THE ECONOMIC FUTURE OF NUCLEAR POWER

A Study Conducted at The University of Chicago

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PREFACE

In 2003, the U.S. Department of Energy (DOE), acting through Argonne National Laboratory (ANL), requested a study of the economic factors affecting the future of nuclear power in the United States. The study was carried out at The University of Chicago.

The present report gives the results of the study. Intended to be a white paper, it is a systematic review of the economics of nuclear power that can serve as a reference for future studies. It does not take a position on policy subjects. Rather, it reviews and evaluates alternative sources of information bearing on the nuclear power industry, and presents scenarios encompassing a reasonable range of future possibilities.

Part I considers factors affecting the competitiveness of nuclear power. Topics include (1) levelized costs, (2) comparisons with international nuclear costs, (3) capital costs, (4) effects of learning by doing, and (5) financing issues.

Part II analyzes gas-fired and coal-fired technologies as the major baseload competitors to nuclear generation. Topics include technologies that could reduce the costs of gas- and coal-fired electricity, future fuel price changes, and the potential economic impact of greenhouse gas control policies and technology.

Part III analyzes several federal financial policy alternatives designed to make nuclear power competitive in the next decade and beyond.

The Appendix provides comprehensive background information underpinning the body of the study. Previous nuclear energy studies were less comprehensive. The demand for new electricity generating capacity in the United States is estimated. A major concern is the viability of new nuclear plants as a way to meet growing electrical demand during the next decade. The study focuses on baseload electrical capacity. Appendices A1 through A9 address the major factors that affect the desirability and the viability of nuclear power. Conclusions include the following:

- Waste disposal issues remain to be settled.
- U.S. policy regarding nonproliferation goals will affect future fuel cycle decisions.
- Regulatory simplification shows promise of reducing plant construction times.
- A transition from oil-based to hydrogen-based transportation could, in the longer run, increase the demand for nuclear power as a non-polluting way to produce hydrogen.
- If gas imports increase, nuclear power could substitute for gas and contribute to energy security.

DOE NUCLEAR POWER 2010 PROGRAM [*]

In FY 2003, the U.S. Department of Energy (DOE) initiated a University of Chicago study on the economic viability of new nuclear power plants in the United States. This report describes the results of that study. According to DOE's Fiscal Year 2005 Budget Report, "the information obtained from this study is used to focus the program's activities on issues of the greatest impact" (DOE 2004, p. 397).

The Nuclear Power 2010 program is a joint government-industry cost-shared effort involved with identifying sites for new nuclear power plants, developing advanced nuclear plant technologies, evaluating the business case for building new nuclear power plants, and demonstrating untested regulatory processes. These efforts are designed to pave the way for an industry decision by the end of 2005 to order a new nuclear power plant. The regulatory tasks include demonstration of the Early Site Permit (ESP) and combined Construction and Operating License (COL) processes to reduce licensing uncertainties and minimize attendant financial risks to the licensee.

The Nuclear Power 2010 program continues to evaluate the economic and business case for building new nuclear power plants. This evaluation includes identification of the economic conditions under which power generation companies would add new nuclear capacity. In July 2002, DOE published a draft report, "Business Case for New Nuclear Power Plants in the United States," which provided recommendations for federal government assistance. DOE continues to develop and evaluate strategies to mitigate specific financial risks associated with deployment of new nuclear power plants identified in that report.

Recently, DOE solicited proposals from teams led by power generation companies to initiate new nuclear plant licensing demonstration projects. Under a cost-sharing arrangement, power companies will conduct studies, analyses, and other activities necessary to select an advanced reactor technology and prepare a site-specific, technology-specific COL application. DOE has already received responses from several utility consortia.

DOE has also initiated a technology assessment of nuclear power plant construction, which is being conducted in cooperation with the power generation companies. That study has assessed schedules and construction methods for the nuclear power plant designs most likely to be built in the near term.

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[*] Source: U.S. Department of Energy (DOE). (2004). "FY 2005 DOE Budget Request, Energy and Water Development Appropriations," Vol. 3, Nuclear Energy, pp. 395-398. http://www.mbe.doe.gov/budget/05budget/content/es/nuclear.pdf.

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ABSTRACT

Developments in the U.S. economy that will affect the nuclear power industry in coming years include the emergence of new nuclear technologies, waste disposal issues, proliferation concerns, the streamlining of nuclear regulation, a possible transition to a hydrogen economy, policies toward national energy security, and environmental policy. These developments will affect both the competitiveness of nuclear power and appropriate nuclear energy policies. A financial model developed in this study projects that, in the absence of federal financial policies aimed at the nuclear industry, the first new nuclear plants coming on line will have a levelized cost of electricity (LCOE, i.e., the price required to cover operating and capital costs) that ranges from \$47 to \$71 per megawatt-hour (MWh). This price range exceeds projections of \$33 to \$41 for coal-fired plants and \$35 to \$45 for gas-fired plants. After engineering costs are paid and construction of the first few nuclear plants has been completed, there is a good prospect that lower nuclear LCOEs can be achieved and that these lower costs would allow nuclear energy to be competitive in the marketplace. Federal financial policies that could help make early nuclear plants more competitive include loan guarantees, accelerated depreciation, investment tax credits, and production tax credits. In the long term, the competitiveness of nuclear power could be further enhanced by rising concerns about greenhouse gas emissions from fossil-fuel power generation.

EXECUTIVE SUMMARY

Context

Developments in the U.S. economy that will affect the nuclear industry in the future include the emergence of new nuclear technologies, decisions about nuclear fuel disposition, proliferation concerns, regulatory reform, a potential transition to a hydrogen economy, national energy security policies, and environmental policies. A successful transition from oil-based to hydrogen-based transportation could, in the long run, increase the demand for nuclear energy as a nonpolluting way to produce hydrogen.

The U.S. Department of Energy (DOE) currently supports research on designs for advanced nuclear power plants that can produce hydrogen as well as increase the sustainability and proliferation-resistance of nuclear energy and help lower nuclear energy costs. DOE also supports the certification of new nuclear reactor designs and the early site permitting process that will help make the licensing of new nuclear plants more predictable. Such predictability promises to lower financial risk by reducing the time required to construct and license new plants.

This study analyzes the economic competitiveness of nuclear, gas-fired, and coal-fired electricity.

Summary of Economic Findings

Economics of Deploying Plants during the Next Decade

- Capital cost is the single most important factor determining the economic competitiveness of nuclear energy.
- First-of-a-kind engineering (FOAKE) costs for new nuclear designs could increase capital costs by 35 percent, adversely affecting nuclear energy's competitiveness.
- The risk premium paid to bond and equity holders for financing new nuclear plants is an influential factor in the economic competitiveness of nuclear energy. A 3 percent risk premium on bonds and equity is estimated to be appropriate for the first few new plants.
- Without federal financial policy assistance, new nuclear plants coming on line in the next decade are projected to have a levelized cost of electricity (LCOE) of \$47 to \$71 per megawatt-hour (MWh). This study provides a full range of LCOEs for first nuclear plants for alternative construction periods, plant lives, capacity factors, and overnight cost estimates. LCOEs for coal- and gas-fired electricity are estimated to be \$33 to \$41 per MWh and \$35 to \$45 per MWh, respectively.

- With assistance in the form of loan guarantees, accelerated depreciation, investment tax credits, and production tax credits, new nuclear plants could become more competitive, with LCOEs reaching $32 to $50 per MWh.

Economics of Deploying the Next Series of Nuclear Plants

- With the benefit of the experience from the first few plants, LCOEs are expected to fall to the range of $31 to $46 per MWh; no continued financial assistance is required at this level.

Future Greenhouse Gas Policies

- If stringent greenhouse policies are implemented and advances in carbon capture and sequestration prove less effective than hoped, coal-fired electricity's LCOE could rise as high as $91 per MWh and gas-fired electricity's LCOE could rise as high as $68 per MWh. These LCOEs would fully assure the competitiveness of nuclear energy.

SUMMARY

Background

The focus of this study is baseload electricity as supplied by nuclear, coal-fired, and gas-fired technologies. Baseload power is power that a utility generates continuously, year round, in anticipation of the minimum customer demand that will occur, regardless of daily and seasonal fluctuations. Nuclear energy, coal, and gas are the major baseload fuel alternatives. Renewables are not considered since they are used minimally to meet baseload demand. While hydroelectric facilities supply baseload generation in some parts of the United States, the major opportunities for hydroelectric projects have already been taken. Table 1 presents the shares of generation furnished by various technologies in the United States. This study synthesizes the current understanding of the factors affecting the economic viability of nuclear power and estimates its viability under a range of future scenarios.

Table 1: Shares of Total U.S. Electricity Generation, by Type of Generation, 2003[a]

Energy Source	Net Generation, Percent
Coal	50.1
Nuclear	20.2
Natural Gas	17.9
Hydroelectric	6.6
Petroleum	2.5
Non-hydro Renewables	2.3
Other Sources	0.4
Total	**100**

[a] Identical to Table A1-1.

Part One: Economic Competitiveness of Nuclear Energy

This study first develops a pre-tax levelized cost of electricity (LCOE) model and uses it to calculate LCOEs for nuclear, coal, and gas generation based on values from recent plant models and data developed for use in those models. The LCOE is the price at the busbar needed to cover operating costs plus annualized capital costs. Table 2 summarizes these results.

Table 2: Summary Worksheet for Busbar Cost Comparisons, $ per MWh, with Capital Costs in $ per kW, 2003 Prices[a]

Technology	Sandia Model GenSim		SAIC Model Power Choice			Scully Capital Report			EIA – AEO 2004	
	r=10%	r=15%	Debt r = 8%; Disc r = 8%	Debt r =10%; Disc r = 8%	Debt r =10%; Disc r = 10%	r = 8%	r = 10%	r = 10%	Debt r =10%; Eq = 15%; Disc r = 10%	Debt r =8%; Eq = 10%; Disc r = 10%
Nuclear (capital cost)	51 (1,853)	83 (1,853)								
Legacy Nuclear (capital cost)			65 (2,000)	70 (2,000)	77 (2,000)					
EIA Reference Case, New Nuclear (capital cost)									63 to 68 (1,752 to 1,928)	
EIA Advanced Technology Case, New Nuclear (capital cost)									43 to 53 (1,080 to 1,555)	
ABWR (capital cost)			53 (1,600)	50 (1,600)	55 (1,600)					
AP 1000 (capital cost)			49 (1,365)	46 (1,365)	51 (1,365)	36 (1,247)	40 (1,247)	44 (1,455)		
Pebble Bed Modular Reactor (PBMR) (capital cost)			40 (1,365)	41 (1,365)	45 (1,365)					
Gas Turbine Modular Helium Reactor (GT-MHR) (capital cost)			39 (1,126)	39 (1,126)	43 (1,126)					
Advanced Fast Reactor (AFR) (capital cost)			57 (1,126)	57 (1,126)	64 (1,126)					
Coal (capital cost)	37 (1,094)	48 (1,094)	43 (1,350)	44 (1,350)	49 (1,350)					38 (1,169)
Gas Turbine Combined Cycle (capital cost)	35 (472)	40 (472)	38 (590)	38 (590)	40 (590)					41 (466)
Gas Combustion Turbine (capital cost)	56 (571)	68 (571)								
Solar-Photovoltaic	202	308								
Solar-Thermal	158	235								
Wind	55	77								

[a] Identical to Table 1-1.

To illuminate the reasons for the ranges of LCOEs estimated in prior studies, this study calculates LCOEs using the cost and performance assumptions used in three plant models identified in Appendix A2 (Table A2-1) and in the National Energy Modeling System (NEMS), as reported in the Energy Information Administration's (EIA's) *Annual Energy Outlook*. The Sandia model, GenSim, does not specify a particular nuclear technology; rather, it adopts EIA's specifications from the 2003 *Annual Energy Outlook* (AEO 2003). At a base capital cost of $1,853 per kW, increasing the discount rate from 10 to 15 percent raises the GenSim busbar nuclear cost from $51 to $83 per megawatt-hour (MWh). GenSim's estimates for competitors to nuclear are: $37 to $48 per MWh for coal, $35 to $40 per MWh for gas turbine combined cycle, and $56 to $68 per MWh for gas combustion turbines. The SAIC model, Power Choice, considers several nuclear technologies; cost estimates range from $39 per MWh for the Gas Turbine Modular Helium Reactor (GT-MHR) to $77 per MWh for existing nuclear technology. Coal-fired costs are on a par with the Pebble Bed Modular Reactor (PBMR) costs, at $43 to $49 per MWh. Gas turbine combined cycle costs are in the range of $35 to $48 per MWh. The Scully model compares alternative financing plans for a technology that broadly corresponds to the AP1000. The busbar cost range is $36 to $44 per MWh. The reference case in EIA's recent *Annual Energy Outlook* (AEO 2004) considers future construction of historical designs. Its assumptions regarding capital costs and interest rates result in a nuclear busbar cost of $63 to $68 per MWh, which is higher than most other studies. However, its cost for coal generation is $38 per MWh. Its advanced technology case lowers capital costs, partly to reflect learning effects in construction, which produces LCOEs of $43 to $53 per MWh.

Worldwide Cost Estimates

This study compares U.S. nuclear busbar costs with those in other countries that use electricity generated from nuclear energy, coal, and gas. U.S. nuclear busbar costs are estimated to be somewhat below the middle of the worldwide range for countries not reprocessing spent fuel, i.e., $36 to $65 per MWh. LCOEs of new nuclear plants in the United States compare favorably to prospective costs for new nuclear plants in France. Table 3 reports the nuclear busbar costs for various countries; separate estimates are provided for fuel cycles that dispose of spent fuel directly and those that reprocess spent fuel.

Table 3: Organization for Economic Co-operation and Development (OECD) Busbar Costs, 75 Percent Capacity Factor, 40-Year Plant Life, $ per MWh, 2003 Prices[a]

Plant Type	**Country**	**Discount Rate (To Derive Net Present Value)**	
		8 Percent	**10 Percent**
		$ per MWh	
Nuclear, Spent Fuel Disposal	Finland, new SWR 1000	36	42
	Canada	39 to 45	48 to 53
	China	44	54
	United States	45	53
	Russia	45	55
	Romania	49	59
	Korea	49	59
	India	52	64
	Turkey	53	64
	Finland	58	68
	Spain	65	78
Nuclear with Reprocessing	China	39 to 50	47 to 61
	France	50	60
	Japan	83	97
Gas Turbine Combined Cycle	OECD average	30 to 66	38 to 65
Advanced Gas Turbine Combined Cycle	United States	26	27
Pulverized Coal Combustion	OECD average	36 to 74	43 to 84
Coal Circulating Fluidized Bed	Canada	56	63
Coal Integrated Gasification Combined Cycle (IGCC)	OECD average	36 to 66	42 to 74

[a] From Tables 2-5 and 2-6.

Overnight Capital Cost Estimates

Capital costs, the single most important cost component for nuclear power, are analyzed in detail. For the Advanced Boiling Water Reactor (ABWR), already built in Asia, and the AP1000, a smaller scale version of which has been certified by the U.S. Nuclear Regulatory Commission (NRC), overnight capital costs, or undiscounted capital outlays, account for over a third of LCOE; interest costs on the overnight costs account for another quarter of the LCOE. Overnight cost estimates from different sources have ranged from less than $1,000 per kilowatt (kW) to as much as $2,300 per kw. This study examines the reasons for the differences in these estimates, with the aim of estimating a narrower plausible range.

One reason that early plants are more expensive is the impact of first-of-a-kind engineering (FOAKE) costs. Several hundred million dollars may be expended to complete the engineering design specifications for Generation III or III+ reactors. Such costs are incurred for early nuclear plants built of any type. Although building a reactor of a particular design in one country may enable transfer of part of the engineering that will be used in another country, some partial FOAKE costs may still be incurred for the first construction in any given country.

FOAKE costs are a fixed cost of a particular reactor design. How a vendor allocates FOAKE costs across all the reactors it sells can affect the overnight cost of early reactors considerably. A vendor may be concerned about its ability to sell multiple reactors and therefore want to recover all FOAKE costs on its first plant. FOAKE costs could raise the overnight cost of the first plant by 35 percent.

This study uses the Advanced Boiling Water Reactor (ABWR), the CANDU ACR-700, the AP1000, and the Framatome SWR 1000 as reasonable candidates for deployment in the United States by 2015.

- An overnight cost of $1,200 per kW is assumed for a generic class of mature designs.
- An overnight cost of $1,500 per kW is assumed for a generic class of designs that require payment of FOAKE costs.
- An overnight cost of $1,800 per kW is assumed for a generic class of more advanced designs that also require FOAKE costs.

Consideration of the four reactor types contributes to the choice of $1,200, $1,500, and $1,800 per kW for overnight costs, a range consistent with estimates identified in EIA's 2004 advanced technology case. (See AEO 2004.)

Learning by Doing

The study finds that reductions in capital costs between a first new nuclear plant and some n^{th} plant of the same design can be critically important to eventual commercial viability. In building the early units of a new reactor design, engineers and construction workers learn how to build the plants more efficiently with each plant they build. A case can be made that the nuclear industry will start with very little learning from previous experience when the first new nuclear construction occurs in the United States. The paucity of new nuclear construction over the past twenty years in the United States, together with the entry of new technologies and a new regulatory system, has eliminated much of the applicable U.S. experience. On the other hand, participation in overseas construction may have given some U.S. engineers experience that is transferable to construction in the United States.

This study uses a range of 3 to 10 percent for future learning rates in the U.S. nuclear construction industry, where learning rate is the percent reduction in cost resulting from doubling the number of plants built. Table 4 summarizes the conditions associated with different learning rates.

Table 4: Conditions Associated with Alternative Learning Rates[a]

Learning Rate (Percent for Doubling Plants Built)	Pace of Reactor Orders	Number of Reactors Built at a Single Site	Construction Market	Reactor Design Standardization	Regulation Impacts
3	Spread apart 1 year or more	Capacity saturated; no multiple units	Not highly competitive; can retain savings from learning	Not highly standardized	Some construction delays
5	Somewhat more continuous construction	Somewhat greater demand for new capacity; multiple units still uncommon	More competitive; most cost reductions from learning passed on to buyers	Narrower array of designs	Delays uncommon
10	Continuous construction	High capacity demand growth; multiple units common	Highly competitive; all cost reductions passed on	Several designs; sufficient orders for each to achieve standardization learning effects	Construction time reduced and delays largely eliminated

[a] Identical to Table 4-6.

The Financial Model

This study employs a financial model for businesses that is based on the following equation:

PRESENT VALUE OF EQUITY INVESTMENT DURING THE CONSTRUCTION PERIOD
= PRESENT VALUE OF NET REVENUE EARNED BY EQUITY OVER THE LIFE OF THE PLANT

where

NET REVENUE = EARNINGS FROM LCOE REVENUE BEFORE INTEREST AND TAXES (EBIT) – INTEREST EXPENSE – TAX EXPENSE + DEPRECIATION – REPAYMENT OF DEBT

Because risk is a major consideration for investors, its treatment in the financial model is an important factor in deriving the required net revenue. The perceived risk of investments in new nuclear facilities contributes to the risk premium on new nuclear construction. Principal sources of risk are the possibilities that construction delays will escalate costs and that new plants will exceed original cost estimates for other reasons. This study uses guidelines from the corporate finance literature, previous nuclear studies, and opinions of investment analysts to specify likely relationships between project risk and risk premiums for corporate bonds and equity capital. Risks associated with building a new nuclear plant are estimated to raise the required rate of return on equity to 15 percent, compared to 12 percent for other types of facilities, and debt cost to rise to 10 percent from 7 percent.

Table 5 specifies the parameter values for LCOE calculations under the assumption that no financial policies benefiting nuclear power are in effect. In using the financial model to study sensitivities, overnight costs of $1,200, $1,500, and $1,800 per kW are used. Table 6 summarizes the "no-policy" LCOEs for the three nuclear capital costs, each under 5-year and 7-year anticipated construction times. These construction times are expected values perceived by investors, based on both previous nuclear construction experience and new information. This study assumes investors will conservatively expect a 7-year construction period for the first few new plants. If actual construction times prove to be 5 years, investors will revise their expectations downward accordingly for subsequent plants.

Table 5: Parameter Values for No-Policy Nuclear LCOE Calculations[a]

Item	Parameter Value
Overnight Capital Cost	$1,200 per kW $1,500 per kW $1,800 per kW
Plant Life	40 years
Construction Time	7 years
Plant Size	1,000 MW
Capacity Factor	85 percent
Hours per Year	8,760 hours
Cost of Debt	10 percent
Cost of Equity	15 percent
Debt Term	15 years
Depreciation Term	15 years
Depreciation Schedule	MACRS[b]
Debt Finance	50 percent
Equity Finance	50 percent
Tax Rate	38 percent
Nuclear Fuel Cost	$4.35 per MWh
Nuclear Fixed O&M Cost	$60 per kW
Nuclear Variable O&M Cost	$2.10 per MWh
Nuclear Incremental Capital Expense	$210 per kW per year
Nuclear Decommissioning Cost	$350 million
Nuclear Waste Fee	$1 per MWh

[a] Identical to Table 5-1.

[b] Modified Accelerated Cost Recovery System.

Table 6: First-Plant LCOEs for Three Reactor Costs, 5- and 7-Year Construction Periods, $ per MWh, 2003 Prices[a]

Construction Period	Mature Design FOAKE Costs Paid, $1,200 per kW Overnight Cost	New Design FOAKE Costs Not Yet Paid, $1,500 per kW Overnight Cost	Advanced New Design FOAKE Costs Not Yet Paid, $1,800 per kW Overnight Cost
5 years	47	54	62
7 years	53	62	71

[a]Identical to Table 5-3.

Table 7 presents a full range of LCOEs for first nuclear plants, for alternative construction periods, plant lives, and capacity factors and for each of the three overnight costs specified in Table 5. The table shows the relative importance of the various characteristics for generation cost. Overnight capital cost is clearly most important, but the two-year difference in construction period is nearly as important. If investors were convinced of the likelihood of a 5-year construction period, they would estimate the generation cost of the $1,800 per kW plant to equal that of the $1,500 per kW plant built in 7 years; similarly, the $1,500 per kW plant anticipated to be built in 5 years would have a generation cost nearly that of the $1,200 per kW plant anticipated to be built in 7 years. Capacity factor also exerts a significant influence on generation cost. However, the effect of longer plant life is relatively minor because these benefits occur in the distant future and are discounted.

Table 7: Effects of Capacity Factor, Construction Period, and Plant Life on First-Plant Nuclear LCOE for Three Reactor Costs, $ per MWh, 2003 Prices[a]

Capacity Factor, Percent	Overnight Cost					
	$1,200 per kW		$1,500 per kW		$1,800 per kW	
5-year construction period						
	Plant Life		Plant Life		Plant Life	
	40 years	60 years	40 years	60 years	40 years	60 years
85	47	47	54	53	62	61
90	44	43	51	50	58	58
95	42	41	49	48	56	55
7-year construction period						
	Plant Life		Plant Life		Plant Life	
	40 years	60 years	40 years	60 years	40 years	60 years
85	53	53	62	61	71	70
90	50	49	58	58	67	66
95	47	47	56	55	64	63

[a]Identical to Table 5-6.

Table 8 presents LCOEs for coal and gas alternatives. Given the capital cost range, the LCOE of new nuclear plants in the absence of federal financial policies is from $53 to $71 per MWh with a 7-year construction time. The range is from $47 to $62 per MWh with a 5-year construction time. Costs remain above the range of competitiveness with coal and gas generation, which have LCOEs ranging from $33 to $45 per MWh. For the $1,500 and $1,800 per kW plants, FOAKE costs of roughly $300 per kW are assumed to be paid off with the first plant, which lowers the LCOE for the second plants by 13 to 15 percent.

Table 8: LCOEs for Pulverized Coal and Gas Turbine Combined Cycle Plants, $ per MWh, 2003 Prices[a]

Coal	33 to 41
Gas	35 to 45

[a]From Tables 5-4 and 5-5.

Part Two: Outlook for Nuclear Energy's Competitors

Gas and Coal Technologies

This study examines the near-term prospects for improvements in gas- and coal-fired electricity generation that would affect their costs relative to nuclear power. Table 9 summarizes the cost estimates, construction times, and thermal efficiencies of fossil-fired electricity generation. Some modest thermal efficiency improvements are foreseen in the near term for gas technologies, but similar improvements for coal technologies appear to be farther in the future. The most common combustion technology used in coal plants recently built in the United States is pulverized coal combustion. Fluidized bed combustion is a cleaner alternative, and the thermal efficiency of most fluidized beds used for power generation is similar to that of pulverized coal. However, the cost competitiveness of fluidized bed combustion remains a question. Integrated coal gasification combined cycle, while attractive from the perspective of thermal efficiency and emissions, is likely to be too expensive to enter the U.S. market in the near term. More advanced coal-fired technologies are still in early R&D stages.

Since fuel costs are generally two-thirds of the levelized cost of gas-generated power, a 5 percentage point increase in efficiency in gas turbine combined cycle plants could decrease the cost of gas-generated electricity by approximately 8 percent.

Table 9: Cost Characteristics of Fossil-Fired Electricity Generation[a]

	Pulverized Coal Combustion	Coal, Circulating Fluidized Bed	Coal, Integrated Gasification Combined Cycle	Gas Turbine Combined Cycle
Capital Cost ($ per kW)	1,189	1,200	1,338	590
Fuel Cost ($ per MWh)	11.26	12.04	9.44	23.60
Total Operations and Maintenance Cost (O&M) ($ per MWh)	7.73	5.87	5.19	2.60
Construction time (years)	4	4	4	3
Current Thermal Efficiency (percent)	30 to 35	30 to 35	40 to 45	55 to 60
R&D Thermal Efficiency Targets (percent)	45	45	60	65

[a] Identical to Table 6-6.

Fuel Prices

This study examines forecasts for three fuels: coal, natural gas, and uranium.

Coal and Gas

Coal supplies worldwide are expected to be sufficiently price elastic that even a doubling of demand would not increase price appreciably. Previous forecasts generally agree that coal production will increase 35 to 50 percent over the next 25 years. Forecasts for the U.S. coal price to utilities uniformly predict a decline of about 10 percent.

Forecasts for natural gas prices are mixed (see Table 10). EIA’s forecasts have changed sharply as prices experienced during the base years of 2000 to 2003 have fluctuated considerably. Expressed in 2003 prices, the Lower 48 wellhead price rose from $3.93 per 1000 cu. ft. in 2000 to $4.24 in 2001, then fell to $3.02 in 2002. The 2003 price of $5.01 was the highest in recent years. EIA’s 2003 forecast for 2020, in 2003 prices, was $3.75, but its 2004 forecast for the same date is $4.34. The 2002 price of $3.02 was below both 2020 forecasts, but the 2003 price of $5.01 was well above both. As Table 10 shows, EIA’s 2004 forecast for 2020 was for an 11 percent increase over 2000 prices, equivalent to a 40 percent increase over 2002 prices but a 13 percent decrease from 2003 prices.

Table 10: Natural Gas Price Projections[a]

Year	2000[b]	2005	2010	2015	2020
NEMS[c], Lower 48 U.S. Wellhead Price, AEO 2003	100[d]	75	86	93	96
NEMS[c], Lower 48 U.S. Wellhead Price, AEO 2004	100[d]	92	88	109	111

[a] Abridged version of Table 7-2, Year 2000=100.
[b] Year 2000=100.
[c] National Energy Modeling System (NEMS).
[d] $3.93 per 1,000 cu. ft.

Sensitivity analyses for gas-fired LCOEs use three alternative time paths for natural gas prices. One is an average of the 2001and 2002 gas price, which results in forecasts for 2010 to 2015 of $3.39 per MMBtu, assumed constant over the plant life. Another uses the 2003 gas price forecast for 2010 to 2015 of $4.30, also assumed constant over the plant life. The third uses EIA's 2004 forecast of gas prices from 2015 through the end of the plant life, which begins at $4.25 in 2015, peaks at $4.51 in 2021, falls to $4.48 by 2025, and remains at that level for the remainder of the plant life. All prices are in 2003 dollars.

Uranium

The supply elasticity of uranium is estimated by several sources to be between 2.3 and 3.3, which should be sufficiently large to keep uranium prices down in the range of $15 per pound over the next several years. Since fuel cost accounts for only about 10 percent of total nuclear generation cost, variation in uranium prices will have only a limited effect on the overall cost of nuclear generation of electricity.

Environmental Policies

As opposed to technology advances and possible fuel price decreases that could reduce coal- and gas-fired costs, environmental considerations could raise the cost of these sources because they emit air pollutants. This study assesses potential cost increases from more stringent environmental compliance for coal- and gas-generated electricity.

- Despite global climate concerns, carbon remains an important but largely uncontrolled emission that could be subject to future controls through carbon capture and sequestration.

- Although the technologies of carbon capture, transport, injection, and sequestration are not yet commercialized, estimates of current and future costs are available.

  Assuming 100 km transportation by pipeline, this study reports the following costs per MWh generated:

  - $36 to $65 per MWh for pulverized coal, including an energy penalty of 16 to 34 percent
  - $17 to $29 per MWh for gas turbine combined cycle, including an energy penalty of 10 to 16 percent
  - $20 to $44 per MWh for integrated gasification combined cycle, including an energy penalty of 6 to 21 percent

- An alternative measurement of the future costs of carbon control can be obtained by examining permit markets. In particular, prices generated through permit market trading can be interpreted as the approximate future cost of reducing present emissions. This study uses a carbon price range of $50 to $250 per ton to construct upper and lower bounds of the electricity cost impact. For coal-fired electricity, the cost impact is likely to be between $15 and $75 per MWh; for gas-fired electricity, the cost impact is likely to be between $10 and $50 per MWh. These estimates are subject to significant uncertainty, particularly because of uncertainty about the overall amount of carbon that will be controlled.

Part Three: Nuclear Energy in the Years Ahead

Nuclear Energy Scenarios: 2015

The year 2015 is chosen as a reasonable year for the first new nuclear plants to come on line, allowing for time lags required for design certification, site selection and planning, licensing, and construction. This study considers the effects of several possible federal policies targeting the first plants.

Individual Federal Financial Policies Considered for the First Plants

- According to this study's financial model, a loan guarantee of 50 percent of construction loan costs would reduce the nuclear LCOE for the lowest-cost reactor from $53 to $49 per MWh (see Table 11).

- Accelerated depreciation would reduce the LCOE for the lowest-cost reactor to $47 per MWh (see Table 12).

- An investment tax credit of 20 percent, refundable so as to be applicable as an offset to a utility's non-nuclear activities, would reduce the nuclear LCOE to $44 per MWh for the lowest-cost reactor (see Table 13).

- A production tax credit of $18 per MWh for the first 8 years (as proposed in 2004 legislation) would reduce the LCOE of the lowest-cost reactor to $38 per MWh, which is within the required competitive range (see Table 14).

This study uses a 7-year construction schedule because the financial community is likely to assume that duration for the first plants constructed, for financial planning purposes. If shorter construction times are proven with early experience, the construction period used for financial planning would be reduced accordingly for subsequent plants.

Table 11: Nuclear LCOEs with Loan Guarantees, $ per MWh, 2003 Prices[a]

Loan Guarantee Policy	Mature Design $1,200 per kW	New Design $1,500 per kW	Advanced New Design $1,800 per kW
0 (no policy)	53	62	71
25 percent of loan	50	58	67
50 percent of loan	49	57	65

[a] From Table 9-3.

Table 12: Nuclear LCOEs with Accelerated Depreciation Allowances, $ per MWh, 2003 Prices[a]

Depreciation Policy	Mature Design $1,200 per kW	New Design $1,500 per kW	Advanced New Design $1,800 per kW
15 years (no policy)	53	62	71
7 years	50	58	67
Expensing (1 year)	47	54	62

[a] From Table 9-4.

Table 13: Nuclear LCOEs with Investment Tax Credits, $ per MWh, 2003 Prices[a]

Tax Credit Policy	Mature Design $1,200 per kW	New Design $1,500 per kW	Advanced New Design $1,800 per kW
0 percent (no policy)	53	62	71
10 percent	47	55	63
20 percent	44	51	58

[a] From Table 9-5.

Table 14: Nuclear LCOEs with Production Tax Credits, $18 per MWh, 8-Year Duration, $ per MWh, 2003 Prices

Tax Credit Policy	Mature Design $1,200 per kW	New Design $1,500 per kW	Advanced New Design $1,800 per kW
0 (no policy)	53	62	71
$18 per MWh, 8-year duration	38	47	56

[a]From Table 9-6.

Combination of Federal Financial Policies and Streamlined Licensing

While the most of the individual financial policies considered in this study appear to be insufficient to enable nuclear power to enter the marketplace competitively, the financial model indicates that a combination of policies at reasonable levels could do so. As shown in Table 15, an $18 per MWh production tax credit for 8 years together with a 20 percent investment tax credit could bring the LCOE of the lower-cost reactors ($1,200 and $1,500 per kW) within the competitive range with a 7-year anticipated construction time. This policy package would bring the LCOE of the $1,800 per kW reactor close to the anticipated competitive range with the 7-year construction time and well within it with a 5-year construction period.

Table 15: Effects of Combined $18 per MWh 8-Year Production Tax Credits and 20 Percent Investment Tax Credits on Nuclear Plants' LCOEs, $ per MWh, 2003 Prices

Mature Design $1,200 per kW		New Design $1,500 per kW		Advanced New Design $1,800 per kW	
Construction Time		Construction Time		Construction Time	
5 years	7 years	5 years	7 years	5 years	7 years
No policies:					
47	53	54	62	62	71
With combination of policies:					
26	31	31	38	37	46

[a]Identical to Table 9-7.

Nth Plants and Nuclear Competitiveness

Under aggressive assumptions regarding learning by doing, the LCOE for the fifth plant, when most learning has been achieved, is $44 per MWh for the lowest-cost nuclear reactor, assuming that for the first plant the business community anticipates a construction period of 7 years and uses a 3 percent risk premium on debt and equity interest rates (see Table 16).

Table 16: LCOEs for the Fifth Nuclear Plant, with No Policy Assistance, 7-Year Construction Time, 10 Percent Interest Rate on Debt, and 15 Percent Rate on Equity
$ per MWh, 2003 Prices[a]

Learning Rate (Percent for Doubling Plants Built)	Initial Overnight Cost, $ per kW	
	1,200 and 1,500	1,800
3	50	58
5	48	56
10	44	52

[a] From Table 9-8.

This study goes on to report LCOEs for the fifth plant assuming that, with favorable regulatory experience, the business community comes to expect a 5-year construction period and more favorable risks, comparable to gas and coal. Under these conditions, the fifth-plant LCOEs for nuclear reactors reach the required range of competitiveness. The two lower-cost nuclear reactors have LCOEs of about $35 per MWh even under the most pessimistic learning rate (see Table 17). If the reduced risk encourages a higher ratio of debt to equity in financing, LCOEs would be further reduced: by nearly 3 percent with 60 percent debt instead of 50 percent or by 8.5 percent with 70 percent debt instead of 50 percent.

This study found that, even under pessimistic learning assumptions, nuclear power could become self-sufficient in the market after cessation of initial policy assistance if overnight costs were $1,200 or $1,500 per kW and a 5-year construction schedule was maintained. Depending on where fossil LCOEs emerge within the ranges calculated here, the $1,800 per kW nuclear plant could become self-sufficient as well.

Table 17: LCOEs for the Fifth Nuclear Plant, with No Policy Assistance, 5-Year Construction Time, 7 Percent Interest Rate on Debt, and 12 Percent Rate on Equity
$ per MWh, 2003 Prices[a]

Learning Rate (Percent for Doubling Plants Built)	Initial Overnight Cost, $ per kW	
	1,200 and 1,500	1,800
3	35	40
5	34	39
10	32	36

[a] From Table 9-11.

Robustness of Conclusions

The results of this study are sensitive to assumptions about overnight costs and plant construction times, but are not very sensitive to assumptions about plant life and capacity factors.

Environmental Policies for Fossil Generation

Stringent measures to control greenhouse gases would raise costs for both gas- and coal-fired plants, making nuclear energy easily competitive in the market place, as shown in Table 18.

Table 18: Fossil LCOEs with and without Greenhouse Policies, $ per MWh, 2003 Prices[a]

	Under Current Environmental Policies	Under Greenhouse Policy
Coal-Fired	33 to 41	83 to 91
Gas-Fired	35 to 45	58 to 68

[a] Identical to Table 9-12.

2025 and Beyond

The long gestation periods involved in nuclear energy research and the long lags entailed in gearing up the nuclear industry to construct new power plants make it prudent to look several decades ahead when making decisions about nuclear energy policy.

Nuclear Energy Technology. The importance of cost reductions from first-of-a-kind-engineering (FOAKE) costs and learning by doing beyond FOAKE has been documented in this study. If presently available Generation III technologies are deployed for several years beginning in 2015, as contemplated in this study, significant cost reductions from their replication could extend to 2025 and beyond. Research and development on Generation III and IV designs is expected to allow commercialization of lower-cost reactors in later years.

Global Warming. The longer the time horizon, the more likely the United States will place an increased priority on global warming, leading to an urgent need to replace coal- and gas-fired electricity generation. In view of the time it takes to gear up the nuclear industry, the prospect of this need is one of the reasons for national concern with maintaining a nuclear energy capability. If environmental policies greatly restrict carbon emissions in the period after 2025, fossil-fired LCOEs could increase by 50 to 100 percent over current levels. Nuclear power would then acquire an unquestioned cost advantage over its gas and coal competitors.

Hydrogen. The widespread introduction of hydrogen-powered vehicles to replace gasoline-powered vehicles would greatly increase the demand for energy to produce hydrogen. Some impacts could occur by 2015, but this study is conservative and does not consider those impacts when projecting demand for nuclear energy in the 2015 timeframe. If the expressed national commitment to developing a commercially viable hydrogen vehicle proves successful, nuclear power could become a major producer of this transportation fuel. A full analysis of the implications of increased demand for hydrogen is beyond the scope of this study.

Despite the many uncertainties in the future beyond 2025, the findings in this study suggest the likelihood of an increased demand for nuclear energy beyond 2025.

APPENDIX

Background

Purpose and Organization of Study

This study aims to synthesize what is known about the factors affecting the economic viability of nuclear power and to estimate its viability under a range of future scenarios. The focus is on generating baseload electricity—nuclear, coal-fired, and gas-fired technologies. Renewables are not considered because they are rarely used to meet baseload demand. While hydroelectric facilities supply baseload generation to some parts of the United States, the major opportunities for hydroelectric projects have already been taken.

Electricity Futures

This study uses two principal types of models to investigate electricity futures:

- *Plant models* calculate the cost of electricity generation from a specific type of power plant. Costs are calculated on a levelized basis (LCOE), combining operating and capital costs to arrive at a cost per megawatt-hour (MWh), that must be recouped in the price of electricity. Costs are calculated at the busbar level in order to focus on electricity generation costs and abstract from locally varying distribution costs.

- *Market models* forecast the demand for electricity and the mix of electricity generating capacity that will come online to meet future levels of expected demand. Aggregate demand and supply functions are estimated and brought together to simulate market behavior, often at the regional level.

Table A-1 summarizes the characteristics of the various plant and market models that are reviewed in this study. The table distinguishes the plant types, forecast horizons, treatments of environmental costs, and nuclear power data sources that have been used.

Table A-1: Plant and Market Model Summary[a]

Model Identification	Plant Type	Forecast Horizon	Treatment of Environmental Costs	Source of Nuclear Power Data
Plant Models				
Scully Capital-DOE (Nuclear Energy)	Nuclear (AP1000)	Up to 2010	No	Vendor, 2002
Electricity Generation Cost Simulation Model (GenSim)/Sandia	Wide spectrum of energy sources	Current year	Has capability	Energy Information Administration (EIA) and Platt's (McGraw-Hill) Database, 2003
MIT Study	Nuclear, coal, gas	Up to 2050	Carbon tax	EIA, 2003
Market Models				
National Energy Modeling System (NEMS)-EIA	Wide spectrum of energy sources	20 years from present	No	EIA, 2003
NEMS-Electric Power Research Institute (EPRI)	Nuclear, coal, gas	Up to 2050	Carbon tax	Vendors, 2002
All Modular Industry Growth Assessment Modeling System (AMIGA)/ Pew Charitable Trust	Wide spectrum of energy sources	Up to 2035	Yes	Argonne National Laboratory, Vendors, 2001
Integrated Planning Model (IPM)/Environmental Protection Agency (EPA)	Nuclear, coal, gas	20 years from present	Yes	EIA
Hybrid Models				
Science Applications International Corporation (SAIC) Power Choice Model	Nuclear, coal, gas	80 years from present	Carbon tax	DOE and Vendors, 2001

[a] Identical to Table A2-1.

Within each model category, different underlying numerical assumptions cause the principal differences in electricity cost projections. The most significant of these are differences in capital costs and interest rates for nuclear capacity, capital costs for coal generation, and fuel costs for gas generation. The market models are sufficiently complex that reasons for differences in their projections frequently are difficult to pinpoint. Plant models are better suited for studying the economic viability of nuclear energy. However, while the plant model structures are straightforward, documentation of underlying data is not always sufficient to allow detailed economic analysis. Four of the plant models, identified in bold font in Table A-1, are used for comparison purposes later in this study: the Scully model, GenSim, NEMS, and SAIC's Power Choice model.

Need for New Generating Capacity in the United States

This study analyzes future electricity demand and compares it with existing capacity to estimate a future time range when construction of added capacity must start. Projections by EIA and the North American Electric Reliability Council (NERC) are compared with projections based on historical relationships between electricity demand growth and gross domestic product (GDP) growth. The historical relationships estimated for this study imply electricity demand growth rates that are roughly one percentage point higher than EIA's forecasts and a half percentage point above NERC's forecasts. From a national perspective, even with an annual growth rate in electricity demand of 2.7 percent, which is above the EIA and NERC forecasts, new capacity will not be needed before 2011. On a regional basis, new capacity may be required as early as 2006. (See Appendix A3, "Need for New Generating Capacity in the United States.")

Major Issues Affecting the Nuclear Power Industry in the U.S. Economy

Technologies for New Nuclear Facilities

The nuclear reactors currently in use in the United States, denoted as Generation II, were deployed in the 1970s and 1980s. They include boiling water reactors and pressurized water reactors. Advanced modular reactor designs are denoted as Generation III. Some have passive safety features, and all have been developed to be more cost competitive. Generation III designs include the ABWR design and the pressurized water reactor, both of which use passive safety systems; they also include the AP600/AP1000 and the light-water-cooled heavy-water-moderated CANDU ACR-700. The nuclear industry has continued to develop yet more innovative Generation III+ designs. Generation III+ designs may have lower generating costs than Generation III designs, but the U.S. Nuclear Regulatory Commission (NRC) has not yet certified them, and their cost estimates have greater uncertainty. DOE is developing Generation IV nuclear energy systems that use even more advanced designs intended to further reduce life cycle costs.

Table A-2 summarizes the characteristics and NRC certification status of the reactor designs reviewed in this study.

Table A-2: Summary of New Reactor Designs[a]

Design	Supplier	Size and Type	U.S. Deployment Prospects and Overseas Deployment	NRC Certification Status
ABWR	General Electric	1,350 MW BWR	Operating in Japan, under construction in Taiwan.	Certified in 1996.
AP1000	Westinghouse	1,090 MW PWR	Additional design work to be done before plant ready for construction.	Design certification expected September 2005.
SWR 1000	Framatome Advanced Nuclear Power (ANP)	1,013 MW BWR	Under consideration for construction in Finland, designed to meet European requirements.	Submission of materials for pre-application review to begin in mid-2004. Pre-application review completion expected 2005.
CANDU ACR-700	Atomic Energy Company, Limited (AECL)Technologies Inc., U.S. subsidiary of AECL	753 MW HWR	Deployed outside Canada in Argentina, Romania, South Korea, China, and India.	Pre-application review scheduled to be completed by NRC, June 2004.
AP600	Westinghouse	610 MW PWR	Additional design work to be done before plant ready for construction.	Design is certified, but actual construction will be superseded by AP1000.
Simplified Boiling Water Reactor (ESBWR)	General Electric	1,380 MW BWR	Commercialization plan not likely to support deployment by 2010.	Pre-application review completion expected in early 2004. Application for design certification to be submitted mid-2005.
PBMR	British Nuclear Fuels (BNFL)	110 MW Modular pebble bed	No plan beyond completion of South African project.	Pre-application review closed September 2002 with departure of Exelon.
GT-MHR	General Atomics	288 MW Prismatic graphite	Licensed for construction in Russia.	Design certification application would begin by end of 2005.
International Reactor Innovative and Secure (IRIS) Project	Westinghouse	100 to 300 MW PWR	Plans to deploy between 2012 and 2015.	Design certification review to begin 2006.
European Pressurized Water Reactor (EPR)	Framatome-ANP	1,545 to 1,750 MW PWR	No decision on U.S. market.	Ordered for deployment in Finland.
System 80+	Westinghouse	1,300 MW PWR	Plants built in Korea. Design not planned to be marketed in United States.	Certified May 1997.
Advanced Fast Reactor; Power Reactor Innovative Small Module (AFR; PRISM)	General Electric, Argonne National Laboratory	300 to 600 MW, sodium-cooled	Began certification in the 1990s.	No action taken.

[a] Identical to Table A4-2.

Nuclear Fuel Cycle and Nuclear Waste Disposal

This study analyzes the economic costs of nuclear power contributed by the nuclear fuel cycle. It also considers two options for spent fuel disposition: (1) on-site storage followed by centralized disposal and (2) on-site storage and reprocessing, followed by centralized disposal. Recycle of mixed-oxide fuel was not considered. The front-end costs of nuclear fuel are relevant regardless of which disposition alternative is used. As shown in Table A-3, these costs amount to $3.50 to $5.50 per MWh or 5 to 12 percent of the cost of nuclear power generation. In the United States, the direct method of spent fuel disposal has been used to date, without reprocessing of spent fuel. The costs of disposal consist of on-site storage costs while awaiting permanent storage, plus a charge levied to pay for eventual permanent storage or disposal at a centralized site. The back-end costs are about $1.10 per MWh, as shown in Table A-4, which is about 2 percent of the overall LCOE. Plausible differences in fuel cycle costs are not a major factor in the economic competitiveness of nuclear power.

Table A-3: Components of Front-End Nuclear Fuel Costs, $ per kg U, 2003 Prices[a]

Process Step	Direct Outlays	Interest Cost	Total Cost
Ore Purchase	222 to 353	94 to 150	316 to 503
Conversion	40 to 94	15 to 35	55 to 129
Enrichment (per kg SWU)	606 to 951	197 to 306	804 to 1,259
Fabrication	193 to 250	54 to 69	246 to 319
Total			**1,420 to 2,209**
$ per MWh			**3.56 to 5.53**

[a] Abridged version of Table A5-1.

Table A-4: Disposal Costs, $ per MWh, 2003 Prices[a]

Fuel Cycle Component	No Reprocessing
Temporary on-site storage	0.09
Permanent disposal at Yucca Mountain	1.00
Total	1.09

[a] Identical to Table A5-2.

Nuclear Regulation

Federal Regulation 10 CFR Part 52 was adopted in the 1990s. It provides for combined construction and operation permitting and is aimed at streamlining the permitting process. The combined Part 52 license is designed to allow investors to resolve many historically important uncertainties before committing large amounts of money to a nuclear facility. This study analyzes the economic advantages that such regulatory streamlining can provide, both directly by reducing construction delays, and indirectly by reducing the risk premium necessary to compensate investors for possible delays or cancellations due to regulatory difficulties. For example, as more new nuclear plants are built well beyond 2015, this study finds that mature designs already in operation could generate energy that could be competitive with gas-fired electricity, if the nuclear licensing period could be reduced to five years (see Table 17 above).

Nonproliferation Goals

This study reviews international arrangements aimed at preventing nuclear proliferation. Some countries have chosen direct disposal of spent nuclear fuel, while others have chosen recycling of spent fuel. In the United States, policy decisions regarding direct disposal versus recycling must be reviewed when DOE considers a second repository. By statute, DOE must report to Congress on or after January 1, 2007, but not later than January 1, 2010, on the need for a second repository. (See Sec. 161(b), P.L. Law 97-425.) The uranium extraction (UREX) process was developed as a variant of plutonium-uranium extraction (PUREX). DOE is currently conducting R&D on further recycling technologies, including pyrometallurgical processing. In the future, an innovative fuel cycle that strongly resists nuclear proliferation, such as pyrometallurgical processing, will be pursued. The President recently announced a policy to cap the deployment of new reprocessing technologies outside a select group of countries. Nevertheless, the future economic viability of nuclear power does not depend on decisions about direct disposal versus reprocessing. As Appendix A6 shows, differences in the cost of nuclear waste handling between these two alternatives is too small to materially affect the economic viability of nuclear power.

Hydrogen

This study reviews the prospects of hydrogen as a transportation fuel that would reduce U. S. dependence on foreign oil and could have potentially large environmental benefits. Mass production costs need to be reduced by roughly one-half to two-thirds to achieve widespread adoption of hydrogen vehicles. The environmental benefits of hydrogen would be tempered to the extent that fossil fuels, with their attendant carbon emissions, were used to produce the hydrogen. Carbon emissions from oil would then simply be replaced by emissions from fossil-fuel power generation or steam methane reforming. Nuclear energy, on the other hand, would provide a pollution-free input to hydrogen production. A hydrogen economy, accompanied by more stringent control of carbon emissions, could greatly expand the demand for nuclear power.

Energy Security

This study considers the energy security benefits of nuclear power as a potential source of hydrogen to replace oil in the transportation sector and more generally as a substitute for gas-generated electricity. Energy security has been analyzed primarily in connection with oil and the political instability of the Middle East. A direct link to electricity is limited by the small amount of electricity produced using oil. However, nuclear energy could help ease oil security concerns if hydrogen is cogenerated for transportation. Currently, the United States imports about 4 percent of its natural gas consumption in the form of liquefied natural gas (LNG), but that percentage could grow if many new gas-fired electricity generating plants are built and if North

American gas production expands only sluggishly. As international trade in LNG becomes more extensive and the United States imports increase, this energy security linkage could become more important, if nuclear electricity substitutes directly for gas-generated electricity.

This study considers potential supply and demand shocks from environmental, national security, and other risks affecting choices among electricity generation technologies. Maintaining some nuclear capacity now could avoid a costly and lengthy adjustment of gearing up a nuclear industry that might otherwise be in a run-down condition. This study uses a decision-making model to develop a numerical example of a portfolio of fossil and nuclear electrical generating capacity. In this example, 25 percent of new capacity would be nuclear. Further research is needed to refine this analysis.