbon Emissions Rates and Oil and Gas Production

OIL AND GAS

	FY 1997 Budget [million $]	Cumul. Budget to 2010 [million $]	Industry Cost Share to 2010	Change in CO_2 Emissions Rates	Cumul. Incr. in Production by 2010 [MMbbl orTcf]	Annual Prod. Incr. at 2010 [MMbbl orTcf]
Advanced Drilling, Completion, and Stimulation Systems						
Oil	2.1	29	19%		90	15
Gas	5.4	61	22%	-0.17 kgC/kWh[a]	3.1	0.36
Advanced Diagnostics and Imaging Systems						
Oil	11.4	154	33%		640	124
Gas	6.8	136	8%	-0.17 kgC/kWh[a]	13.4	2.3
Reservoir Life Extension						
Oil	14.4	93	24%		521	72
Gas	2.0	12.3	120%	-0.17 kgC/kWh[a]	3	0.5
Gas Processing and Storage	6.8	53	20%	100 to 115% of oil to diesel[b]		18-55[c]
Oil Processing	5.8	36	25%		4	1
Crosscutting and Environmental						
Oil	4.8	32	12%		353	32
Gas	2.6					
Analysis & Planning, Technology Transfer, and Program Support (Oil)	7.4					
Total Oil Production & Processing	45.9	344			1608	278-315
Total Gas Production & Processing	23.6	262			20	2.6

[a] Assumes 55 percent efficient gas (6,200 Btu/kWh heat rate) replaces 35 percent efficient coal (9,760 Btu/kWh heat rate) in power generation.
[b] The process of converting gas to diesel fuel and burning the fuel in transportation emits 100 to 115 percent of the amount of CO_2 emitted from refining crude oil to diesel fuel and burning it. The 100 percent value derives from efficiencies gained by coproducing electricity and liquids. Petroleum refining is assumed to be 83 percent efficient for comparison.
[c] DOE estimates 18 to 55 million barrels per year of liquids production from coal might be possible by the year 2010. The same range is assumed here for gas to liquids and is much more likely and is included in total oil production and processing.

Table 4.2: DOE Fossil Energy R&D Program: Costs and Impacts on Carbon Emissions Rates and Oil and Gas Production (Continued)

COAL AND ADVANCED POWER SYSTEMS

	FY 1997 Budget million $	Cumulative Budget to 2010 million $	Industrial Cost-Share	Change in CO_2 Emissions Rates	Increase in Annual Production at 2010 [MMbbl]
Coal Preparation	5.1	66	20%		
Direct Liquefaction (including Advanced Research & Environmental Technology)	6.8	55	15%	>200%	18-55[e]
Indirect Liquefaction	4.3	43	20-50%	160 to 220% [d]	18-55[e]
Coal Advanced Power Systems (including Advanced Research & Technology Development)	84.3	1300	67%	-0.041 (42%) to - 0.104 kgC/kWh (60%)[f] or -0.22 kgC/kWh with sequestration[g]	
Gas Advanced Power Systems Turbines (60% efficiency combined cycle) Fuel Cells (70% efficiency combined cycle)	 47 50	 304 436	 11% 40%	 -0.007[h] to -.017[f] kgC/kWh -0.018[h] to -0.18[f] kgC/kWh	
Environmental Retrofit	1.5	26	25%		
Sequestration	1.1	21.6	20%		
Total Coal (Including AR&TD)	103	1510			
Total Gas Power	97	740			
Total Coal and Advanced Power Systems	200	2250			
Grand Total (including oil and gas)	270	2794			

[d] The indirect process of converting coal to liquids and burning the liquids emits about 160 to 220 percent of the carbon of the process of refining petroleum to transportation liquids and burning these. The 160 percent value derives from efficiencies gained in coproducing electricity and liquids. Petroleum refining is assumed to be 83 percent efficient for comparison.

[e] Possible (very optimistic) synthetic fuel production by 2010-2015, from DOE Coal and Power Systems R&D Programs document

[f] Compared to a pulverized coal fired power plant at 35 percent thermal efficiency.

[g] Sequestration is assumed to capture 80 percent of the carbon emissions.

[h] Compared to a natural gas combined cycle at 55 percent thermal efficiency.

Table 4.3: Potential CO_2 Emissions Reductions from Advanced Coal and Gas Power Systems[a] (in millions of metric tons per year (MMtpy) of carbon)

	Year			
	2000	2005	2010	2015
Gas				
Increased incremental generation (billions of kWh/y) for each 5 year period (Table 8A of AEO 97)[b]	156	227	187	294
Cumulative power generation from advanced gas systems:				
Assuming all additions from 1996 to 2005 are 55 percent efficient systems	156	383	383	383
Assuming all additions from 2006 to 2010 and 3/4 of the additions from 2011 to 2015 are 60 percent efficient systems	0	0	187	408
Assuming 1/4 of the additions from 2011 to 2015 are 70 percent efficient systems	0	0	0	74
Cumulative carbon dioxide emission reductions [millions of metric tons of C per year]:				
Resulting from 55 percent efficiency plants	25	62	62	62
Resulting from 60 percent efficiency plants	0	0	32	69
Resulting from 70 percent efficiency plants	0	0	0	13
Total carbon emission reduction assuming advanced (55 to 70% efficiency) gas systems[c]	25	62	94	144
Total carbon emission reduction assuming 55% efficiency natural gas combined-cycles used throughout the period	25	62	92	140
Carbon emission reductions resulting from 60 and 70% efficiency technologies compared to 55% efficiency technologies[d]	0	0	2	4
Coal				
Increased incremental generation (billions of kWh/y) for each 5 year period (Table 8A of AEO 97)	126	57	88	110
Cumulative power generation from advanced coal systems:				
Assuming all additions from 1996 to 2005 are 42 percent efficient systems	126	183	183	183
Assuming all additions from 2006 to 2010 are 50 percent efficient systems	0	0	88	143
Assuming½ of all additions from 2011 to 2015 are 50 percent efficient systems	0	0	0	55
Cumulative carbon dioxide emission reductions [millions of metric tons of C per year]:				
Resulting from 42 percent efficiency plants	5	7	7	7
Resulting from 50 percent efficiency plants	0	0	6	10
Resulting from 60 percent efficiency plants	0	0	0	6
Total carbon emission reduction due to advanced coal systems	5	7	13	23

[a] Emission reduction estimates are relative to the average carbon emissions (0.246 kgC/kWh) from fossil generation in 1995, as reported in AEO 97.

[b] For example, 156 billion kWh/y is the difference in power generation rate due to new gas capacity between 1996 and 2000.

[c] Alternatively, if the comparison is to a gas turbine with the average efficiency of the current fleet (~36%), the reduction due to advanced combined cycles of 55 to 70% efficiency is about 50MMtpy in 2015.

[d] It should be noted that if advanced combined cycle gas power at 60% and 70% efficiency is compared to the best current gas combined cycle of 55% efficiency, the reduction in emissions from the efficiency improvement in gas power is only about 4 MMtpy by 2015. This indicates the diminishing returns due to more efficient gas systems.

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