SECRETARY OF ENERGY ADVISORY BOARD

MEMORANDUM FOR: Secretary Ernest J. Moniz

FROM: John Deutch
Chair, Secretary of Energy Advisory Board

DATE: October 3, 2016

SUBJECT: Transmittal of SEAB Task Force Report on The Future of Nuclear Power

SEAB has approved the report of the The Future of Nuclear Power Task Force at its public meeting of September 22, 2016.

You charged the Task Force to describe a new nuclear power initiative that would lead to a situation in the period 2030 to 2050 where one or several nuclear technologies were being deployed at a significant rate. The Task Force has assumed a scale for this initiative of 3,000 to 5,000 megawatts electric (MWe) annually.

The Task Force identified major barriers that need to be overcome for such an initiative to be successful and described a comprehensive program for the initiative. The Task Force believes that the principal justification for this initiative is the vital contribution nuclear power can make to reduce worldwide carbon dioxide emissions. Carbon emission charges or equivalent production payments are necessary to improve the economic competitiveness of nuclear power compared to natural gas generation.

True to its charge, the Task Force focused on describing the requirements for such an initiative and did not address its practicality or necessity. It remains for the next Administration and Congress to decide whether to pursue such an initiative.

The Task Force report concludes: *…there is no shortcut to reestablish a vigorous U.S. nuclear power initiative that could be a major source of carbon-free generation. To be successful, such an initiative will take time, significant public resources, restructured electricity markets, and sustained and skilled management attention.* If the nation wishes to have a significant nuclear power option in the 2030 – 2050 time period, it must undertake the measures recommended in the Task Force report.

U.S. Department of Energy

Secretary of Energy Advisory Board Report of the Task Force on the Future of Nuclear Power

September 22, 2016

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Acronyms

2DS	2°C Scenario (from EIA's Annual Energy Outlook)
AEO	Annual Energy Outlook
BWR	Boiling water reactor
CCS	Carbon capture and storage
CNSC	Canadian Nuclear Safety Commission
CO_2	Carbon dioxide
COL	Combined license
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ESP	Early site permit
FERC	Federal Energy Regulatory Commission
FOAK	First-of-a-kind
GAIN	Gateway to Accelerated Innovation in Nuclear
GHG	Greenhouse gas
GW	Gigawatt
GWe	Gigawatt-electric
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
kWe	Kilowatt-electric
kWe-hr	Kilowatt-electric-hour
kWh	Kilowatt-hour
LCOE	Levelized cost of electricity
LWR	Light water reactor
MCF	The volume of a thousand cubic feet of natural gas
MMBtu	Million British thermal units
MW	Megawatt
MWe	Megawatt electric
MWth	Megawatt thermal
NEAC-NRT Subcommittee	Nuclear Reactor Technology Subcommittee of the Nuclear Energy Advisory Committee

NGCC	Natural gas combined cycle
NGNP	Next Generation Nuclear Plant
NRC	U.S. Nuclear Regulatory Commission
OECD	Organization for Economic Cooperation and Development
ONR	U.K. Office of Nuclear Regulation
PWR	Pressurized water reactor
RPS	Renewable Portfolio Standard
SCC	Social cost of carbon
SCM	Social cost of methane
SEAB	Secretary of Energy Advisory Board
SMR	Small modular reactor
TVA	Tennessee Valley Authority

Executive Summary

Secretary Moniz charged this Task Force to describe a new nuclear power initiative that would lead to a situation in the period 2030 to 2050 where one or several nuclear technologies were being deployed at a significant rate. The principal motivation for this initiative is the vital contribution that nuclear power, along with wind, solar, and other renewable technologies, can make worldwide to reduce carbon dioxide emissions, thus slowing global average temperature increase and the resulting adverse climate change. An active U.S. nuclear power industry has the important added national security benefit of advancing nonproliferation policy objectives, and, in addition, it can provide the technology and practice to assure the safe, secure, and effective management of nuclear waste. The Task Force has assumed a target range for this initiative of 3,000 to 5,000 megawatts electric (MWe) annually.

The Task Force did not address whether the initiative it describes is practical or necessary. The purpose is to describe a potential option for the nation that may prove attractive, for example, if natural gas prices rise more rapidly than currently expected, or less attractive, for example, if the future electricity system does not rely extensively on base load power.

Five factors explain the private sector's current reluctance to invest significantly in U.S. nuclear power: the absence of an established price for carbon emission; significant technical, cost, and regulatory uncertainties of new nuclear technologies; nuclear waste management and public acceptance; projected market conditions; and unanticipated intervening events internal or external to the project, such as a nuclear accident, with effects that exceed the time horizon of private investors.

Based on estimates of the Department of Energy's (DOE's) Energy Information Administration (EIA), the Task Force finds that the levelized cost of electricity (LCOE) for new nuclear generation should be competitive with the LCOE of other generating technologies, provided that overnight capital construction costs are about $2,000 per kilowatt-electric (kWe) (compared to the $5,000 per kWe estimated today).

However, there are two key issues that must also be addressed for full cost competitiveness to be achieved for both existing and advanced U.S. reactors. First, nuclear overnight capital costs must decline, and electricity markets must recognize the value of carbon-free electricity generation based on the social cost of carbon emissions avoided, either by assessing a carbon-emission charge on electricity generation or, alternatively, by extending a production payment on carbon-free electricity generation of about $0.027 per kilowatt-electric-hour (kWe-hr) ($213 million for a 1,000 MWe reactor operating at 90% capacity factor) for a period of time.

Second, many aspects of the rules governing electricity rates and dispatch in different parts of the country make it challenging to value base load nuclear generation appropriately. Examples include the rate structure in wholesale capacity markets, preferential dispatch rules for renewable generation, and rates that are inadequate to assure recovery of investment. These rules have led to early U.S. plant retirements and discouraged development and investment in new plants.

The Task Force Believes that Significant Market Restructuring Is a Prerequisite for the Success of Any Nuclear Power Initiative

Existing Nuclear Plants

For existing nuclear plants, the Task Force endorses DOE's efforts to work with the Federal Energy Regulatory Commission (FERC), State regulatory authorities, and regional and independent system operators to encourage arrangements that will preserve the U.S. fleet until the end of their useful life, subject to continued compliance with prevailing safety and environmental regulations. **The Task Force believes this is essential if U.S. carbon goals are to be achieved**.

New Nuclear Plants

For new nuclear plants, in the absence of a national carbon-emission pricing policy, the Task Force recommends that the Administration seek a production payment of approximately $0.027/kWe-hr for carbon-free electricity generated for a time period to be determined. An analogous production payment should be set for carbon-free renewable electricity–generating technologies at a level where such support is not already provided.

Assuming the existence of this production payment, the Task Force does not believe current light water reactor (LWR) plants require significant additional support, assuming market imperfections are resolved. The Nuclear Regulatory Commission (NRC) has licensed large LWRs for construction and operation in the United States. Small modular LWRs are receiving financial support from DOE's Office of Nuclear Energy for design certification, licensing, and early siting. DOE should work with the NRC expeditiously to resolve issues associated with SMRs, such as the size of the Emergency Planning Zone and the number of operators in the control room (see Section II).

Advanced Nuclear Reactors

The Task Force recommends that the United States undertake an advanced nuclear reactor program to support the design, development, demonstration, licensing and construction of a first-of-a-kind (FOAK), commercial-scale reactor.

Since the infancy of commercial nuclear power at the end of World War II, it is not an exaggeration to say that scientists and engineers in industry, DOE laboratories, and universities have investigated every reactor technology and associated fuel cycle to some degree. Large-scale LWRs have evolved over time with respect to technical performance and safety and have emerged as the leading deployed technology. However, both interest in fossil fuel–free electricity generation and appreciation of the tremendous technical evolution that has occurred in areas such as measurement and control and in systems engineering and integration have led government and private venture capital to invest in early-stage advanced nuclear reactors of various sorts. DOE's Generation IV program has sponsored the study of several variants.

Each of the candidate systems has different reactor operating characteristics and prospects for surpassing existing LWRs in a number of key performance indicators, such as lower overnight capital costs (perhaps 30% less), higher thermal efficiency (perhaps

30% higher), safety (a factor of 10 fewer expected incidents per year of reactor operation), higher-temperature operation (improving efficiency, reducing water use, and providing possibly useful process heat), and fuel utilization (perhaps a factor of 50% or greater for some advanced concept/fuel cycles). The United States will regain its preeminence in global nuclear power if such advances can be realized by one or more advanced nuclear reactor systems. For this reason, the Task Force believes consideration of an advanced nuclear reactor initiative is both timely and warranted (see Section V).

The Task Force Recommends a Four-Phase Advanced Nuclear Reactor Program:

The first phase (technology down select) of the initiative involves conducting the technology development, engineering, and systems analysis necessary to establish technological readiness, estimated capital costs, and LCOE of the candidate technologies. Milestone 1 is the down select decision to proceed with one (or more) of the technologies.

This second phase (subsystem development and reactor demonstration preparation) is devoted to obtaining subsystem development and validation, front-end engineering design, and NRC demonstration plant licensing. Milestone 2 is the decision point to proceed with the demonstration project.

The third phase (demonstration plant operation) is devoted to construction and operation of a demonstration plant and preparing a detailed design for a FOAK commercial plant. Milestone 3 is the decision point to proceed with the FOAK plant.

The fourth phase (FOAK reactor plant operation) consists of construction and operation of a FOAK commercial-scale plant. This phase concludes with an explicit determination at Milestone 4 that private investors, banks, utilities, and owner/operators of electricity generation plants will commit to a first wave of construction of these advanced nuclear plants.

Although estimates are very uncertain, the Task Force midpoint estimate is that such a four-phase program would require about 25 years and $11.5 billion for at least some advanced technologies. The Federal Government would share these costs; the proportion paid by each partner would vary according the project risk. The following table provides an illustration of the division of public/private responsibility.

Table 1. Advanced Nuclear Reactor Program, Division of Public/Private Responsibility

Estimated Project Cost Split by Phase	Federal Share	Private Firm Share	Total
Phase I	$2 billion	$0	$2 billion
Phase II	$1.5 billion	$1.5 billion	$3 billion
Phase III	$1.75 billion	$1.75 billion	$3.5 billion
Phase IV	$0	$3 billion	$3 billion
TOTAL	$5.25 billion	$6.25 billion	$11.5 billion

Other countries are likely to be interested in participating in the program, which perhaps would include making significant financial contributions. However, the Task Force notes that any significant financial participation is likely to be accompanied by expectations of work share and participation in the initiative governance, which have disadvantages (see Section VII).

Safety and Licensing Of Nuclear Reactors

The NRC must be involved in all four phases of the advanced nuclear reactor initiative. The NRC is the global gold standard for rigorous attention to reducing accident risk. The review and licensing process, however, is lengthy and expensive, with much of the cost borne by applicant user fees. At present, the NRC reviews and licenses only LWRs for power production. The NRC is working to develop a capability to review and license non-LWR technologies for power applications, and there is great interest in the advanced nuclear reactor community in a less expensive and more rapid process.

Some developers may be tempted to seek licensing and/or build lead reactors in countries that are perceived to have less time-consuming regulatory systems. If this choice compromises safety, the risk of accidents will increase. A safety or security incident anywhere in any country has implications throughout the world, so any reduction of safety and security standards is of considerable concern. Accordingly, some foreign licensing authorities considering a new reactor design are likely to seek advice and assistance from the NRC. While such engagement with the NRC might improve international nuclear safety, the licensing of a new design for operation in the United States will require formal and comprehensive NRC review.

The Task Force believes that the current licensing framework is sufficiently flexible to accommodate a staged licensing process that will be more efficient and predictable than the present system. This expansion of the NRC scope will require additional resources. The Administration and Congress should consider adjustment of the current arrangements for funding the NRC, and the Task Force recommends that there be some Federal cost sharing (see Section VIII).

International Linkage

For the second half of the 20th century, U.S. leadership in commercial nuclear technology and U.S. origin plant construction around the globe allowed the United States to further its nonproliferation objectives by exerting a compelling influence to slow the spread of nuclear fuel-cycle technologies, such as enrichment and reprocessing. The Task Force believes that if nuclear deployment is flat or declining in the United States and European Organization for Economic Cooperation and Development (OECD) countries, it is inevitable that leverage in nuclear power and its associated fuel cycle will move to those countries—notably China, India, Russia, and South Korea—that are aggressively expanding their nuclear programs. The implications for nuclear proliferation should be an important criterion in the selection of different technology types, and the United States' ability to influence such decisions internationally will inherently depend on the country's involvement in the development of advanced nuclear technology.

The Task Force underscores several international considerations that must accompany any domestic nuclear initiative:

- DOE and the NRC should continue aggressive international programs in an effort to assure that U.S. technology and safety/security processes continue as a benchmark for others.
- The United States should take the lead, working with the International Atomic Energy Agency (IAEA), to assure that nuclear facilities, both at home and abroad, are secure against terrorist attack, theft of nuclear materials, and cyber intrusion.
- If the United States decides to initiate a program to build demonstration plants for Generation IV technologies, it should be open to foreign participation, especially from close allies like the United Kingdom, France, Japan, and South Korea.

Program Management

The Task Force recommends that a quasi-public corporation be established, governed by an independent board of directors, nominated by the President and confirmed by Congress, with the authority and responsibility to undertake all four phases of the advanced nuclear initiative. The corporation should be funded by a one-time congressional appropriation. The enabling legislation structure should permit the corporation to operate in a largely commercial manner, free of the Federal acquisition and personnel restrictions and the annual budget/appropriation cycle. This is an appropriate structure for a highly technical development/deployment program that must operate effectively and consistently over many years. This approach reduces risk for private-sector investors who remain concerned over stable U.S. government policy regarding nuclear power. In Phases I and II, the corporation would work closely with DOE national laboratories and, in Phases III and IV, with investors and financial institutions (see Section X).

This study should alert the reader that there is no shortcut to reestablish a vigorous U.S. nuclear power initiative that could be a major source of carbon-free generation. To be successful, such an initiative will take time, significant public resources, restructured electricity markets, and sustained and skilled management attention.

I. Background

A renaissance in nuclear power would be a major benefit to the world's energy future. Massive increases in global electrification will be needed to create the possibility of improving the quality of human life in the developing world. Unlike other electricity-generating technologies, nuclear power does not emit carbon[a] and, thus, can make an important contribution to avoiding costly and socially disruptive global warming. This is the primary motivation for the United States to undertake an initiative to achieve *the capability to deploy new nuclear power plants at scale, at the rate of 3 to 5 gigawatts-electric (GWe) per year, in the time period 2030–2050*.[b]

In addition, the United States has a strong national security interest in regaining world leadership in commercial nuclear power technology. If the United States does not have a vigorous and innovative nuclear power program, it will be disadvantaged in its ability to influence nuclear power trends elsewhere in the world regarding safety and nonproliferation.

At present the U.S. nuclear reactor fleet is aging, and there is little near-term prospect for construction of new nuclear power plants beyond the five units currently committed; four units are under construction, and Watts Bar Unit 2 recently restarted.

Finally, it is good stewardship of the Nation's future to invest in research, development, and demonstration for a broad range of energy technologies.

Accordingly, Secretary of Energy Ernest J. Moniz charged the Secretary of Energy Advisory Board (SEAB) to form a Task Force on the future of nuclear power to

> "describe the landscape that must be crossed to go from today's situation of reliance largely on light water reactors to a situation in the period 2030 to 2050 where one or many nuclear technologies have reached technical and commercial maturity and are deploying at a rate that has the possibility of carbon free nuclear power generation contributing 20% of global electricity generation."

The Secretary of Energy's full charge to the Task Force is in Appendix A, and the Task Force membership is listed in Appendix B.

The Task Force has approached its charge first by reviewing the outlook for nuclear power in the United States and elsewhere in the world. The review identifies several major challenges that a new nuclear initiative must surmount if it is to succeed. The report outline discusses each of these challenges and identifies specific steps that need to be taken to meet the challenge. These are:

- Economic cost, value, and market risk for nuclear power
- Safety and licensing

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[a] The IEA 2015 Energy Technology Scenario for limiting average global temperature increase to 2°C below pre-industrial levels (i.e., the 2DS scenario) includes a doubling of world nuclear capacity by 2050, which it is not on track to meet.

[b] This objective goes beyond the congressional Energy Policy Act 2005 mandate that DOE deploy a next-generation prototype reactor by 2021. In June of 2014, the Government Accountability Office reviewed the DOE's Next Generation Nuclear Plant (NGNP) Project: www.gao.gov/assets/670/664298.pdf.

- Choice of nuclear technology
- Schedule and cost for nuclear power technology innovation
- Nuclear waste management and public acceptability
- International linkages.

These challenges represent risks to a private investor, and these risks explain why private investors and private capital have not been making commitments for the deployment of nuclear technology at the scale necessary in countries with developed energy markets (although considerable venture capital has been available to explore advanced nuclear technologies).

The U.S. government played a decisive role in the development and deployment of nuclear power in its early period, 1955–1975. However, U.S. government support for nuclear has declined sharply since the 1980s. **The Task Force believes that a nuclear initiative is not possible without a revived commitment of government support**. The Task Force believes the justification for Federal Government support for such an initiative—carbon-free electricity—which would require far more funding than what the Federal Government is spending to support nuclear power today, is different than the justification in the past, which was technology development. The Task Force recommends government policies and incentives that are appropriate and identifies those that are not.

Finally, the legislative and executive branch must decide on an effective management structure for this nuclear initiative should it go forward. In this report, the Task Force examines this issue and makes recommendations.

The purpose of the charge to the Task Force is clear. First, the Task Force has not been asked to examine whether this nuclear energy initiative is of greater priority than other energy or other initiatives that are on the country's agenda. The Task Force is charged with describing what needs to be done to make such a nuclear energy initiative successful. Second, the Task Force has not been asked to review the current DOE nuclear energy research and development (R&D) program. The DOE Office of Nuclear Energy supports the nuclear technology base for the Nation that allows private firms, national laboratories, and universities to create technology options for the future. The Task Force's focus is on the downstream innovation stages of demonstration and deployment.

The Task Force understands that commercial nuclear power is a system that consists of (1) a nuclear reactor technology that generates electricity and (2) fuel-cycle and waste management activities that support this electricity generation. Progress on waste management is important for public acceptability of nuclear power. The Task Force makes certain observations about these vital fuel-cycle and waste management activities but acknowledges that its analysis is incomplete, especially for new, advanced technologies for which there is little or no practical field experience.

II. The Outlook for Nuclear Power in the United States and the Rest of the World

Four main publications have informed the Task Force's judgment about the outlook for the future of nuclear power: (1) the International Energy Agency's (IEA's) 2015 Nuclear Energy Technology Roadmap, which presents future world energy scenarios;[1] (2) Mycle Schneider's World Nuclear Industry Status Report;[2] (3) the complete description of nuclear reactors presently deployed, under construction, and planned given in IAEA's Power Reactor Information System (PRIS) database;[3] and (4) EIA's 2013 International Energy Outlook, which discusses the outlook for world nuclear power.[4] Absent a change in government policy or an unexpected significant shift in relative prices in world electricity markets, the trends are quite clear:

- There are 442 reactors operating worldwide; an additional 66 are presently under construction (see Figure 1).

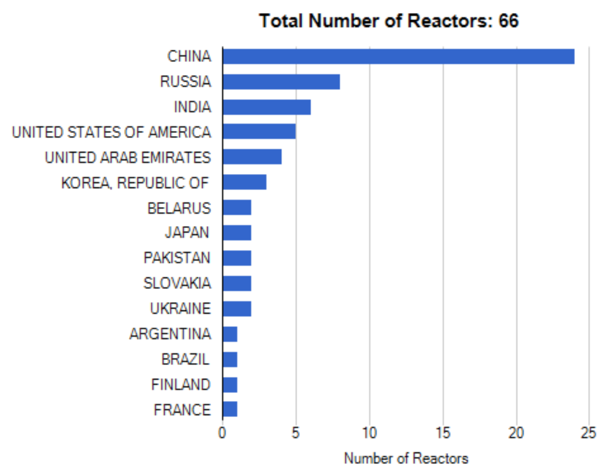

Figure 1. Number of reactors under construction, as of February 4, 2016[5]

- At the time the IEA report was issued, there were 99 nuclear reactors operating in the United States, totaling 104 GWe capacity. Five plants will come online, and 33 reactors have been permanently shut down.[c] U.S. installed capacity is expected remain roughly constant until about 2030. However, the Task Force notes the recent announcements of premature closure (because of issues with electricity market structure discussed below) and suggests that additional closures will occur.[d]

[c] The plants coming online include Vogtle Units 3 and 4 (Southern Company) and Virgil C. Summer Units 2 and 3 (South Carolina Electric and Gas); these are Westinghouse AP1000s. Tennessee Valley Authority (TVA) has completed construction of Unit 2 at Watts Bar, a Westinghouse pressurized water reactor (PWR) started in 1973 with construction halted in 1988.

[d] In June 2016, Pacific Gas and Electric announced its intention to close its Diablo Canyon two-unit nuclear plant at the end of its original operating licenses in 2024 and 2025, and announced it would not seek to relicense it for operations beyond that period. Some believe that if the California Renewables Portfolio Standard included nuclear power, these closures might not have been necessary. Exelon announced in June 2016 the early retirement of its Clinton and Quad Cities nuclear plants because of their inability to

- Globally, the IEA projects under its aggressive 2°C global temperature increase scenario (2°C Scenario, or 2DS) that nuclear will produce about 17% of world electricity generation (see Figure 2).[6]

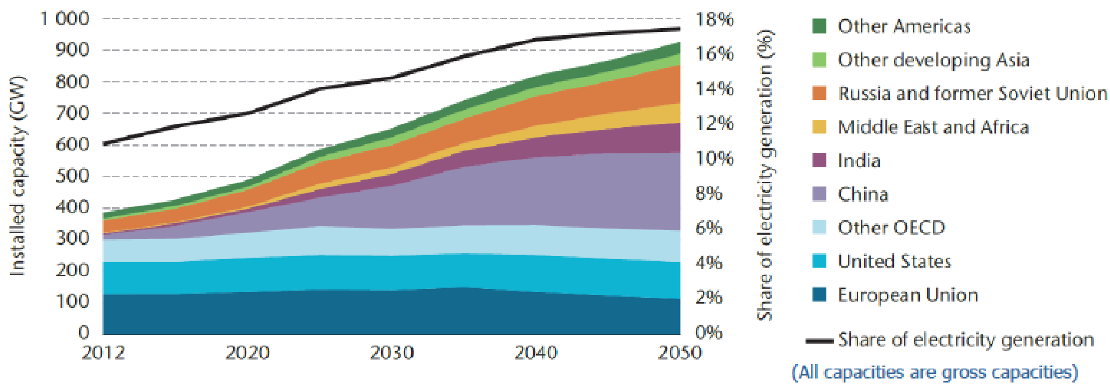

Figure 2. Nuclear generation capacity in the 2DS by region, in gigawatts (GW)[7]

The following are projections based on the IEA 2DS:

- European installed nuclear capacity will grow only slightly, due mostly to Eastern European former Soviet Union states, such as Poland and Bulgaria, that intend to replace former Soviet-era reactors.
- Asian OECD countries (Japan and South Korea) and Russia will continue to expand nuclear capacity.
- Major growth in nuclear deployment will occur in China and India.
- A significant number of countries in Latin America, Asia, and Africa will introduce nuclear power, but the deployment in each of these countries (including the United Arab Emirates, Turkey, Bangladesh, Jordan, Vietnam, Saudi Arabia, and Egypt) will be modest (i.e., less than 5 GWe).[8]

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reach an agreement with Illinois legislature on a rate structure for dispatch from these plants that provided sufficient revenue to justify their continued operation. Exelon's Braidwood, Illinois, two-unit 2,389 MWe nuclear station, which is located 60 miles from the Clinton plant, remains in operation because it receives more favorable regulatory treatment. In July 2016, Omaha Public Power District notified NRC of its plan to close Fort Calhoun because retirement "is in the best financial interest of the district." See "OPPD board votes to decommission Fort Calhoun Station," Omaha Public Power District, June 16, 2016, http://www.oppd.com/news-resources/news-releases/2016/june/oppd-board-votes-to-decommission-fort-calhoun-station/.

Table 2. Present and Projected Worldwide Nuclear Power Capacity and Generation[9]

	Installed Nuclear Capacity Gigawatts		Nuclear Electricity Generation Billion kWe-hr		Total Electricity Generation Billion kWe-hr		Percent Nuclear Generation	
Region/Country	2015	2040	2015	2040	2015	2040	2015	2040
OECD								
United States	104	113	820	903	4165	5212	20%	17%
OECD Europe	124	142	892	1073	3787	4765	24%	23%
OECD Asia	45	82	301	576	1858	2374	16%	24%
Total OECD	288	359	2124	2715	10838	14240	20%	19%
Non-OECD								
Non-OECD Europ/Eurasia	49	85	344	630	1725	2807	20%	22%
Russia	28	55	197	416	1081	1729	18%	24%
Non-OECD Asia	54	236	401	1868	8062	17023	5%	11%
China	40	160	298	1289	5740	11595	5%	11%
India	7	52	49	396	1100	2736	4%	14%
Middle East	1	15	6	113	859	1405	1%	8%
Africa	2	12	15	89	666	1537	2%	6%
Central and South America	4	10	26	77	1159	2023	2%	4%
Brazil	2	7	14	55	590	1217	2%	5%
Total Non-OECD	109	358	792	2777	12471	24794	6%	11%
Total World	397	717	2917	5492	23309	39034	13%	14%

The aging of the nuclear fleet is an additional important factor. Much of the U.S. fleet will reach 60 years of age beginning in 2030, as indicated in Figure 3. If license extensions beyond 60 years are not granted, it is entirely possible that nuclear retirements will occur in significant quantities. Older reactors may experience higher operations and maintenance expenses, lower capacity factors, and additional capital cost for new safety requirements.

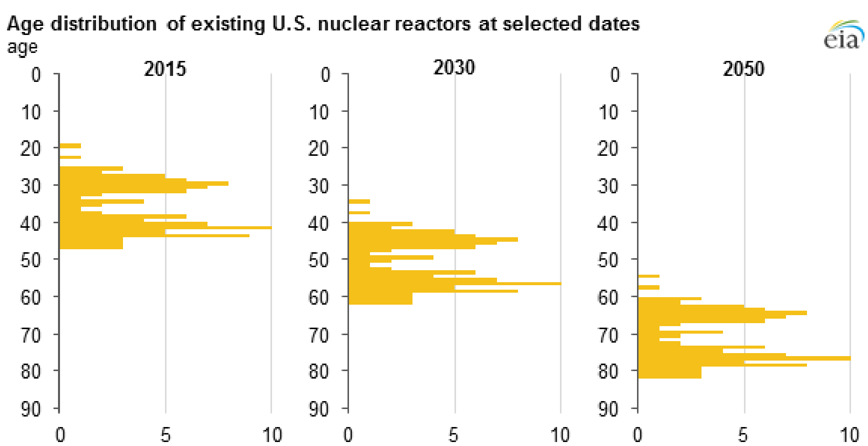

Figure 3. Age distribution of existing U.S. nuclear reactors at selected dates[10]

The global fleet is also aging, as shown in Figure 4:

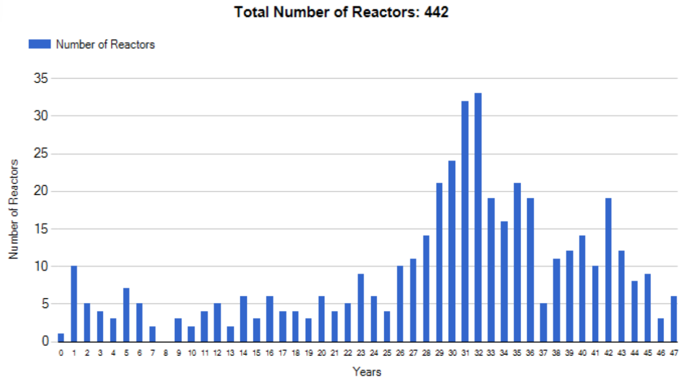

Figure 4. Age of the global nuclear fleet[11]

For nuclear energy to maintain a share of global electricity generation of about 20%, new construction will be required for both additional capacity and to replace what may be a substantial number of retirements.

III. The Economic and Market Risks Facing Nuclear Power and the Justification for Government Action

In OECD countries that have mature energy markets, an important consideration is the cost of nuclear-generated electricity compared to alternative electricity-generating technologies, such as natural gas and solar.

Private and Public Costs of Electricity Generation

Energy system **private costs** refer to the costs that are incurred by investors and operators in commercial markets. Private costs are important in the United States and other countries where the investment and operation of electricity generation plants are generally in the hands of private firms (in the case of large-scale, grid-connected generating facilities) or individuals (in the case of most distributed generation). Private costs include all aspects of the integrated system from the nuclear steam supply system, which includes the reactor, steam generators, turbine-generators, control and safety subsystems, plant engineering design, licensing, and site preparation, as well as many additional "owner costs" such as insurance and administration. **Overnight capital cost** is the sum of these costs incurred prior to initial system operation not including interest accrued during construction.

Overnight capital cost (measured in $/kWe) is the largest contributor to the LCOE for nuclear generation. Much effort has been expended to understand the history of overnight cost for nuclear power plants in the United States and to compare these costs with the experiences of other countries. These are complex comparisons because of differences in many factors, including design, safety requirements, interest rates, construction time, and different assumptions for the cost of capital and government subsidies. Some attribute this high overnight cost to excessive and changing NRC safety requirements and the lengthy construction time caused by delays due to intervener actions. Others point to owners not properly managing engineering, production, and construction activity and costs.

A recent study by Lovering, Yip, and Nordhaus on the historical cost of nuclear power reactors summarizes the situation well.[12] The negative learning experience in the United States is illustrated by the trend in U.S. overnight construction cost, as shown in Figure 5. An earlier report by the *Cour de Comptes* on the French experience is also informative,[13] as is the subsequent review published by CERNA-MINES ParisTech.[14]

Lovering, Yip, and Nordhaus also examine cost trends in Germany, France, and South Korea. As indicated in Figure 6, South Korea has the best experience with an overnight capital cost of about $2,500/kWe (2010 USD) compared to U.S. overnight capital costs, which knowledgeable observers believe to be in excess of $5,000/kWe (2010 USD).

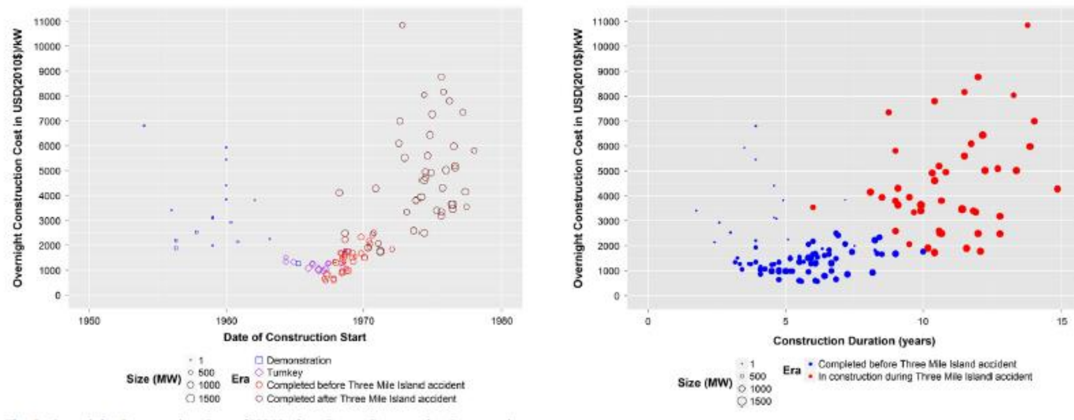

Figure 5. Overnight construction of U.S. nuclear reactors by start date and by years of construction

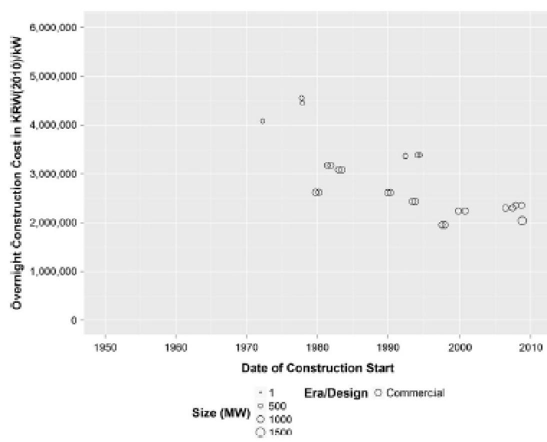

Figure 6. Overnight construction of South Korean nuclear reactors by start date Most South Korean reactors are constructed in pairs.

To summarize, the overnight capital cost for a new pressurized water reactor (PWR) system in the United States is estimated to be in the range of \$5,000–\$6,000/kWe; however, the experience of South Korea suggests that overnight capital costs in the range of \$2,500/kWe are possible.[e]

External costs are costs that are not captured in commercial markets. One example is the external cost that confronts base load electricity generators comes from the presence of intermittent wind and solar electricity generators on the grid.[f] A fair

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[e] Ted Nordhaus (private communication) suggests several reasons for South Korea's lower overnight capital costs, including standardized design, multiple reactors at each site, a single utility, and a single builder; South Korea was also a late adopter that imported and then indigenized a mature design and supply chain.
[f] Joskow explains that levelized costs are not always appropriate for ranking electricity-generating alternatives. An electricity plant that produces electricity with a relatively high levelized cost may be more valuable than a plant with a lower levelized cost if the plant with a high levelized cost delivers electricity more reliably and more cheaply when the price of electrical energy is high—that is, during periods of peak demand. Paul L. Joskow, *Comparing the Costs of Intermittent and Dispatchable Generating Technologies,* Working Paper (Cambridge, MA: Massachusetts Institute of Technology, Center for Energy and

comparison of renewables with base load power would include the cost of the backup power capacity to meet electricity demand when renewables are unavailable.

Important **public external costs** include (1) the impact on human health from criteria air pollutants, such as particulates and sulfur dioxide, and (2) the damage to climate resulting from greenhouse gas (GHG) emissions, which is estimated to be $41 per metric ton of carbon dioxide (CO_2) equivalent. This is the social cost of carbon[g] (SCC).[15] See Section VIII and Appendix E for a discussion of nuclear safety.

Both the renewable and nuclear power private costs of generation should be credited by a value that reflects their advantage in terms of lower criteria pollutant emissions and carbon-free emissions relative to conventional natural gas or coal electricity generation. A proper comparison of the cost of alternative electricity-generating technologies is based on the sum of the public and private costs.

Comparing the Public and Private Costs of Different Electricity-Generating Technologies

Many public and private organizations analyze and project the costs of electricity generation today and in the future. These estimates are based on many assumptions, including market performance, fuel prices, regulatory mandates and subsidies, the pace of technical change (especially changes that lower the unit cost of production), and market prices. The estimates often extend to 2050 or 2100 and beyond and assume world conditions are not impacted by conflict, catastrophic disease, or other disruptive events. Needless to say, the degree of uncertainty surrounding such estimates is very large indeed. The range of estimates is sufficiently wide to include those who believe "photovoltaic costs will continue to decline," "natural gas will go back to $10 MCF in five years,"[h] and the "the next generation nuclear reactor will have an overnight capital cost ½ of today's." These claims may prove true, but no one can know. This wide range of estimates explains the risk that private investors see in energy projects.

Despite the uncertainty, such cost projections are necessary and useful. They provide some guidance to the public, policymakers, firms, and researchers about energy's future and influence attitudes about what policies are desirable and necessary. There is widespread agreement that the wide range of uncertainty calls for creating options and buying insurance to hedge consequences of unknown outcomes.

The Task Force chose to focus on the EIA's Reference case projections of the costs of electricity-generating technologies in their 2016 Annual Energy Outlook (AEO), as well as the model for electricity-generation LCOE described in Appendix C.[i] The advantage of using the EIA source is that consistent assumptions are used across the different technology cases. The projections clearly illustrate the economic challenge that faces

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Environmental Policy Research, revised February 2011). A short version appears in the *American Economic Review Papers and Proceedings* 101, no. 3 (2011): 238–241.

[g] The SCC is the monetized value of the climate damages from the release of a ton of CO_2.

[h] The unit MCF represents the volume of one thousand cubic feet of natural gas.

[i] The Task Force thanks Harshil Sahai, Daniel Stuart, Syed Muhammad Faraz Hayat, Henry Zhang, and all members of the Energy Policy Institute at the University of Chicago for assistance in compiling this table. The source of the numbers in Table 3 is explained in Appendix C.

the nuclear initiative under study. Table 3 compares the cost of current nuclear power technologies with coal- and natural gas–fired electricity generation, also comparing the external carbon and non-carbon (health) costs of these technologies. The entries are for new plants that are projected to come online beginning in 2022, which is the necessary estimated lead time for a new nuclear plant. The first set of columns reports the EIA AEO 2016 estimates directly. These estimates have several assumptions about current and future policy built into them, which are detailed in the table notes and Appendix C. The second set of columns aims to strip out all impacts of policy from the derivation of private costs and reports the GHG and non-GHG (e.g., health effects from airborne particulate matter) as separate columns, and then reports the social costs as the sum of private and external costs. Additionally, this second set of columns reports on the private and external costs of renewable technologies that are backed up by natural gas.

There are three important messages:

- Nuclear LCOE does not compete with coal, natural gas, and renewables if only private costs are considered.
- Nuclear LCOE does compete with coal and renewables when external costs are considered, as well as intermittency costs for renewables, but not with natural gas at EIA’s 2016 natural gas price projections.
- Natural gas prices are notoriously volatile, as are EIA natural gas price projections. Under EIA’s 2015 natural gas price projections, nuclear LCOE would be competitive with natural gas when external costs are considered or when natural gas plants are equipped with 90% carbon capture and sequestration.

Table 3. The Private, External, and Social Costs of Electricity

			EIA AEO 2016 Estimates∗					*Policy-Neutral Estimates†*			
Type of Energy	**Technology**	**Capacity Factor (%)**	**Capital Cost (¢/kWh)**	**Fixed O&M Cost (¢/kWh)**	**Variable O&M + Fuel Cost (¢/kWh)**	**Transmission Cost (¢/kWh)**	**Private Cost (¢/kWh)**	**Private Cost (¢/kWh)**	**GHG External Cost (¢/kWh)**	**Non-GHG External Cost (¢/kWh)**	**Social Cost (¢/kWh)**
Base-loading Technologies											
Fossil Fuels	Conventional Coal	85	6.2	0.4	3.0	0.1	9.8	8.0	5.8	3.6	17.4
	Advanced Coal with CCS	85	9.7	0.9	3.2	0.1	14.0	10.7	4.1	UTQ	14.8
	NGCC	87	1.4	0.1	4.2	0.1	5.8	5.3	2.9	0.2	8.4
	NGCC with CCS	87	2.9	0.4	5.0	0.1	8.5	7.9	1.1	UTQ	8.9
Other	Nuclear	90	7.8	1.2	1.1	0.1	10.3	10.4	0.1	UTQ	10.5
	Hydroelectric	58	5.8	0.4	0.5	0.2	6.8	6.5	0.0	UTQ	6.5
Combined Intermittent and Peaking	Wind (onshore) backed up with Natural Gas Combustion Turbine	85	-	-	-	-	-	8.8	2.3	0.1	11.3
	Solar (PV) backed up with Natural Gas Combustion Turbine	85	-	-	-	-	-	8.8	3.2	0.1	12.1
	Hydroelectric backed up with Natural Gas Combustion Turbine	85	-	-	-	-	-	6.8	1.4	0.1	8.3
Intermittent Technologies											
Renewables	Wind (Onshore)	40	4.9	1.3	0.0	0.3	6.5	7.0	0.1	UTQ	7.1
	Solar (PV)	25	7.1	1.0	0.0	0.4	8.5	10.3	0.3	UTQ	10.5

Note: NGCC = Natural Gas Combined Cycle. UTQ = Unable to Quantify. All units are in 2015 USD, unless otherwise noted.

∗EIA AEO 2016 Estimates: All plants have an online date of 2022, except for conventional coal , whose online date is 2020. Assumes a nominal 7.9% WACC for all technologies except Coal with CCS, which has a 10.9% WACC to account for potential carbon regulation. Conventional Coal is unchanged since EIA AEO 2015, which assumes an 11.1% WACC. Individual MACRS depreciation schedules for each technology, which includes tax benefits for renewables. Also assumes an investment tax credit for renewables. For hydroelectric, assumes seasonal storage so that it can be dispatched within a season. Fuel cost projections and inflation come from EIA's NEMS model.

*†**Policy-Neutral Estimate**s: All plants have an online date of 2022. Identical nominal WACC of 7.9% and 20-year MACRS depreciation schedule for all technologies, removing the tax advantages for renewable technologies. Fuel cost projections from published EIA reports and fixed 2.1% inflation rate from EIA projections. GHG costs come from NREL estimates of GHG emissions and EPA estimates of natural gas methane leakage, SCC, and SCM. Non-GHG costs come from the NAS.*

Experts will differ over the numbers used in Table 3, especially with regard to projections of future costs. However, it is an illustration, not a complete picture of the range of possible outcomes. For example, the Task Force chose to use peaking natural gas power to compensate for the intermittency of renewables. Some would argue that storage is developing so rapidly that it will prove to be a more economic, carbon-free choice in the future. Others would argue that the costs of carbon capture and sequestration could be much lower than what EIA is estimating. The LCOE costs are based on EIA's capital cost reports and projected fuel Reference case prices, and the weighted average cost of capital is based on EIA AEO 2016 assumptions. Many parameters will turn out to be different than assumed in the calculations leading to the results reported in Table 3.

EIA's AEO 2015 estimated a natural gas price of $4.72 per million British thermal units (MMBtu) in 2016, with 2.4% annual real escalation through 2040. The capital cost[j] of new nuclear power plants would need to fall to the level of $3,307/kWe for nuclear power generation to be equal on a private cost basis with natural gas when the natural gas price exceeds $4.72/MMBtu.

EIA's AEO 2016 estimated a natural gas price of $3.46/MMBtu in 2016, with 2.4% annual real escalation through 2040. The capital cost[j] of new nuclear power plants would need to fall to the level of $1,986/kWe for nuclear power generation to be equal on a private cost basis with natural gas when the natural gas price exceeds $3.46/MMBtu.

If only private costs are considered, nuclear power must achieve this low level of capital cost in order to compete with natural gas. This change in 1 year of EIA estimates illustrates the sensitivity of nuclear power electricity breakeven cost estimates to natural gas prices.

Today, energy market expectations seem to be that both North American and global natural gas prices will remain low for the indefinite future. Therefore, it is particularly important to determine the breakeven overnight capital cost of nuclear as a function of natural gas prices for natural gas generation in the case of (1) carbon capture and storage (CCS), (2) no CCS, and (3) no CCS but bearing the social cost of GHG emissions.

Since the LCOE of natural gas is sensitive to fuel costs and the LCOE of nuclear is sensitive to overnight costs, it is interesting to compare the nuclear capital cost and natural gas price under different assumptions: (1) the private cost of the natural gas combined cycle (NGCC) plant, (2) the private cost of an NGCC plant with CCS, and (3) the private cost of an NGCC plant that pays the SCC and the social cost of methane (SCM).

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[j] The overnight capital costs for nuclear refer to project costs incurred during planning and construction of the project. These costs are paid from debt and equity capital contributions. Interest on the debt contribution during construction is accumulated as *allowance for interest during construction*. The total cost is the sum of the overnight capital cost and allowance for interest during construction. The return and repayment of the debt is often done by equal annual payments based on the weighted average cost of capital, which is the average of the return expected for debt and equity capital at the time of initial operation.

Figure 7 illustrates the relationship between the nuclear capital cost and baseline natural gas prices that gives equal LCOE for nuclear and NGCC in different configurations.

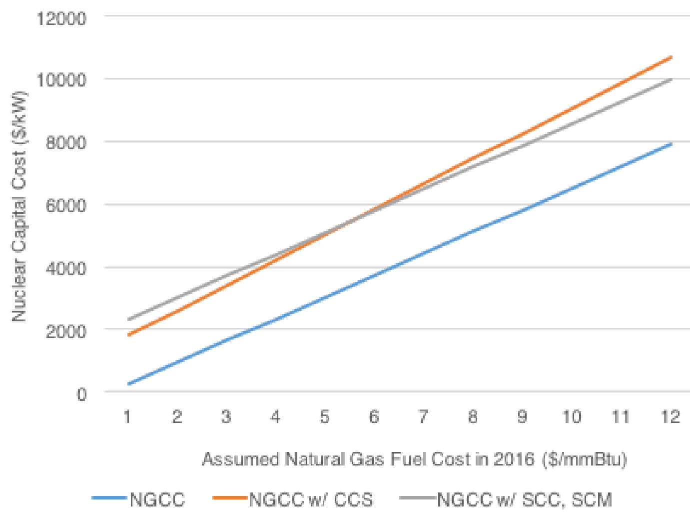

Figure 7. Combinations of nuclear capital cost and natural gas fuel cost for equalizing LCOEs with nuclear power

Assuming the acquisition cost of natural gas is $3.46/MMBtu in 2016 with EIA-equivalent annual real escalation through 2040, the private LCOE for (1) an NGCC plant is $0.0526/kWe-h (without CCS), which would equal the LCOE of a nuclear plant with a capital cost of $1,968/kWe; (2) an NGCC plant with CCS is $0.0786/kWe-h, which corresponds to a nuclear plant with a capital cost of $3,787/kWe, and (3) an NGCC plant that pays the charge of $41/metric ton of CO_2 effective SCC[k] and $1,975/metric ton of methane effective SCM is $0.0821/kWe-h, which equals a nuclear plant with a capital cost of $4,030/kWe (see Appendix C).

If the NGCC plant pays the public cost of GHG emissions either directly by paying the SCC and SCM or by installing CCS, a nuclear plant with a capital cost in the ballpark of $4,000/kWe will achieve the same LCOE.[l] If nuclear capital cost were $4,000/kWe, then the price of natural gas would need to be $6.39/MMBtu in 2016 for the private basis LCOE of these two generating technologies to be equal.

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[k] By "effective" SCC, we mean the weighted-average SCC over all EPA projections until 2050, weighted by real discount factors. With constant marginal emissions (metric tons CO_2/kilowatt-hour) per year, carbon costs are then the effective SCC multiplied by marginal emissions. This is analogous for SCM. We obtain EPA forecasts for SCM and SCC. See 3% scenario of EPA, "Table 2. SC-CO_2 and SC-CH_4 Estimates [2007$ per metric ton]," in *Whitepaper on Valuing Methane Emissions Changes in Regulatory Benefit-Cost Analysis, Peer Review Charge, Questions, and Responses* (Washington, DC: EPA, 2015), https://www3.epa.gov/climatechange/pdfs/social%20cost%20methane%20white%20paper%20application%20and%20peer%20review.pdf; and "The Social Cost of Carbon," EPA, last modified August 9, 2016, https://www3.epa.gov/climatechange/EPAactivities/economics/scc.html.

[l] Note that this assumes that an NGCC plant with CCS emits no GHGs, but this is not true in practice. If we account for these emissions, at natural gas prices of $3.46/MMBtu in 2016 with EIA-equivalent annual real escalation, the breakeven nuclear overnight capital cost equating LCOEs of nuclear and NGCC plants is $4,523/kWe with emission charges $60/metric tons CO_2 effective SCC and $1,975/metric tons CH_4 effective SCM. This results in a crossover between with and without CCS breakeven lines (both with carbon and methane costs) at a natural gas price of -$0.9/MMBtu because the heat rate of the NGCC-CCS system is greater than the heat rate of the NGCC or NGCC-SCC-SCM system.

The Task Force cautions overemphasizing LCOE as the sole measure for analyzing the economics of advanced nuclear reactors. EIA, in a recent paper, points to factors such as projected utilization rates, the existing resource mix, and capacity factors as key attributes that make comparison of various technologies using LCOE problematic; EIA says that LCOE "can be misleading as a method to assess the economic competitiveness of various generation alternatives."[16] Furthermore, other factors will come into play in the judgment of investors and the energy marketplace about the competitiveness of an advanced nuclear technology multiple years from now. These include how well a zero-carbon electricity source would be valued under State and Federal carbon policy, subsidies or price supports, a future electricity market's valuation of the high capacity factor of nuclear power relative to intermittent renewable technologies in comparing dispatchable and nondispatchable generation, electricity portfolio diversification, and the specific advantages of advanced designs such as lower water use. (See footnote d; the announcement of the closure of two units at Diablo Canyon might have been avoided if nuclear power were included in a clean energy portfolio standard.)

The Task Force examined how these 2016 results for nuclear capital overnight breakeven cost changed from the results of AEO 2015. The changes are substantial due to a sharp decline in the cost of grid-connected photovoltaics from $0.125/kWe-hr in 2015 to $0.085/kWe-hr, as well as a reduction in the estimated natural gas prices: AEO 2015 predicted a natural gas price of $4.72/MMBtu in 2016, which AEO 2016 reduced to $3.46/MMBtu. The 30-year gas price projection comparison between AEO 2016 and AEO 2015 is presented in Figure 8:

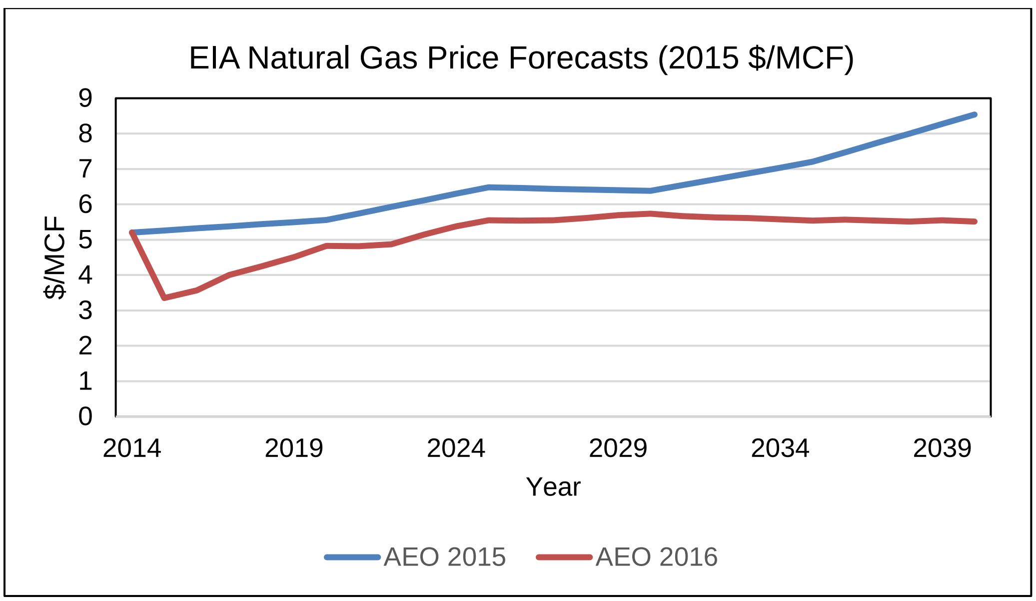

Figure 8. EIA natural gas price forecasts (2015 $/MCF)

The higher natural gas profile means that the nuclear overnight capital cost breakeven is in the range of $4,000 to $4,500 in 2015 compared to $3,800 to $4,000 in 2016. **Low natural gas prices drive the need for lower nuclear overnight capital cost to achieve equal LCOE cost**. Given the uncertainty in natural gas prices over any 30-year time horizon, it would be a very brave investor indeed who would base an entire portfolio on the assumption that the price of natural gas will remain below $5 to $6 per thousand cubic feet of natural gas (MCF). Nuclear power makes economic sense in a balanced portfolio when the social cost of carbon emissions is taken into account and market conditions are addressed, as discussed in the next section.

Electricity Market Design and Policy Impediments to Nuclear Energy

Current policies and market designs fail to recognize fully the zero-carbon, base load, nonproliferation, and other values of nuclear power generation in the United States.[m] **The Task Force believes that the success of the nuclear initiative under consideration will require reforms that resolve these market design and policy shortcomings**. There are a number of options, summarized below, that might address these challenges, but determining their efficacy will require further analysis and depend on specific circumstances in individual U.S. states and regions. The most efficient policies will likely involve the direct pricing of carbon emissions linked to the Federal Government's SCC.

Challenge 1: Carbon Pricing

Most states do not have carbon-pricing programs (e.g., cap-and-trade programs or carbon taxes). Those states that do have carbon pricing (e.g., the Regional Greenhouse Gas Initiative states and California) have carbon prices below the SCC. Implementation of the EPA Clean Power Plan, which is uncertain, is intended to drive a national carbon price and is projected to produce CO_2 prices below the SCC. The EPA plan also contains several provisions that could disadvantage or adversely affect nuclear.

Potential Options to Address Carbon Pricing

- Encourage states to adopt Clean Power Plan mass-based goals (as opposed to rate-based goals) covering both existing and new emission sources; increase the stringency of the rule so that the implied carbon price is equal to the Federal SCC; reform the Clean Energy Incentive Program and Renewable Energy Set-Aside to make those provisions technology neutral; and modify the Output-Based Allocation to eliminate the adverse impact on nuclear energy
- Increase the stringency of current state carbon programs (e.g., Regional Greenhouse Gas Initiative and California's cap-and-trade program), and expand programs to other states and link prices to the SCC
- Establish a national price on carbon emissions linked to the SCC through Federal legislation of a carbon-emission charge, performance standard, or similar market-based emission reduction policy
- Experiment with a market for zero-carbon capacity contracts.

[m] The challenges and potential responses outlined in this section have been influenced by a paper prepared for a May 2016 symposium at Stanford University entitled "Nuclear Value and Market Viability: What Are the Options?" and sponsored by Stanford's Steyer-Taylor Center for Energy Policy Finance and the Shultz-Stevenson Task Force of the Hoover Institution.

Challenge 2: Renewable Energy Policies

Federal renewable energy production and investment tax credits and state Renewable Portfolio Standards (RPSs) spur the deployment of renewable generation. However, in some cases, RPS has suppressed wholesale prices during hours of high renewable output and resulted in the dispatch of renewable electrical generation ahead of base load power generators, including nuclear. This serves to adversely impact the value of base load generation (see footnote d). In some circumstances, the Federal renewable energy production tax credit, which allows producers to bid negative prices into energy markets and has driven hourly energy prices below zero, has reduced revenues to nuclear and other generators in competitive markets.

Potential Options to Address Renewable Energy Policies

- Establish new or expand current Federal or state financial supports for existing or new nuclear plants. The most direct approach would be a production payment, but other policy tools are available (e.g., investment tax credits and loan guarantees).
- Expand state RPS programs to become "Low-Carbon Portfolio Standard" programs or the equivalent by including nuclear and other zero-carbon technologies. A variant of this was recently adopted by New York State, where a new 50% RPS now requires incumbent utilities to "pay for the intrinsic value of carbon-free emissions from nuclear power plants" operating in the state by purchasing "Zero-Emission Credits."[17]
- Require renewable generators to bundle their intermittent generation with firming (i.e., backup) capacity in order to provide a non-intermittent resource and/or allocate a share of the incremental system costs resulting from intermittency.

Challenge 3: Market Design

Regional transmission organizations administer the electric transmission grid and competitive wholesale markets for energy, capacity, and ancillary services. The design and operation of these markets are under regular regional transmission organization review, along with review by generators, consumers, FERC, and others. These markets are organized to ensure reliability of service at minimum cost, but they are often asked to achieve other goals too. Many decisions about these markets can affect the economics of nuclear power.

Potential Options to Address Market Design[n]

- Reform energy pricing by raising the offer caps on hourly energy prices
- Reform capacity pricing by extending the term of capacity products and/or providing stronger on-peak unit availability incentives, as has been pursued in the New England and PJM Interconnection markets

[n] Electricity market structure and design are currently the subject of widespread and intensive interest. One recent informative study is Lisa Wood, Ross Hemphill, John Howat, Ralph Cavanagh, Severin Borenstein, Jeff Deason, and Lisa Schwartz, *Recovery Of Utility Fixed Costs: Utility, Consumer, Environmental and Economist Perspectives* (Berkeley, CA: Lawrence Berkeley National Laboratory, 2016), LBNL-1005742, Report #5, https://emp.lbl.gov/sites/all/files/lbnl-1005742_1.pdf.

- Experiment with separate markets for as-available (interruptible) power and on-demand (firm) power.

IV. The Government's Role

Any Federal energy and environment initiative should be clear about the government's role in that initiative. Several of the challenges involved in the nuclear power initiative that the Task Force is considering can only be addressed and resolved by government policies and actions.

These challenges include the following:

- Maintaining a nuclear technology base that creates future capability and human capital
- Establishing a stable market and regulatory structure enforced by State and Federal authorities, which is needed by private investors
- Assuring safety and security in the construction and operation of nuclear power reactors and associated fuel-cycle facilities both domestically and internationally
- Managing the international linkage of nuclear power, especially nonproliferation, safety, and waste management activities
- Addressing the management of nuclear waste.

The Task Force addresses each of these challenges in this report.

The Task Force's principal purpose is to describe an initiative led by the United States to achieve nuclear deployment at scale in the 2030 to 2050 time frame. An important consideration is the Federal Government's role in supporting energy innovation in the later stages of demonstration and deployment. This consideration is a matter of debate about the success of the Federal Government taking action that normally is the province of the private sector, based on judgments about the adequacy of markets to meet future societal energy and environment needs. The position of the Task Force on this matter is captured by the following the sentiment:

> "The social cost of reducing carbon emissions in the long term requires major technical change. Currently, we—the United States and the world—do not have the necessary mechanisms in place and are not devoting the level of resources necessary to encourage the needed private sector adoption of new technology. Successful government action requires both more resources and a willingness to change the conventional approach to government's support for energy technology commercialization."[18]

The fundamental justification for the Federal Government to provide incentives for low-carbon electricity-generating technologies, whether renewables, CCS, or nuclear, is that the market does not properly value low-carbon technologies; put another way, the market does not charge GHG-emitting technologies with the social cost of these emissions. If a carbon emission charge was in place and was applied uniformly, private investors would make decisions between alternative generating technologies that properly reflected their social costs. In the absence of a GHG emission charge, the government has the responsibility to decide on actions that will "level the playing field." Of course, the extent of such compensating incentives and their nature can be debated and will depend on many factors, such as the ability of the government to craft and administer an effective assistance program and the existence of other policies that compete for available public resources.

As explained in Section V, the likely time frame of a nuclear initiative of the nature explored here would be 10 years or more, and the initiative would require significant government resources. Accordingly, the initiative will require consistent support from successive administrations and sessions of Congress in order to be successful. The best chance of achieving this is broad bipartisan support based on extensive discussion of the purpose of the initiative with many different stakeholders.

Nuclear Waste Management

Nuclear power does result in the production of highly radioactive spent fuel, which must be isolated from the environment for an extended period. The Federal Government has responsibility for disposing of spent fuel, and it has notably failed as yet to fulfill its responsibilities. Congress has directed that the social cost of the disposition program should be embedded in the cost of nuclear power; consumers of nuclear power pay a fee to cover the cost of the disposal program (1 mill/kWe-hr).[o] The current balance in the resulting nuclear waste fund is in excess of $31 billion.[p]

[o] 1 mill is equal to one-tenth of a cent.

[p] Payments to the fund have temporarily been stopped because of the Federal Government's failure to establish a program for the disposing of spent fuel. Nat'l Ass'n of Regulatory Util. Comm'rs v. DOE, 736 F.3d 517 (D.C. Cir. 2013).

V. Technology Readiness and Selection

A key step in assessing the proposed nuclear initiative is the selection of which technology or technologies should be pursued. The answer depends on three judgments: (1) technology readiness, (2) safety, and (3) prospects for achieving low-cost electricity. Considerable analysis of the candidate nuclear technologies has been performed over the years, notably by DOE's Next Generation Nuclear Plant[19] (NGNP) and its participation in the international Generation IV nuclear collaboration.[20] DOE recently presented its draft vision for the development of advanced reactors.[21] In addition, there are presentations available from The Third Way, a think tank that reports on the activities of some of the many new ventures (over 40 firms) that are being pursued by the private sector to promote advanced reactor technologies.[22]

The Task Force considers in turn the PWRs and boiling water reactors (BWRs) being developed and deployed today, and then advanced reactor concepts.[q]

Pressurized Water Reactors (AP1000, APR1400, APWR, EPR) and Boiling Water Reactors (ESBWR, ABWR)

Present AP1000 costs are too high for widespread deployment in the United States under current market conditions. It is possible these costs will decline in future builds, but nobody knows. There is no need for direct U.S. government technology support for this class of Generation III+ reactors.

If a carbon charge and a reasonable market structure were in place, these reactors might prove commercially viable for merchant owner/operators. If a carbon charge is not in place, the Federal Government could choose to extend a production payment to nuclear generators to reflect the value of carbon-free generation. A production payment in the range of \$0.015–\$0.027/kWe-hr (0.5–0.9 kg CO_2/kWe-hr) would be equivalent to \$30/metric tons SCC.[r, s] The production payment design would include the possibility of future payback and time limits.[t]

The Task Force believes if a carbon emission charge—or production payment in lieu of such a charge—is in place, then many, but not all, of the existing subsidies for zero-carbon electricity-generating technologies could be eliminated. Undoubtedly, some

[q] Other nuclear technologies, such as Canada's Heavy Water and the United Kingdom's Magnox reactors, that have been deployed in the past were not considered by the Task Force to be viable candidates today.
[r] A 1,000 MWe plant operating at 90% capacity factor produces 7.88 x 10^9 kWe-hr/year. If the SCC is \$30 per metric ton of CO_2 emitted, the value of the avoided social cost is \$189 million/year, assuming 0.8 kg CO_2/kWe-hr.
[s] Such a carbon avoidance production payment would also be extended to renewable electricity–generating technologies, where this is not already in place.
[t] The Energy Policy Act of 2005 provided a \$0.018/kWe-hr tax credit for up to 6,000 MWe of new nuclear capacity for the first 8 years of operation, up to \$125 million annually per 1,000 MWe. The benefit was to be allocated among reactors that filed license applications by the end of 2008 and began operating before 2021. As of 2009, 17 firms had announced plans to file license applications for 29 units. Mark Holt, *Nuclear Energy Policy* (CRS Report No. RL33558) (Washington, DC: Congressional Research Service, 2009), http://research.policyarchive.org/2927.pdf.

subsidies will remain. Nuclear power would continue to require the backstop of the Price-Anderson nuclear liability insurance.[u]

Small Modular Reactors

The SMR version of LWRs (NuScale and possibly others) might turn out to be cheaper than the large-scale plants, especially if many units are manufactured; however, as yet there is no evidence that this is so. SMRs may have other advantages even if their capital cost per kWe is higher than the AP1000, such as passive safety, less water usage, and greater safety and security due to underground deployment. Moreover, SMRs offer investors a smaller financial project that is more manageable. Of course, SMRs may have disadvantages as well, such as more complicated power island integration.

Opportunities exist for DOE to advance the development of SMRs. One possibility is assistance in developing low-cost manufacturing of SMR reactor modules. DOE's Naval Reactor program, with its expertise in system integration and efficient packaging, is often cited as having experience relevant to manufacturing SMR technology. However, DOE does not have a history in manufacturing technology, and such assistance would need to address ownership of intellectual property. DOE could also facilitate the licensing process for SMR applicants.

Another possibility is for DOE or the Department of Defense to offer a Federal site and take-or-pay electricity off-take contacts to reduce risk for initial SMR owner/operators. These steps should be considered independent from provision of Federal production payments (in the absence of a carbon charge) to compensate carbon-free electricity producers for the avoided social costs of carbon emissions.

Advanced Nuclear Reactors

In 2014, Congress directed DOE to perform a planning study to provide recommendations for moving forward on an advanced test or demonstration reactor.[v] DOE's Office of Nuclear Energy requested that the Nuclear Reactor Technology Subcommittee of the Nuclear Energy Advisory Committee (NEAC-NRT Subcommittee) help define the scope and process for conducting this planning study. (Small Modular LWRs were not included in this study.) At the March 2016 SEAB Task Force meeting, the chairman of the NEAC-NRT Subcommittee and two DOE laboratory experts described the results of their work to date. The DOE study, which relies on Global Nuclear Energy Partnership and NGNP Generation IV work, identified two technologies as "highly mature": the modular high temperature gas-cooled reactor (Areva) and sodium-cooled fast reactor (General Electric).

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[u] A good description of Price-Anderson Nuclear Liability Act is given on the National Association of Insurance Commissioners' website: http://www.naic.org/cipr_topics/topic_nuclear_liability_insurance.htm.

[v] The congressional request, as stated in the appropriated budget, was "$7,000,000 is for an advanced test/demonstration reactor planning study by the national laboratories, industry, and other relevant stakeholders of such a reactor in the U.S. The study will evaluate advanced reactor technology options, capabilities, and requirements within the context of national needs and public policy to support innovation in nuclear energy."

"Highly mature" implies two important judgments: (1) the "mature" technologies require $1 billion–$2 billion in technology development costs and 13 years to complete construction and start-up testing of a pre-commercial initial plant, and (2) the capital cost of either of these plants and the LCOE are likely to be in the range of PWRs, i.e., ± 20%.

Less Mature Advanced Nuclear Technologies

The DOE study judged that other proposed nuclear technologies were of lower maturity (supported by less engineering data) and therefore would require longer development periods and greater cost to reach a point where the first commercial-scale plant could be established. In particular, these technologies would likely require a technology demonstration plant in advance of a first commercial unit.[w] This set of technologies included:

- Lead-cooled fast reactor
- Molten salt reactor
- Fluoride high-temperature reactor
- Supercritical water reactor
- Very-high-temperature reactor gas-cooled reactor
- Gas-cooled fast reactor.

For a given plant capacity, these advanced technologies have the same size, complexity, and high cost of Gen III+ LWRs. Each of these advanced nuclear concepts has features that could lead to advantages over Gen III+ reactors and that, together, would make the technology a compelling choice. Examples of such features are: higher temperature operation (greater efficiency), lower pressure operation, higher burn-up (better resource utilization), and improved passive safety features. Appendix D lists some opportunities for cost reduction in generic reactor designs.

The DOE study is based heavily on prior Generation IV studies and may not have given adequate consideration to more radical design concepts, such as nuclear batteries, thorium fuel cycles, or fusion.

Recommendation: Two-Part Nuclear Initiative

Based on technology readiness, the Task Force recommends the United States adopt a two-part nuclear initiative to accelerate our clean energy future:

Part 1: For Technology-Ready LWRs

For technology-ready LWRs, new deployments should receive a production payment (assuming the absence of a carbon emission charge), with perhaps some of the additional risk-reducing DOE efforts for SMRs mentioned above.[x] The scale of the

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[w] France, China, and Russia have recent experience with liquid metal sodium-cooled reactors and their fuel fabrication. The United States has not had any operational experience since the 1980s. Hence, a technology demonstration may be required.

[x] Renewable electricity–generating technologies such as wind and solar should be eligible for this production payment replacing existing subsidies.

production payment should be about $0.027/kWe-hr, or $213 million per year for a 1,000 MWe plant operating with a 90% capacity factor.

As discussed in Section III, LCOE is one important measure, but only one of several measures, for evaluating the economic competitiveness of nuclear power versus other technologies in the electricity market. The Task Force discussion of the economic and market risks facing nuclear power in Section III of this report emphasizes that, if nuclear power is in a market where it is competing with other electricity-generating technologies, those technologies must bear the social cost of their carbon emissions; otherwise, nuclear and renewable technologies should receive a production payment. If an emission charge is applied to fossil technologies, the cost of nuclear power is likely to be competitive if the technology is deployed.

Part 2: For Emerging Technologies

For emerging technologies, the Task Force recommends launching an advanced nuclear reactor program now that will reduce risks and lead to U.S.-based capacity to produce and deploy advanced reactor technologies in the 2030–2050 time frame.

The program for advanced nuclear reactors should consist of four phases separated by clear milestones that must be passed successfully to continue. The separation into four phases reflects the uncertain nature of the outcome of the effort.

The Task Force believes that more R&D is needed on the alternative advanced nuclear options before an informed comparison can be made on the performance, cost, and safety characteristics of these new technologies relative to existing LWR systems. Therefore, the Task Force recommends that the first phase of this advanced nuclear reactor R&D program undertake engineering work focused on narrowing the uncertainties around these characteristics of advanced nuclear reactor technologies. The intention should be to review after a period of time, assumed to be 5 years, the readiness of one (or more) advanced nuclear reactor technologies for a demonstration/deployment project.

The Federal Government has made many investments in low-carbon electricity-generating technologies—such as solar, wind, and geothermal technologies and gas and coal carbon capture and sequestration—without full confidence they would beat the LCOE of conventional fossil fuel electricity generation. Federal support is justified for advanced nuclear as long as there is a “reasonable probability” of the technology being competitive in a future level marketplace in which low- or zero-carbon emissions are valued.

Section VII provides a schematic timeline for this proposed project and its projected financial requirements. While these are highly uncertain, the Task Force believes they give a useful impression of the scale of the proposed initiative. The Task Force also proposes a separate management structure for managing this longer-term initiative.

VI. Importance of the Ongoing DOE Nuclear Energy R&D Program

The Task Force was not asked to review the current DOE Office of Nuclear Energy R&D program or to suggest additional R&D initiatives that might be considered if funds were available. However, the Task Force wants to emphasize the importance of DOE's current nuclear energy program investments in people, facilities, and R&D that create technology options for the future. Therefore, the Task Force does not recommend the reallocation of a portion of the current Office of Nuclear Energy program to the expansion of advanced nuclear reactor R&D, if additional funding is not available.

The Task Force was asked to comment on "requirements for new development and test facilities that can serve one or more of the technologies under development with the possibility that several countries will be interested in sharing the cost and use of such facilities" (see Appendix A). The Task Force is aware that the Office of Nuclear Energy has been concerned about the adequacy of the suite of U.S. nuclear testing facilities and has been considering the contribution that a new test reactor could make to advancing several of the advanced reactor concepts that are under development. Several references are available that compare the capabilities of existing test reactors around the world, as well as those that are under construction.[y] The existing test reactors in the United States and Europe focus on the use of water (H_2O and D_2O) as a coolant and concentrate on thermal flux conditions that represent or accelerate conditions expected in existing LWRs. However, several existing and planned test reactors contain loops that allow testing of materials and fuels in coolants proposed for advanced reactors. For example, France is building the Jules Horowitz Reactor with water, gas, and sodium test loops.[23] Japan,[z] China, India, and Russia have test and demonstration reactors with flux and coolant conditions representative of sodium-cooled fast reactors. Furthermore, molten salt and lead systems are planned in Europe, Russia, and China.

The Task Force does not believe a new test reactor is necessary for the demonstration/deployment initiative it is examining. Each reactor technology community expresses different testing needs and is actively making arrangements with existing facility operators for their unique testing requirements. Although it may be desirable for the long-term health of the U.S. nuclear technology base, committing to the construction and operation of such a U.S. multipurpose test facility requires significant time and resources. Successful operation of such a facility requires a long-term, substantial commitment for base funding (as was learned with the Fast Flux Test Facility experience of the 1980s). The Task Force believes that if a U.S. test reactor project goes forward, the United States should seek international cooperation, both substantive and financial. DOE's extensive involvement in the international Generation IV activities suggests that

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[y] For example, see International Atomic Energy Agency (IAEA), "Research Reactor Database," IAEA, accessed May 21, 2016, https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?rf=1; or J. Rempe, D. Knudson, J. Daw, T. Unruh, B. Chase, K. Davis, R. Schley, J. Palmer, C. White, and K. Condie, *Status Report on Efforts to Enhance Instrumentation to Support Advanced Test Reactor Irradiations* (Idaho Falls, ID: Idaho National Laboratory, 2014), INL/EXT-13-30427, http://www.osti.gov/scitech/biblio/1164843/.

[z] Although the Jōyō and Monju nuclear reactors are currently not operating, Japan is continuing efforts toward their restart.

international interest in participating might be high. Before proceeding, however, DOE should determine whether there are (or will be) sufficient facilities around the world where advanced fuels can be irradiated.

VII. Schedule and Cost of an Advanced Nuclear Reactor Initiative

The Task Force believes it important to give an estimate of the time and cost that would be required to successfully complete a new nuclear initiative. Evidently, there is a wide range of uncertainty in such an estimate since it involves many judgments on many factors, including (1) NRC safety licensing, (2) fuel qualification, (3) reactor technology demonstration, which depends on technical readiness, (4) fuel-cycle integration, and (5) funding levels. The Task Force recommends a four-phase program to divide the effort into stages to reduce overall risk and identify "off-ramps" should they be necessary:

Phase I: Down Selection Phase

The first down selection phase of the initiative focuses on performing the technology development, engineering, and systems analysis necessary to establish technological readiness, estimated capital cost, and LCOE of the candidate technologies. The purpose of this phase is to provide the basis for selecting one or more advanced nuclear technologies that are judged to have the greatest potential for exceeding the safety, cost, and performance characteristics of LWRs, such as water usage or fuel-cycle benefits. If none of the advanced concepts demonstrates a "reasonable probability" of exceeding these goals, the project should be abandoned at this Milestone 1. **The Task Force believes that Phase I consideration of advanced nuclear reactor systems should include the possibility of new candidate reactor concepts and not be restricted to the candidate set discussed in Section V that has been defined up to the present**. This will encourage compelling new approaches to come forward. Down selection of the advanced reactor concept to be pursued is the responsibility of the management structure described in Section X.

Phase II: Reactor Demonstration Preparation Phase

This second reactor demonstration preparation phase will be devoted to design, licensing, and subsystem development for a demonstration reactor. Milestone 2 is the decision point to proceed with the construction and operation of the demonstration plant.[aa]

Phase III: Demonstration Plant Operation Phase

The third demonstration plant operation phase focuses on preparing a detailed design for a FOAK commercial plant. This phase acquires the information needed for a more in-depth analysis of the commercial viability of an advanced nuclear reactor technology (relative to LWR technology) both in the United States and elsewhere in the world. Milestone 3 is the critical project decision point. A project should not proceed to FOAK

[aa] We refer to two different reactors in different stages of development: (1) A *demonstration plant* is intended validate integrated functioning of components and subsystems and to define the envelope of efficient operation. The capacity is often less than expected full scale; the unit is not expected to produce electricity or to have all the balance of plant features expected on a commercial plant. (2) A *FOAK plant* is at commercial scale, based on supply chain components, and is suitable for establishing a blue print for serial production.

plant construction and operation without a confident judgment of commercial viability. It is in this phase that the owner/operator proceeds to secure the licensing approvals, electricity off-take agreements, and financing needed to support the Phase IV FOAK plant.

Phase IV: FOAK Reactor Operation Phase

The fourth FOAK reactor operation phase concludes with an explicit determination at Milestone 4 that private investors, banks, utilities, and owner/operators of electricity generation are prepared to commit to a first wave of construction of these advanced nuclear plants.

In order to address this question, the Task Force prepared a generic development template, which was circulated to advanced reactor developers and potential owner/operators of nuclear plants to determine the range of estimates among practitioners. Five firms responded to this request, reporting on five advanced nuclear technologies (four fission technologies and one fusion technology) and one integral LWR-SMR technology.[bb] These responses have influenced and informed the generic template that the Task Force has developed. The Task Force generic template differs significantly from the firm responses, underscoring the broad range of uncertainty in each numerical estimate. To give an impression of the breadth of uncertainty in these estimates, the following table gives the range that the four advanced fission nuclear reactor technologies span for total cost and for time from conceptual design to initial operation of a FOAK commercial plant.[cc]

Table 4. Estimated Costs and Time Requirements for Four Advanced Fission Nuclear Reactor Technologies

	Total Estimated Cost (2014 $)	**Total Time Required**
Range of Estimates Received	$1.7 billion–$4.0 billion	12–23 years

The Task Force estimate of the total cost and time to completion of this program, based on the template described below, is $11.5 billion over 25 years; this, however, includes in the initial $2 billion a 5-year Phase 1 down select period for significant R&D not included in the submissions of the vendors. In addition, it is unlikely that the project would proceed to Phase IV FOAK plant construction unless there was strong indication of advantages over existing LWR designs.

[bb] The responding firms were Tri-Alpha, X-energy, NuScale, Transatomic, General Atomics, and Southern Nuclear.
[cc] The data provided by the firms are proprietary.

Generic Template for Advanced Nuclear Technology Demonstration and Deployment

The purpose of the template is to give an impression of the scale in terms of time and money needed to successfully accomplish the deployment of a new nuclear reactor technology. The Task Force doubts that it is possible to reduce dramatically the time and resources indicated for such a project for many advanced technologies. Moreover, these estimates do not include any back-end fuel-cycle-related costs. The Task Force recognizes that there are considerable differences in strategies being followed by nuclear developers. Some developers do not plan to build and operate a "demonstration plant"; rather, they plan to proceed from component testing and licensing directly to FOAK construction and operation. Furthermore, different licensing strategies may emerge other than the Part 50 (assumed in the template) and Part 52 processes described in Section VIII and Appendix E of this report. Nevertheless, the Task Force finds that the suggested template is useful for framing the issues associated with deploying a new reactor technology.

The advanced nuclear template describes a timeline and cost to take a single advanced nuclear reactor concept through development, demonstration, and construction of a FOAK operating plant. The Task Force believes, however, that there should be flexibility in the down selection process during the early Phases I and II. There is a possibility that information and analysis points to pursuing two concepts through the demonstration phase before selecting one concept for FOAK deployment. With this flexibility in mind, the Task Force is proposing a program initiative rather than prescribing a rigid path.

The program, irrespective of which reactor technology is pursued, has a high cost and a long timeline. The Task Force believes it would be a mistake for the United States to launch this initiative without understanding the size of the resource commitment and the sustained period of time required. The government costs to accomplish the innovation considered in this section do not include the production payment for avoiding carbon emissions that the Task Force recommends as the primary necessary incentive for commercial deployment of a proven new nuclear technology.

Respondents to the SEAB Task Force information request were asked to identify barriers to advanced nuclear reactor technology innovation. Two issues were mentioned: (1) regulatory uncertainty, in particular the NRC's capacity for licensing non-LWR nuclear technologies, and (2) availability of sustained Federal financial support for the development effort. Licensing considerations are considered below in Section VIII. The financing of the initiative is addressed in the next part of this section.

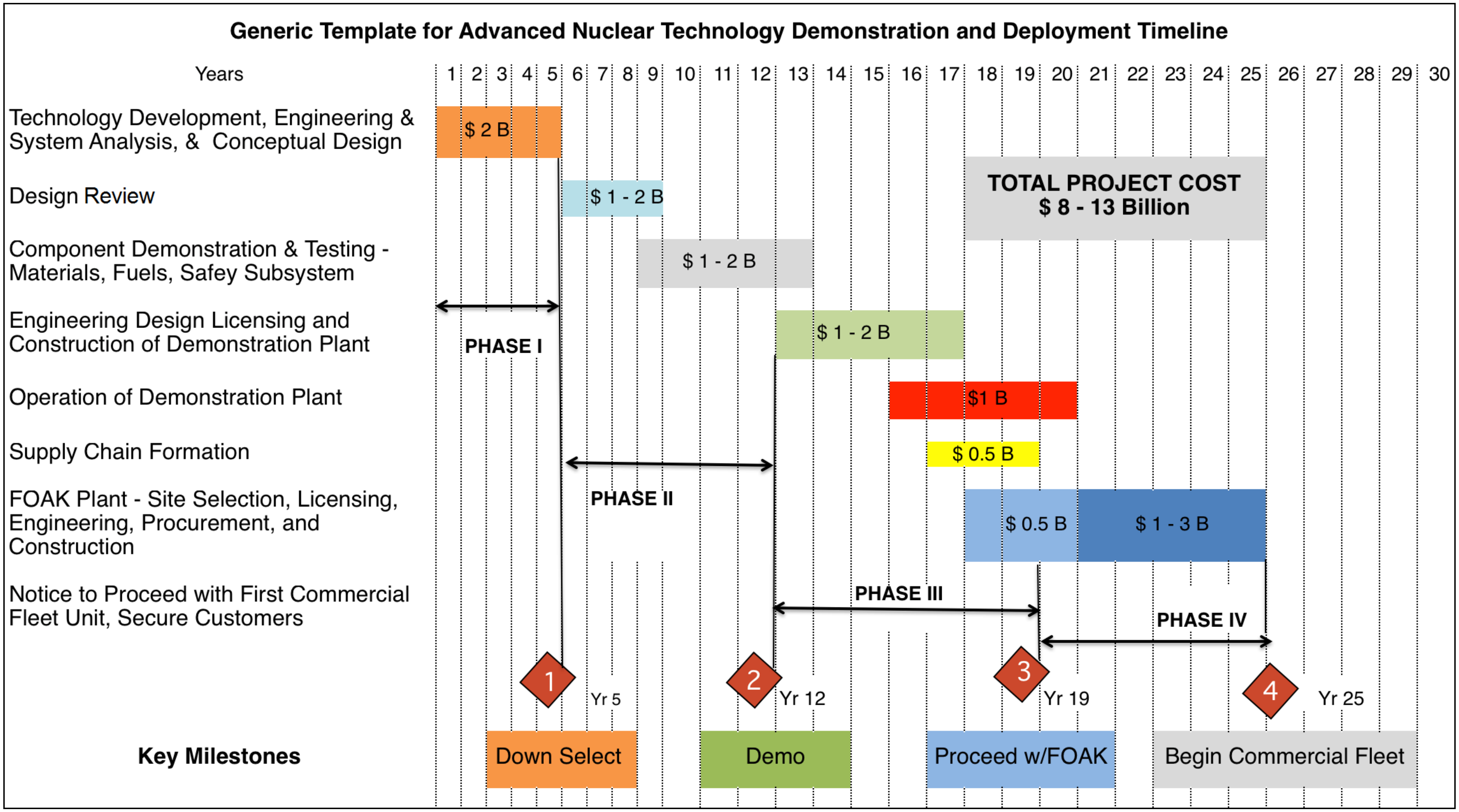

Figure 9. Generic template for advanced nuclear technology demonstration and deployment timeline

Financing the Program

The Federal Government, international partners, and the private sector should share the substantial technical development costs of the nuclear power initiative.[dd] Four factors explain the private sector's reluctance to invest: (1) the absence of an established price for carbon emission; (2) significant technical, cost, and regulatory uncertainties of new nuclear technologies; (3) projected market conditions; and (4) unanticipated intervening events internal or external to the project, such as a nuclear accident, with effects that exceed the time horizon of private investors.

The risk will narrow as the project progresses, so the sharing of the costs in the different phases of the initiative should be different. The support mechanisms should also not be the same in different phases of the project. In Phases I and II, the uncertainty in resolving technical, cost, and regulatory issues means that the private sector is unlikely to be willing to bear much of the cost. In Phases III and IV, risks are reduced and private sector participation should increasingly become possible. This difference in the risk of commercial viability between the Phases I and II and Phases III and IV of the initiative point to a different level of public funding needed to finance the initiative and to different mechanisms for public support.

Cost Sharing and Intellectual Property Considerations

Almost all DOE energy research, development, and demonstration programs require cost sharing by private sector award recipients. The reasons are that cost sharing means that firms have "skin in the game" and share an interest in successful project outcomes. Cost sharing allows DOE to stretch available R&D dollars to cover more projects. Of course, firms that cost share expect to have preferential access to the intellectual property that results from the development effort, and DOE routinely grants intellectual property rights to private firms that cost share in energy research, development, and demonstration projects.

This practice runs counter to one of the major objectives of Federal support for technology demonstration, which is to create knowledge for a broad set of competing entities. Federal efforts to accelerate the adoption of technology go beyond enabling a single firm that has entered into a cost sharing agreement to achieve a monopoly position. The purpose is to establish a new technical capacity among several competing firms in the industrial sector.[ee] (DOE frequently sponsors industry consortia to advance technology; for example, in 1993, DOE established the Partnership for a New Generation of Vehicles to diffuse knowledge broadly within an industry.)

Thus, the Task Force believes it is appropriate for the Federal Government to cover all the incremental costs of the Phase I work the initiative directs in order to retain as much

[dd] The Task Force refers to "Federal–private cost sharing" rather than the broader term "public–private partnership" because the later suggests a broader range of considerations, such as the planning and management of the overall initiative.

[ee] In this regard it is noteworthy that early Federal assistance to commercial nuclear power technology resulted in the creation of four competing firms: Westinghouse, General Electric, Babcock and Wilcox, and Combustion Engineering.

leverage over use of the intellectual property generated by this public investment. Of course, background intellectual property remains with the firm that developed it. If cost sharing is necessary in this phase, a mechanism should be developed to assure future of payback for all or a portion of government assistance to reflect the market advantage enjoyed by the participating team.

Phase IV consists of the construction of a FOAK commercial reactor, and appropriate agreements to monetize electricity output should be in place. At this point, there should be sufficient confidence of the commercial viability of the new advanced reactor technology so that the private sector can bear the entire cost, anticipating the revenue from the electricity generated and assuming provision of an allowance has been made for the carbon-free nature of the technology as discussed above. In Phase IV, the responsibility for constructing the FOAK reactor is with the private sector owner/operator that is bearing the cost of the project.

It is possible that even the provisions assumed here—a stable electricity market structure and a production payment for the carbon-free value of electricity production—will not be enough to reassure private investors about the risk of a FOAK reactor. The likelihood of private investment would be higher if there were examples of private financing of LWR plants. However, for advanced reactors, private investors might be uncertain the FOAK plant will operate at design levels of efficiency and availability. In this latter case, there would be both "pros" and "cons" to extending even a greater level of public assistance.

The circumstances in Phases II and III are more uncertain for going forward to Phase IV. A judgment will need to be made at these milestones to determine how project costs should be divided between the government and private sector participants, as well as the mechanism of such government assistance (e.g., loan guarantees, above market guaranteed purchase, equity participation, investment tax credits, etc.).[ff] Phase IV investors in a FOAK plant may prefer an investment tax credit to some or all of the benefits of a $0.027/kWe-hr production payment that reduces their risk exposure to less-than-successful plant operation. A production payment, in contrast to an investment tax credit, requires successful plant operation for a payout to occur.

The following table shows estimates (mid-range except for Phase IV in the generic template) of the effect of these assumed splits on public and spending on a project to develop and deploy one reactor technology. **The public and private shares are roughly equal for the entire project, but the public share of expense is greater in the early, higher-risk phases of the project**.

[ff] Some investors might prefer an investment tax credit, which reduces their capital at risk in the event that the project fails, to a larger production payment that only yields revenue if the project operates as expected.

Table 5. Mid-Range Estimates of Federal and Private Project Costs

Estimated Project Cost Split by Phase	Federal Share	Private Firm Share	Total
Phase I	$2 billion	$0	$2 billion
Phase II	$1.5 billion	$1.5 billion	$3 billion
Phase III	$1.75 billion	$1.75 billion	$3.5 billion
Phase IV	$0	$3 billion	$3 billion
TOTAL	$5.25 billion	$6.25 billion	$11.5 billion

International Participation

The United States has been an active participant in international nuclear activities for decades. (See the discussion in Section IX on international linkages.) The United States is currently active in the International Framework for Nuclear Energy Cooperation (formerly the Global Nuclear Energy Partnership) and Generation IV International Forum, which has been considering the technical readiness and the prospects for commercial viability of advanced nuclear fission reactor technologies.[24] It is quite possible that some of the ten active organizations in the Generation IV International Forum would be interested in participating in a U.S.-led advanced nuclear reactor initiative.[gg]

The Task Force believes the participation of one or more foreign partners would be welcome from three points of view: technical contribution, cost sharing, and opportunity to shape future commercial deployments around the world.

Of course, international participants will expect concrete benefits from their participation and funding, such as work share, access to intellectual property, the right to deploy new advanced reactors in their countries, and commercialization of the new reactor technology in other countries alongside the United States. These matters will need to be negotiated among the sponsoring parties. The Task Force cautions against entering into a multilateral governance structure because of the complexity of management and decision making it would add to the reactor initiative.

[gg] The ten nations in the Generation IV International Forum are Canada, the People's Republic of China, Euratom, France, Japan, the Republic of Korea, the Republic of South Africa, the Russian Federation, Switzerland, and the United States.)

VIII. Safety and Licensing of Nuclear Reactors

The United States' licensing process is the global gold standard for rigorous attention to reducing accident risks. However, the cost burden is substantial; licensing involves a formidable front-end investment and can approach $1 billion because of the required submission of extensive confirming data to support the performance of the safety systems. In this section, the Task Force summarizes its views about licensing in the context of the development/deployment stages discussed in the previous section. Appendix E presents a detailed elaboration of the points made here.

LWRs

Understandably, the NRC's current experience and regulatory requirements are focused on LWR technology. There is a need for guidance with regard to issues affecting SMRs based on LWR technology. Their different characteristics may justify modification of requirements for emergency planning zones, security requirements, control room staffing, insurance, and perhaps other matters. The NRC is pursuing these matters and should continue to do so. Their resolution plays a part in the economics of these plants and thus affects their commercial viability as well as the viability of SMRs using non-LWR technology.

Advanced Reactors

The NRC does not currently have general design criteria for advanced nuclear reactors or recent experience in processing applications for non-LWR designs, but it has recently released a report on its vision and strategy for achieving safety for non-LWR reactors.[hh] DOE has worked with the NRC for several years to develop design criteria for advanced reactors. That work is important and should continue because all parties would benefit from a framework to guide licensing decisions.

As discussed in the previous section, advanced technologies typically develop in stages or graduated steps in which increasing levels of investment are made at each stage as risks are retired. Accordingly, there is current interest in the establishment of a stepwise licensing process for advanced reactors that conforms to the investment stages.[ii] The aim is to reduce regulatory risk by providing guidance at early stages as to the general acceptability of a design, and then to provide input along the engineering pathway as to whether the requirements for licensing are adequately satisfied. The NRC should seek to provide clear and early guidance regarding regulatory requirements for those vendors

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[hh] Nuclear Regulatory Commission (NRC), *NRC Vision and Strategy for Safely Achieving Effective and Efficient Non-LWR Mission Readiness* (NRC, draft), ML16139A12, http://www.nrc.gov/docs/ML1613/ML16139A812.pdf. This includes a 9-year timeline for NRC to complete readiness activities required to be prepared to review a non-LWR design certification application under 10 C.F.R. Part 52 or a non-LWR licensing review under 10 C.F.R. Part 50.

[ii] See, for example, Ashley E. Finan, *Nuclear Innovation: Strategies for Advanced Reactor Licensing* (Cambridge, MA: Nuclear Innovation Alliance, 2016), http://www.nuclearinnovationalliance.org/#!advanced-reactor-licensing/xqkhn; Jeffrey Merrifield, *U.S. Nuclear Infrastructure Council Task Force: Issue Brief on the Framework for Advanced Reactor Licensing Modernization* (Washington, DC: Nuclear Infrastructure Council, 2016), http://media.wix.com/ugd/760734_804492aec73c4284b0577281d5b3a5a7.pdf. Bills are pending in both the House (H.R. 4979) and the Senate (S. 2795) that require the NRC to develop a stepwise licensing approach.

who seek to pursue a non-LWR technology and regarding whether the proposed design satisfies the requirements. DOE has worked with the NRC to assist in the development of such guidance,[25] but much remains to be done to develop approaches that are risk-informed and performance-based. The NRC recently sought public comments concerning draft design criteria for advanced reactors and should continue this effort.[26] The Task Force concurs with the desirability of providing regulatory guidance that can reduce the uncertainty along the various investment stages in the development of an advanced reactor design. In fact, a DOE-NRC team that examined the licensing approach concluded that the application of existing licensing processes could provide an effective and efficient means for licensing that would protect NRC and applicant resources.[27]

Early-Stage Interactions in Phase I

This interactive process can and should start with pre-application meetings with NRC staff to develop understanding of the reactor technology, the project schedule, testing requirements, deliverables, and NRC review budgets. This process should involve an early identification of significant issues and of the means for their resolution. This licensing project plan can and should be subject to review and, as necessary, modification as the relationship between the applicant and the NRC staff evolves. The use of topical reports, standard review plans, exemptions to LWR requirements, and guidance documents will diminish the uncertainty associated with the various stages of design review. Hence, the NRC has indicated that its existing processes enable it to provide early feedback to applicants pursuing an advanced design.

DOE has established the Gateway to Accelerated Innovation in Nuclear (GAIN) to provide the nuclear community with access to technical, regulatory, and financial support necessary to move innovative advanced nuclear energy technologies to commercialization, while ensuring the continued safe, reliable, and economic operation of the existing nuclear fleet.[jj] An important part of this effort is improving communication and understanding between nuclear reactor developers and the regulatory community. DOE should expand its efforts to assist in the licensing of advanced designs and in the development of codes and data to facilitate the analysis of safety decisions. DOE should also ensure that private industry and universities have access to capabilities bearing on advanced reactors from across the DOE complex.

Interactions in Phase II

Some vendors of advanced designs may need a prototype reactor to advance their technical approach. In addition to the normal licensing processes,[kk] two other avenues are available to provide the foundation for a FOAK plant: a license by NRC under article Atomic Energy Act Section 104(c) or a DOE authorization (perhaps with NRC participation, but without an NRC license) to perform studies at a DOE site bearing on an

[jj] The DOE GAIN website is found at: https://gain.inl.gov/SitePages/Home.aspx.

[kk] Commercial NRC licenses are issued under authority of Section 103 of the Atomic Energy Act. Medical therapy reactors and reactors for R&D are issued under Section 104. The latter have much lower power than a typical commercial power reactor and generally receive less extensive regulatory scrutiny because they present lower risk.

advanced design. Section 202(2) of the Energy Reorganization Act stipulates that a DOE demonstration reactor requires an NRC license “when operated in any…manner for the purpose of demonstrating the suitability for commercial application of such reactor.”[28] Nonetheless, a DOE non-power reactor could be constructed on a DOE site without an NRC license to assist in the evaluation of systems that might be used in a power reactor. However, it would take some time for DOE to develop a suitable process for authorizing a new reactor. If an NRC Section 104(c) license is pursued, it is unclear if the relaxed regulatory scrutiny applied to reactors holding 104(c) licenses would be applied to reactors with power levels higher than about 20 megawatts thermal (MWth).

In either case, it will be essential that a vendor or potential owner/operator have significant stakes in the project.

Interactions in Phase III

The construction and operation of a FOAK plant will require processes for evaluation of a site and for assuring that all the safety requirements have been met. A license to operate will inevitably require regulatory scrutiny similar to that undertaken at the operating licensing stage under either Part 50 or Part 52. There is no escape from the requirement that an operating plant provide adequate protection of the public health and safety and be consistent with the common defense and security.

The staged process has greatest relevance for the licensing of non-LWR advanced nuclear reactors. The Task Force offers these additional comments:

While the NRC can and should find ways to make the overall licensing process speedier and less costly, the Task Force does not believe that significant reductions in either time or cost are likely. Public comment, formal commission proceedings, and judicial review will remain part of the process before a reactor goes into operation. On the other hand, important efficiencies and earlier certainty can be provided in the design-review stage of licensing. Legislation to further a stepwise approach is not necessary if existing mechanisms for early guidance are employed.

It should be understood that assurances provided by NRC staff during the stages of review of an application can be helpful in reducing uncertainty, but these assurances are not necessarily binding. The NRC, the Advisory Committee on Reactor Safeguards, the Atomic Safety and Licensing Board Panel, and, ultimately, the courts have the opportunity to review and reverse staff determinations and are often urged to do so by interveners at the various formal stages of the licensing process. Public confidence is enhanced by the opportunity for the affected public to challenge NRC decisions, and any stepwise process will have to accommodate public involvement in licensing matters. Such involvement can result in uncertainty and delay.

Adjustment of the current arrangements for financing the NRC should be considered. Under current law, the NRC recovers 90% of its budget from fees charged to licensees and applicants. The 10% Federal component is intended to encompass work that does not directly benefit current licensees or applicants, such as the NRC’s international activities and its supervision of Agreement States. The licensing of advanced reactors requires adequate funding for NRC review, and current licensees may understandably object to the usage of funds that they provide to subsidize activities that offer them no benefit. Applicants for advanced reactors confront significant fees for such reviews at a time when their resources are limited. Some Federal cost sharing should be provided on an ongoing basis for work related to advanced reactors, perhaps with an opportunity to recover costs if an advanced design is commercially successful.

It is clear, however, that if licensee fees remain at their current level and there is not an offsetting increase in the NRC budget, the capacity for regulatory review will be limited. Recent legislation would provide DOE with $5 million in Fiscal Year 2017 to assist the NRC in building its capacity to license advanced nuclear reactors, and other legislative proposals on capping fees have been made.[29] In addition, the NRC recently revised its fee structure for SMRs.

Some observers point out that the regulatory approaches of both Canada and the United Kingdom include regulatory processes that formally provide considerably more flexibility in licensing than either Part 50 or Part 52 and are more compatible with investment needs (see Appendix E for details).[30] These approaches present a sensible basis for the NRC's consideration of a stepwise regulation of advanced nuclear reactors using existing regulatory tools. However, important differences will remain, in particular the opportunity for extensive public involvement in licensing matters that is required in the United States.

Certain developers may be tempted to seek licensing of lead reactors in countries that are perceived to have "easier" regulatory systems. To the extent that this choice compromises safety, the risk of an accident will increase. Since a safety or security incident anywhere in any country has implications throughout the world, there is an important international linkage of nuclear power that must be considered, as discussed in the next section.

IX. International Linkages

The potential for nuclear energy expansion in the future has significant international dimensions.

First, public confidence in the safety of nuclear energy could be undermined globally by a nuclear accident in any country, including the risk that a severe accident could have impacts across national boundaries.

Second, nuclear power (along with other U.S. critical infrastructure) must demonstrate that it is secure against terrorist attacks on nuclear facilities and that terrorists cannot exploit nuclear power programs to obtain materials for nuclear explosive or radiological weapons.

Third, there are nonproliferation issues associated with commercial nuclear power. To the extent that nuclear power technology—whether conventional LWR technology or advanced nuclear reactor technology—enables countries to acquire fuel-cycle facilities and fissile material for nuclear weapons, it increases the risk of the spread of weapon-usable material, thus undercutting U.S. strategic interests and undermining international peace and security.

Fourth, the U.S. economy will profit for supplying nuclear systems, subsystems, technology, and services to international markets.

The United States has been a global leader in seeking a safe, secure, and safeguarded international regime for nuclear power since President Eisenhower's 1953 Atoms for Peace initiative. The current nonproliferation regime is based on several international treaties: the Treaty on the Nonproliferation of Nuclear Weapons, the Convention on Nuclear Safety, and the Convention on the Physical Protection of Nuclear Material. The primary international organization for implementing these treaties is the IAEA, which carries out mandatory safeguards under the Treaty on the Nonproliferation of Nuclear Weapons and provides technical assistance to promote nuclear safety and security. In addition to treaties and institutions, the international regime includes a host of multilateral membership associations comprised of like-minded states, such as the Nuclear Suppliers Group, the World Association of Nuclear Operators, the Global Initiative to Combat Nuclear Terrorism, and the International Nuclear Regulators' Association.

Unlike the nuclear safeguards system, the regimes for safety and security are essentially voluntary, based on national self-interest to avoid nuclear accidents or security incidents, but without any mandatory international inspection mechanism to ensure that effective standards for safety and security are being deployed and maintained. International efforts to reduce the vulnerability of nuclear facilities to terrorist or cyber attacks have been less coordinated and should be strengthened.

Under current international conditions, a fundamental strengthening of the current nuclear safety and security regimes—based on national sovereignty—seems unlikely. National regulators and nuclear energy organizations will remain the dominant players, along with private industry in countries with a market economy. Hence, the ability of the

United States to reinforce safety and security in foreign countries depends fundamentally on American example, influence and assistance, rather than enforcement of mandatory international legal requirements. The outlook for international action to strengthen the nuclear infrastructure against cyber or terrorist attacks may be somewhat better because of greater awareness of the threat among the public and their political leaders.

At the moment, the United States has an influential voice on policies relating to safety, security, and safeguards because the U.S. deploys more nuclear reactors than any other country and because much of the reactor fleet elsewhere in the world depends on the technology and analysis capability originated in the United States. Indeed, the NRC is viewed as providing the “gold standard” for regulatory oversight and is a model for most other countries. But, absent a continuing strong domestic nuclear program, the United States will not retain the same capacity to influence others that it enjoys today.

At the same time that new U.S. nuclear construction is stalled and aging reactors are likely to be retired in increasing numbers, most of the planned expansion of LWRs is taking place in China, Korea, Russia, India, Pakistan, and many other countries, including several countries that are new entrants, such as Turkey, Vietnam, and the United Arab Emirates. Although U.S. industry retains a toehold in the international market as a second-level supplier, most exports of LWRs are likely to come from state-backed vendors in Russia, China, France, and South Korea. Under these circumstances, in which U.S. participation in the nuclear enterprise is in decline and the nuclear programs of others are growing, the capacity for the United States to define the rules of the road will diminish.

The Task Force believes that DOE and the NRC should continue aggressive international programs in an effort to assure that U.S. technology and safety processes continue to be a benchmark for others. Further, the United States should make a special effort to interact with countries with ambitious plans for expanded nuclear power and export, such as China and South Korea. In the case of Russia, resumption of full cooperation on nuclear safety and security—as well as R&D on nuclear energy—will require overcoming political obstacles created by the Ukraine conflict. The Task Force joins many other groups calling for greater attention to be paid to the threats of terrorism and cyber attacks to nuclear facilities around the world.

Although much of the Generation IV advanced nuclear reactor power technology was developed in the United States, current Generation IV programs are taking place in foreign countries (e.g., Russia, China, India, South Korea, France, and others). These foreign advanced nuclear reactor programs are larger than those in the United States, and several foreign countries have demonstration and prototype facilities in operation or under construction.

The United States has a limited role in some of these projects, mainly providing technical assistance, such as Idaho National Laboratory providing assistance to France’s ASTRID sodium-cooled fast reactor project, Idaho National Laboratory and Argonne National Laboratory participating in the PRISM-type sodium-cooled fast reactor in South Korea, and Oak Ridge National Laboratory supporting construction of a molten salt reactor in China. U.S. laboratory involvement in these foreign projects will help to maintain human capital and expertise if the U.S. decides to purse a new Generation IV demonstration-scale project in the United States. Because most countries interested in Generation IV technology are already pursuing their own national projects, there may be limited opportunities to attract foreign capital and participation in a new advanced nuclear technology initiative in the United States. Nonetheless, as mentioned earlier, if the United States decides to initiate a program to build demonstration plants for Generation IV technology, it should be open to foreign participation, especially from close allies like the United Kingdom, France, Japan, and South Korea.

Over 40 firms, backed by private capital, are working on advanced nuclear fission and fusion technologies.[29] Some of these firms may decide to locate their efforts in other countries that they perceive may offer access to capital for development as well as easier safety and licensing requirements that are more attractive than what is available in the United States.

TerraPower has signed a memorandum of understanding with the China National Nuclear Corporation to collaborate in building traveling wave reactors for sale internationally. TerraPower is believed to have spent over $300 million so far on the design, mostly at the DOE national laboratories (Idaho National Laboratory, Pacific Northwest National Laboratory, and Argonne National Laboratory) and universities, on a wide range of topics from neutronics to materials to modeling and simulation. TerraPower and the China National Nuclear Corporation are working toward a joint venture that will begin construction of a 600 MWe demonstration plant in 2026 and will move forward to a 1 GWe FOAK plant. The Chinese will license these plants. TerraPower is pursuing an approach to include the NRC in this process, but an arrangement has not yet been worked out. While NRC involvement with foreign licensing authorities in considering a new reactor design improves nuclear safety, a comprehensive NRC review is required before a new design is certified or licensed for operation in the United States.

The future development of Generation IV programs has important national security implications. For decades, the United States has led international efforts to limit the spread of enrichment and reprocessing associated with LWRs because of concerns that these fuel-cycle facilities could be used for military as well as peaceful purposes. Different types of Generation IV technologies raise different proliferation concerns. Some designs are intended to utilize fuel enriched above the 5% level normally used in LWRs, although still below the high level normally required for nuclear weapons. Other designs are intended to operate on fuels based on plutonium extracted from LWRs, which would encourage expansion of reprocessing or pyroprocessing facilities. Still others are intended to minimize proliferation risks. In any event, the implications for nuclear proliferation will be one of the important criteria for U.S. selection of different technology types, and the United States' ability to influence such decisions internationally will inherently depend on U.S. importance as a player in the development of advanced nuclear technology.

X. What Organizational Approach Should Be Advanced to Implement the Nuclear Power Initiative the Task Force Is Considering?

The government has a role in addressing each of these challenges:

- The NRC is responsible for domestic licensing. Both DOE and the NRC address safety and security for international facilities (discussed in the body of the report).
- Both Congress and state regulatory agencies have responsibility for adopting a regulatory market structure that provides access and compensation for nuclear power and other base load electricity generation (discussed in the body of the report).
- The Department of State and DOE have complementary responsibilities for international fuel-cycle issues. DOE and the NRC have joint responsibility for promoting internationally effective safety standards, including inspection and enforcement, and physical and cyber security standards, at nuclear facilities (discussed in the body of the report).

The Task Force has evaluated three options for an organizational approach to plan and manage the key programmatic activity (described in Section VII) of this nuclear initiative. The choice should be based on which organizational approach—as created, not as ideally conceived—would best satisfy key requirements for meeting the specified milestones of schedule, budget, and technical performance of the nuclear power initiative. These requirements include the following:

- **A stable financial plan free from the annual congressional budget cycle for the program presented in this report**. As discussed in this report, private investment should not be expected until technology options have been selected and project risk has been reduced.
- **Authority to deploy a variety of contractual support mechanisms, appropriate to stage of development of the selected reactor projects**. This recommendation is also discussed in this report. For example, in earlier stages the mechanism is likely to be direct performance contracts with appropriate intellectual property and cost sharing obligations. In the later stages, the mechanism could involve partnerships with private sector investors, guaranteed off-take agreements, loan guarantees, etc.
- **Freedom from Federal acquisition regulations so that program development and deployment can proceed under commercial practice**. The Federal Acquisition Regulation imposes many audit, cost accounting, procurement, set-aside, and reporting requirements that add cost and time to innovation efforts and are not present in a commercial environment. The quasi-public corporation would be required to submit annual reports of its activities and an accompanying financial statement to Congress and the executive branch for oversight of its progress.

- **Access to adequate technical and financial expertise required for due diligence before program decisions are made, in particular the DOE national laboratories**.
- **Authority to terminate a project that does not meet milestones or is judged not to have the prospect to achieve economic costs of power**.
- **Freedom to use commercial employment practices in the hiring and removal of project staff**.

The three organizational options are:

- **Choice 1: Laissez-faire policy initiatives are adopted** (rate structure, safety and security, perhaps a CO_2 emission charge) that enable market-driven investment. The following are the arguments for this approach:
  - The amount of private equity capital that has been committed to advanced nuclear projects, said to be $1.4 billion, indicates that private sector has the capacity and willingness to invest if project risk is reduced by government policy.
  - Congress will not approve funding for an organization structure with the six requirements above.
  - The U.S. electricity system is in a period of great change, and the future role of utilities, large base load generating plants (such as nuclear plant owner/operators), and on-grid versus distributed generation is highly uncertain. In short, the future customer for nuclear plants is not known, and depends on the future electricity market structure.
- **Choice 2: DOE plans and manages the initiative**. The following are the arguments for this approach:
  - DOE has access to the technical expertise of its national laboratories.
  - DOE has experience with managing large-scale nuclear energy projects (although its record is decidedly mixed).
  - DOE has established relationships with Congress that will ease the interaction been the project and Congress, which will inevitably occur even in the improbable event Congress grants the above six requirements. However, it will be difficult for DOE to insulate the initiative from annual appropriations and from intervention by other agencies, such as the Office of Management and Budget, EPA, and Department of the Treasury, that will seek to influence the evolution of the project.
- **Choice 3: Establish a quasi-public corporation governed by an independent board of directors** nominated by the President and confirmed by the Senate, with the authority and responsibility for executing the initiative. This or similar mechanisms have been proposed and some have been adopted in the past (e.g., the Communications Satellite Corporation, 1962; the Synthetic Fuels Corporation, 1980; and the Blue Ribbon Commission on America's Nuclear Future, 2012, for nuclear waste management). The following are the arguments for this approach:
  - It is the clearest and most likely way for Congress to grant special operating exceptions supported by tax payer money.

- In practice, a quasi-public corporation will act more like a private sector entity than a government agency unit.
- If established, this option has the greatest chance of running an initiative that demonstrates the risk reduction required for private investment.

Efforts have been made to craft organization structures in between models 2 and 3, such as the Clean Energy Deployment Administration in 2009, but these have not attempted to attach all the flexible conditions such as those reviewed above to such a structure.

Choice 1 needs no affirmative governmental action and runs the greatest risk that nothing will happen (at least for the foreseeable future). Choice 2 places greater trust in DOE and their congressional oversight and appropriations committees to successfully manage an initiative of this scope than most informed observers have. Choice 3 will have congressional opposition from both left and right.

The Task Force believes that choice 3 has the best chance of success. The advanced nuclear reactor quasi-public corporation would have responsibility for all four phases of the development and demonstration program described above.

The Task Force emphasizes the need for focus during Phase I. The quasi-public management organization should select a small number of candidate teams (approximately six) with the required technical skills and management system required to complete all four phases of the initiative. Some of the private sector entities pursuing advanced technologies would be expected to participate in these teams. In Phase I each team needs to develop design, engineering, and material data information to support down selection. During this phase, the limited number of teams would also interact with the NRC, allowing the NRC staff to focus on an appropriate regulatory framework for advanced nuclear reactor concepts. The Phase I R&D should evolve seamlessly into the later phase demonstration, that is, Phases II and III. This is the reason the Task Force recommends that the quasi-public corporation manage Phase I rather than DOE.

The responsibility for establishing a new market structure, adopting a mechanism that properly recognizes the emission costs of carbon, and streamlining the licensing process would remain with the executive branch agencies.

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Appendix A: Task Force Terms of Reference

The Secretary of Energy
Washington, D.C. 20585

December 4, 2015

MEMORANDUM FOR THE CHAIR
SECRETARY OF ENERGY ADVISORY BOARD

FROM: ERNEST J. MONIZ

SUBJECT: Establishing a New Secretary of Energy Advisory Board (SEAB) Task Force on the Future of Nuclear Power

I request that you form a Secretary of Energy Advisory Board (SEAB) Task Force on the Future of Nuclear Power. Nuclear power is an important carbon free power source for the U.S. and the world. Beginning around 2030, a significant number of operating U.S. nuclear reactors will reach 60 years of age and a considerable portion of these are likely to go out of service. Utility planning for carbon free baseload replacement capacity will start years earlier. Accordingly, interest is increasing in exploring the possibility of major new deployment of nuclear power in the time period 2030 – 2050.

To be successful, any nuclear deployment must satisfy the following metrics:

- Safety, including compliance with existing or modified regulatory requirements
- Technical readiness
- Proliferation resistance
- Low cost of generation – through two lenses: private costs and private costs that include the cost of CO_2 emissions avoided
- Effective nuclear waste management

Purpose of the Task Force: The SEAB Task Force on the Future of Nuclear Power will describe the landscape that must be crossed to go from today's situation of reliance largely on light water reactors to a situation in the period 2030 to 2050 where one or many nuclear technologies have reached technical and commercial maturity and are deploying at a rate that has the possibility of carbon free nuclear power generation contributing 20 percent of global electricity generation.

The Task Force should devote attention to:

(1) Regulatory requirements such as design certification, construction and operating licenses.

(2) Historical operating performance such as capacity factors, O&M expenses of U.S and other country reactors.

(3) Evolving end-user requirements for nuclear energy systems, which might move beyond electricity production only to include a broader range of energy products

and services (including, but not limited to, process heat, hydrogen production, and desalination).

(4) The set of candidate reactor technologies that are of sufficient technical maturity and development promise to evolve to a deployed technology, at scale.

(5) Requirements for new development and test facilities that can serve one or more technologies under development with the possibility that several countries will be interested in sharing the cost and use of such facilities.

(6) The sequence of (perhaps overlapping) tasks that need to be completed in order to achieve the goal.

(7) The tasks include at least:

- Reactor design
- Component development, testing, and certification, (fuel pins/assemblies, pumps, valves, control systems)
- Engineering the integrated system
- Subsystem fabrication and manufacturing
- Assembly and test of prototype system and integration with balance of plant
- Procurement, construction, and deployment plans with supporting contracts
- Licensing reviews and safety authorizations

The Task Force's principal charge is to develop an illustrative schedule with a range of estimates, for the time and cost necessary to pass technical milestones for each task. We anticipate that the range is likely to be at least 10 to 15 years to achieve sustained production levels, with an order-of-magnitude development cost of at least $10 billion dollars. This time scale points to the urgency of considering the future of nuclear power now if there is to be an opportunity for different technologies to have a material impact in the 2030-2050 period.

The Task Force is also asked to address four interrelated questions:

(1) How would the substantial development costs be financed? There are three possibilities: the Federal government (using one or more direct or indirect assistance mechanisms), the private sector, or a government-industry partnership.

(2) Are there prospects for sharing these large development costs with other countries such as China, France, India, Japan, Russia, and South Korea that have interest in expanding nuclear electricity generation?

(3) Beyond development cost, there will be substantial cost for one or more "first-of-kind" reactors. While substantial, these early deployment costs will occur after regulatory approvals are received and technology and cost risks are narrowed. Are there possibilities for Federal loan guarantees, early purchase for Federal use, etc., to support a portion of the costs of this early deployment phase?

(4) How would this development/commercialization project be managed? There is much to be said for private sector management that would benefit from practical commercial experience and avoid the cumbersome procurement regulations that

accompany any form of U.S. government assistance (that would need to be sustained over several administrations).

In order to maintain a practical scope for a one-year effort, the Task Force should not address the implications of greatly increased deployment of reactors for the front and back end of the fuel cycle.

The offices within the Under Secretary for Science and Energy will support the Task Force's work, as needed. The membership of the SEAB Task Force should include one or more members of the DOE's Nuclear Energy Advisory Committee (NEAC).

Designated Federal Officer: Karen Gibson, Director, Office of Secretarial Boards and Councils.

Schedule: The Task Force will submit quarterly reports to SEAB of its progress and submit a final report by December 2016.

Appendix B: Members of the Task Force on the Future of Nuclear Power

John Deutch, Institute Professor and former Dean of Science and Provost, Massachusetts Institute of Technology; former Director of Central Intelligence Agency; former Deputy Secretary of Defense; and former Under Secretary of DOE; Task Force Chair*

Michael Greenstone, Milton Friedman Professor of Economics and Director, Energy Policy Institute, University of Chicago; former Chief Economist for President Obama's Council of Economic Advisers; former Director, Hamilton Project at the Brookings Institution*

Shirley Ann Jackson, President, Rensselaer Polytechnic Institute; Member of the President's Council of Advisors on Science and Technology (PCAST); Co-Chair, President's Innovation and Technology Advisory Committee in PCAST; former Chair, United States Nuclear Regulatory Commission*

William Madia, Vice President, Stanford University; former Executive Vice President for Mergers and Acquisitions, Battelle; former Director of Oak Ridge and Pacific Northwest National Laboratories

Richard Meserve, President Emeritus, Carnegie Institution for Science; former Chairman, Nuclear Regulatory Commission*

Dan Reicher, Executive Director, Steyer-Taylor Center for Energy Policy and Finance, Stanford University; former Director of Climate Change and Energy Initiatives, Google; former Assistant Secretary of Energy for Energy Efficiency and Renewable Energy and Chief of Staff, DOE*

Joy L. Rempe, Principal, Rempe and Associates LLC; former Laboratory Fellow, Idaho National Laboratory

Gary Samore, Executive Director for Research, Belfer Center for Science and International Affairs at the Kennedy School of Government, Harvard University; former White House Coordinator for Arms Control and Weapons of Mass Destruction; former Vice President for Studies at the Council on Foreign Relations; former Special Assistant to the President and Senior Director for Nonproliferation and Export controls*

Clay Sell, President, Hunt Energy Horizons; former Deputy Secretary and Chief Operating Officer, Department of Energy; former Special Assistant to President George W. Bush

Phil Sharp, Retired President, Resources for the Future; former U.S. Congressman

Steven Specker, Retired President and Chief Executive Officer, Electric Power Research Institute; retired General Electric

Joe C. Turnage, Retired Senior Vice President, Constellation Energy Nuclear Group; Senior Vice President, Strategy of UniStar Nuclear Energy; former Senior Vice President and Chief

Technology Officer, Pacific Gas & Electric Company's PG&E National Energy Group; former President, Tenera Energy LLC

* Denotes SEAB member

Appendix C: LCOE Model Assumptions

Introduction

We follow the methodology of Greenstone and Looney (2012)[1] (which references Du and Parsons (2009)[2]) to generate levelized costs for each technology. All calculations were performed using the EPIC (Energy Policy Institute of Chicago) LCOE model; please contact Harshil Sahai (harshil@uchicago.edu) for further information.

Table 1: LCOE Parameter Assumptions by Model

Parameter	EIA AEO 2016	Greenstone & Looney (2012)[1]	Current Model
Capacity (MW)	NEMS 2016	EIA 2012	EIA 2016,[3] EIA 2015[4] for coal
Capacity Factor (%)	EIA 2016[5]	EIA 2012	EIA 2016,[5] EIA 2015[6] for coal
Heat Rate (Btu/kWh)	NEMS 2016	EIA 2012, fixed	NEMS 2016‡ overnight
Overnight Cost ($/kW)	NEMS 2016	NEIA 2012, fixed	NEMS 2016‡ fixed O&M
Fixed O&M Costs ($/kW-Yr)	NEMS 2016	EIA 2012	NEMS 2016‡
Variable O&M Costs ($/MWh)	NEMS 2016	EIA 2012	NEMS 2016‡
Transmission Investment ($/kWh)	NEMS 2016	None	EIA 2016[5] imputed for renewables with backups, EIA 2015[6] for coal*
Hydroelectric Seasonal Storage Costs	NEMS 2016	None	None
Waste Fee ($/kWh)†	NEMS 2016	0.001	0.001
Decommissioning Cost ($million)†	NEMS 2016	350/2000 ratio of decommissioning cost to overnight cost[2]	350/2000 ratio of decommissioning cost to overnight cost[2]
Carbon Intensity (kg of CO_2 equivalent/MMBtu)	Assumes coal with CCS has 30% carbon capture	EIA 2012, $21 SCC	National Renewable Energy Laboratory 2015[7] interpolated SCC projections,[8]* assumes coal with CCS has 30% carbon capture (i.e., 30% of conventional coal)
Natural Gas Methane Leakage (%)	None	None	1.1%,[9, 10, 11] interpolated SCM projections[12]*
Non-Carbon Costs	None	NAS 2010[13]	NAS 2010[13]*
Inflation Rate	NEMS 2016	3%	2.1%‡
Fuel Costs	NEMS 2016	EIA SEDS 2012,* EIA 2012	EIA SEDS 2014,[14]† EIA 2016 projections[15, 16]
Tax Rate	NEMS 2016	37%	38% assumed by NEMS 2014[17]
Nominal WACC	7.9 % assumed by EIA 2016,[5] 10.9% for coal and coal with CCS	7.7/10%,‡ 10%	7.9 % assumed by EIA 2016[5]
Plant Life	30 years	40 years	30 years
Online Year	2022	2014	2022
Construction Schedule	NEMS 2016	Follows Du and Parsons (2009)[2]	NEMS 2016‡
Depreciation Schedule	IRS MACRS 2015[18]	IRS MACRS 2012, all 20 year schedules	IRS MACRS 2015,[18] all 20-year schedules

Note: * To 2015$ using gross domestic product implicit price deflator.[19] †Applies to nuclear only, with no projected fuel price changes. ‡Contacted the EIA to receive these (Christopher.Namovicz@eia.gov).
Acronyms: NEMS – National Energy Modeling System; SEDS – State Energy Data System; IRS – Internal Revenue Service; MACRS – Modified Accelerated Cost Recovery System; NAS – National Academy of Sciences; WACC – weighted average cost of capital; O&M – operations and maintenance

Selected Assumptions

1. **Plant Life:** We assume plants have an order date of 2016, then wait for 0 or more years, and then undergo a construction schedule that ends with an online year of 2022, assumed by EIA.[5] At this point, the plant has a financial life of 30 years, also assumed by EIA (2016).[3]

2. **Combined Plants:** In order to ensure a fair comparison across technologies with different capacity factors, we construct a renewable plant (wind, solar photovoltaic, or hydroelectric) with a natural gas combustion turbine backup such that the total plant has an equivalent capacity of 85%.

   - We are given the capacity factors p_r, p_b and capacities C_r, C_b for the renewable and turbine plants, respectively. Then, we operate the turbine so that it produces the following output:

     $$O_b = (0.85 \cdot C_r) - (p_r \cdot C_r).$$

     So, the total capacity factor of the plant (relative to the renewable plant) is:

     $$\frac{O_b + p_r \cdot C_r}{C_r} = 0.85.$$

   - As for costs, we make sure to add the fixed costs of both plants, use individual outputs to compute the variable costs, and use an output-weighted average to compute the carbon and non-carbon costs between the renewable and combustion turbine plants.

3. **Overnight Costs and Heat Rates:**

Table 2: Assumed Overnight Costs and Heat Rates

Technology	Overnight Capital Cost (2015$/kWh)	Heat Rate (Btu/kWh)
Conventional Coal	3,521	8,770
Advanced Coal (with CCS)	4,957	9,486
Conventional Natural Gas	947	6,457
Advanced Natural Gas (with CCS)	2,034	7,507
Nuclear (PWR)	5,574	10,449
Natural Gas Combustion Turbine	644	9,018
Hydroelectric	2,770	–
Solar (Photovoltaic)	1,997	–
Wind (Onshore)	1,819	–

Source: Contacted the EIA to receive these (Christopher.Namovicz@eia.gov).
Acronyms: CCS – carbon capture and storage; PWR – pressurized water reactor; Btu – British thermal unit; kWh – kilowatt-hour.

4. **Transmission Investment:**

   - We assume that plants pay a fixed fee (per MW of capacity) per year in transmission costs. As a result, we may use EIA 2015 and 2016[6, 5] estimates of levelized transmission costs[a, 6] or all technologies except the combined renewable plants with natural gas backup.

- For the combined plants, we back out the fixed fee for each component, and then add both fixed fees and calculate a present value.
  - Specifically, for each individual plant (wind, solar, hydro, natural gas combustion turbine), we find the fixed fee T_F (\$/kW) given the levelized transmission cost T_L (\$/kWh) as

$$T_F = T_L \times c \times 8766$$

  - In this equation, *c* is the capacity factor of the plant in question. We then calculate the present value of the sum of yearly fixed fees (weighted by capacity) for each individual plant.

5. **Carbon Intensity:**
   - Instead of using EIA (2012) reports, we switch to the National Renewable Energy Laboratory's (2015),[7] given its credibility and updated point estimates of life-cycle g-CO_2 equivalent/kWh (grams of CO_2 equivalent per kWh) by technology.

6. **Natural Gas Methane Leakage:** We add, in addition to carbon costs, the social costs of methane leakage from natural gas production.
   - We use EPA (2015)[9] to obtain methane emissions from natural gas systems. We then use a 2013 EPA estimate of gross natural gas withdrawals.[10]
   - We calculate the leakage rate using a simple ratio of emissions to withdrawals (scaled by the density of methane[11]), yielding a leakage rate of 1.1%.
   - We finally convert from leakage to levelized methane costs roughly as follows:

$$\mathrm{CH_4 costs}\left(\frac{\$}{\mathrm{kWh}}\right) = \text{leakage rate}\left(\frac{\mathrm{CH_4}}{\mathrm{gas}}\right) \times \text{heat rate}\left(\frac{\mathrm{gas}}{\mathrm{kWh}}\right) \times \text{social cost of } \mathrm{CH_4}\left(\frac{\$}{\mathrm{CH_4}}\right)$$

7. **Adjustment for Social Cost of Greenhouse Gas Projections:**
   - To account for projections in SCC and SCM over the lifetime of the plant,[8, 12] we define an "effective SCC" based on levelized carbon costs:[b]

$$\begin{aligned} Carbon\ Costs\left(\frac{\$}{kWh}\right) &= \frac{Total\ NPV\ of\ Carbon\ Costs\ (\$)}{Total\ NPV\ of\ Output\ (kWh)} \\ &= \frac{\sum_{t=1}^{30} D_t \cdot \pi_t \cdot CI \cdot HR \cdot O \cdot SCC_t}{\sum_{t=1}^{30} D_t \cdot \pi_t \cdot O} \\ &= \underbrace{\frac{\sum_{t=1}^{30} D_t \cdot \pi_t \cdot SCC_t}{\sum_{t=1}^{30} D_t \cdot \pi_t}}_{\text{Effective SCC}} \times (CI \cdot HR) \end{aligned}$$

[a] Coal and gas with CCS from EIA (2015)[6] as these were not updated in the 2016 report.
[b] An identical approach is used for SCM, replacing CI=Carbon Intensity with LR=Leakage Rate.

Where

- t = Year
- D_t = Discount rate = $\left(\frac{1}{1+7.9\%}\right)^t$
- π_t = Inflation multiplier = $(1 + 2.1\%)^t$
- CI = Carbon Intensity (tCO_2/MMBtu)[7]
- HR = Heat Rate (MMBtu/kWh)
- O = Output (kWh)
- SCC_t = Interpolated Social Cost of Carbon in Year t (\$/tCO_2)[8]

8. Non-Carbon Costs:

- We do not deviate from Greenstone and Looney (2012)[1] for calculating non-carbon costs. These are life-cycle estimates from the National Academy of Sciences (2010)[13] report for coal and natural gas plants. For other plants, we are unable to quantify non-carbon external costs.

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Appendix D: Opportunities for Technical Advances to Reduce Cost and/or Improve Performance

Design

- Reducing primary system pressure could reduce costs of piping and components.
- Increasing primary system temperature could increase thermodynamic efficiency and reduce water resource requirements (increasing siting flexibility).
- Designs with fewer systems and components (e.g., valves, pumps, etc.) could reduce costs and shorten construction times.
- With regulatory approval, passive systems could reduce costs associated with reactor systems and containment structures.
- Higher power density could provide more megawatts electric (MWe) for a given site footprint.
- Incorporation of security into the plant/building design (e.g., underground buildings with minimum access points) could reduce security personnel requirements and lower costs.

Manufacturing

- Modularization of major components could reduce costs of construction.
- Reducing the size of major components could reduce costs of deployment.
- Standardization could reduce costs by capturing learning curve experience and procurement.
- Improving the capability to manufacture required components (e.g., helical steam generators) could reduce investment risk and cost.

Procurement and Construction

- Modular field deployment could reduce construction costs.
- Advanced digital configuration management systems could reduce rework and costs.
- Developing a mature supply chain, including alternative suppliers, could reduce costs through competition.
- Contractually allocating risk appropriately through procurement/construction contracts could align interests between vendors and owners and reduce costs.

Operations and Management

- Designs with maintenance processes that focus less on required staffing will lower costs.
- Increasing fuel cycle lengths and shortening outage durations will lower costs.
- Establishing plant digital data-centric configuration management systems using a three-dimensional model as a user interface will reduce costs and allow greater productivity.
- Automated personnel monitoring and dosimetry will reduce costs and improve personnel safety.
- Establishing a central database of plant component and training/qualification information

could improve efficiency in human resource development and allocation.

Fuel

- Designs with improved fuel utilization (including those with higher burn-up) would lower costs.
- Maximizing the operating-cycle length per cost of fuel could improve economic performance.
- Emphasizing accident tolerance in the selection of fuel, cladding, and structural and control materials to improve safety by precluding melting and combustible gas generation could reduce the number and costs of plant safety systems.

Deployment Efficiency

- Reducing the size of the footprint of a plant would create greater options in deployment.
- Reducing the size of the emergency planning zone would reduce licensee costs for emergency planning drills and increase deployment options.
- Reducing the amount of capital at risk before income generation would increase the likelihood of investment.
- Providing load-following capability would be attractive in some markets.

Licensing Risk

- Technological readiness could reduce licensing risk, as well as investment risk.
- The availability of necessary experimental/test data is essential to reducing licensing risk.
- Creating regulatory familiarity with design features (perhaps in a staged manner) could reduce licensing risk.

Appendix E: Nuclear Regulation

The construction, operation, and decommissioning of nuclear reactors is subject to stringent regulation by the NRC. The burden and delay associated with this regulatory scrutiny have increased the cost of new reactors and inhibited the pursuit of construction, particularly of advanced designs.

Existing Licensing Approaches

All of the existing U.S. reactors, with the exception of the four Westinghouse AP1000 reactors now under construction, were licensed by the NRC under the regulatory scheme defined in 10 C.F.R. Part 50. Under the Part 50 approach, a licensee for a prospective reactor first obtains a construction permit and then, after construction is completed, seeks an operating license. The regulatory procedures associated with a construction permit involve a review of the suitability of the site and an evaluation of the general appropriateness of the reactor technology. A thorough review of the reactor technology is conducted during the evaluation for an operating license application. At both stages of the process, interveners may challenge the staff's proposed approvals; this can result in extensive hearings before the NRC's Atomic Safety and Licensing Board, followed by review in the courts.

The Part 50 process was criticized because of its cost and delay. Of particular concern was the fact that the NRC might impose requirements at the operating license stage that required extensive and expensive retrofits of an already-built reactor. This was the case for reactors that were under construction at the time of the Three Mile Island accident and were subject to extensive additional regulatory requirements. As a result, in the 1990s, Congress laid the ground for a second licensing process that is defined in 10 C.F.R. Part 52. The process was intended to reduce the regulatory uncertainty associated with the Part 50 process.

Under Part 52—the regulatory approach used for four of the reactors currently under construction—the licensing process can involve three separate components. First, a prospective licensee can obtain an early site permit (ESP). An ESP defines the "environmental envelope" for a reactor at a particular site. One can pursue an ESP in advance of selecting the reactor technology or even having a firm's commitment to complete construction. The permit can be "banked" for a period of 20 years. Second, a prospective operator can obtain a combined license (COL) that authorizes both construction and operation, if license conditions are satisfied; it too can be banked. A COL serves to avoid much of the regulatory risk associated with a Part 50 operation license because it is issued before construction starts, although actual operation is conditioned on satisfying certain "Inspections, Tests, Analyses, and Acceptance Criteria" that are specified in the COL. Finally, a vendor of a reactor technology can pursue a design certification from the NRC. After review of the adequacy of the design to achieve safety requirements, the NRC can promulgate a rule certifying the design. This can occur long before there is a commitment to actually construct the design, although the NRC has used customer interest as a consideration in the priority that it gives to the review.

Each of these components allows an applicant to avoid regulatory risk. That is, an operator that has the benefit of an ESP and a design certification can cite these authorizations in its application for a COL. Matters resolved in connection with the ESP or the design certification cannot be reexamined, which limits the scope of the licensing proceeding and the resulting regulatory risk.[a] Moreover, the bounds of the license requirements are defined in the COL. Because the COL is issued before any safety-related construction (absent authorization), the danger of regulatory changes during construction is reduced.[b]

Neither of these processes, at least in their pure forms, is thought to meet the licensing needs of those pursuing advanced technologies. Part 50 presents unacceptable financial risks because the NRC only determines whether a given design can be licensed after construction is complete and an operating license is pursued.[c] At that stage, many billions of dollars have already been invested. Moreover, the Part 50 approach requires the identification of a site, which requires an actual end user, whereas design certification under Part 52 can be achieved without a particular site in mind.

Although the design certification authorized under Part 52 provides early certainty as to the design's adequacy, it requires an essentially complete design to be defined in the application. The cost for a design certification can approach $1 billion because it requires the submission of a complete design for NRC review, along with all the necessary test data. Design certification, thus, also involves a formidable front-loaded investment. Moreover, once a design certification is achieved, changes in the safety features necessitate a new regulatory process to introduce the modifications. Thus, Part 52 may serve to "freeze" the design prematurely.[d]

The Need for a New Approach

The commercial deployment of a new reactor technology can involve a multi-billion dollar investment that is made over many years. As a general matter, investments in advanced technologies are typically made in stages or graduated steps in which increasing levels of investment are made at each stage as risks are retired. Some of the risks associated with the pursuit of an advanced reactor technology are technical, e.g., an idea for a new approach may not pan out upon further detailed scrutiny. Another risk arises from the market: namely, that the new design may prove unattractive to potential purchasers. Yet another risk is a regulatory risk—the risk that the NRC under the existing regulatory processes may find a new technical approach to be unacceptable. This latter risk is claimed to be particularly inimical to investment in a novel technology because the regulatory risk may be difficult for an applicant to assess.

[a] An applicant for a combined license need not have the benefit of an early site permit or a design certification. That is, the applicant can pursue a combined license in a proceeding in which issues relating to the adequacy of the site and of the design are resolved. In such a case, the applicant still has the benefit of regulatory certainty before construction has started.

[b] All licensees face some risk of regulatory change. The NRC can require retrofits at any reactor if the change is necessary to provide adequate protection of public health and safety or to assure common defense and security. Requirements that resulted from lessons learned following the Fukushima accident were imposed on licensees in order to assure adequate protection of public health and safety. In addition, the NRC may require retrofits based on a weighing of comparative benefits and costs. 10 C.F.R. 50.109.

[c] Some of the risk can be resolved earlier through topical reports on various subjects with bearing on licensing. These serve to allow the early identification and resolution of issues by the staff, but do not provide finality. Matters can be reopened by the NRC itself, the Advisory Committee on Reactor Safeguards, the Atomic Safety and Licensing Board, or the courts in review of the NRC's decision.

[d] Some of those pursuing advanced designs have indicated that they will license the first reactor or reactors using Part 50 and then pursue design certification under Part 52 once the design has stabilized.

As a result, there are proposals for the implementation of a staged regulatory process in which regulatory issues are resolved in a step-wise fashion that is compatible with a staged series of investments.[e, f] Under this proposed licensing scheme, regulatory issues would be resolved in stages that accommodate the ever-growing tranches of investment as risk is reduced.

While the NRC has indicated that further experience in the licensing of non-LWR designs may reveal the need for a new regulatory framework, flexibility within the existing regulatory framework, supplemented by additional guidance, may be able to provide early regulatory feedback.[g] The staff welcomes and, in fact, encourages pre-application meetings with applicants so that there is a common understanding of the regulatory process. The staff can issue pre-application safety evaluation reports and guidance documents and can review topical reports, technical reports, regulatory exemption approaches, and so forth as way to address technical issues, and thereby reduce the risk, long before an application is formally resolved.[h] In this way, the staff can effectively implement a staged process.[i] In fact, the usage of a standard design approval under 10 C.F.R. Part 52, Subpart E, explicitly allows staged submission of major portions of a design for approval.

In order for the step-wise process to be truly effective, the process should be guided by a licensing project plan that is worked out at the outset between the applicant and the NRC that defines project schedules, testing requirements, deliverables, and NRC review budgets. In short, the process should involve the establishment of guidelines that would define the working relationship among the parties and would accommodate an applicant's legitimate need for early resolution of certain issues as a means to determine whether further investment is warranted.

Both Canada and the United Kingdom (U.K.) have regulatory processes that as a formal matter provide considerably more flexibility in licensing than either Part 50 or Part 52, and they are cited as models that are more compatible with investment needs.[j] Both the Canadian

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[e] See, for example, Ashley E. Finan, *Nuclear Innovation: Strategies for Advanced Reactor Licensing* (Cambridge, MA: Nuclear Innovation Alliance, 2016), http://www.nuclearinnovationalliance.org/#!advanced-reactor-licensing/xqkhn; Jeffrey Merrifield, U*.S. Nuclear Infrastructure Council Task Force: Issue Brief on the Framework for Advanced Reactor Licensing Modernization* (Washington, DC: Nuclear Infrastructure Council, 2016), http://media.wix.com/ugd/760734_804492aec73c4284b0577281d5b3a5a7.pdf.

[f] Bills are pending in both the House (H.R. 4979) and the Senate (S. 2795) that would require the NRC to develop a step-wise licensing approach.

[g] See, Nuclear Regulatory Commission (NRC), *NRC Vision and Strategy for Safely Achieving Effective and Efficient Non-LWR Mission Readiness* (NRC, draft), ML16139A12, http://www.nrc.gov/docs/ML1613/ML16139A812.pdf.

[h] It should be noted that these tools serve to allow the early identification and resolution of issues by the staff, but do not provide finality. Matters can be reopened by the Commission itself, the Advisory Committee on Reactor Safeguards, the Atomic Safety and Licensing Board, or the courts in review of an NRC decision. However, the introduction of a procedure to provide finality would almost inevitably introduce delay.

[i] A DOE-NRC team has concluded that the application of existing licensing requirements could provide an effective and efficient means for licensing that would protect NRC and applicant resources. See, Department of Energy Office of Nuclear Energy, *Next Generation Nuclear Plant Licensing Strategy: A Report to Congress* (Washington, DC: Department of Energy Office of Nuclear Energy, 2008), http://www.energy.gov/sites/prod/files/4.4_NGNP_ReporttoCongress_2010.pdf*;* D. Petti et al., *Advanced Demonstration and Test Reactor Options Study* (Idaho Falls, ID: Idaho National Laboratory, 2016), INL/EXT-16-37867, https://art.inl.gov/INL%20ART%20TDO%20Documents/Advanced%20Demonstration%20and%20Test%20%20Reactor%20Options%20Study/ADTR_Options_Study_Rev2.pdf.

[j] See, Ashley E. Finan, *Nuclear Innovation: Strategies for Advanced Reactor Licensing* (Cambridge, MA: Nuclear Innovation Alliance, 2016), http://www.nuclearinnovationalliance.org/#!advanced-reactor-licensing/xqkhnFinan.

Nuclear Safety Commission (CNSC) and the U.K. Office of Nuclear Regulation (ONR) provide feedback to an applicant about a design at an early stage. Canada provides a pre-licensing vendor design review that starts at a stage where the conceptual design is complete and serves to apprise a vendor of the overall acceptability of a reactor design. The vendor design review process involves three phases: (1) an evaluation of compliance with regulatory requirements once the conceptual design is complete; (2) a pre-licensing assessment based on the design's preliminary engineering program; and (3) a pre-construction follow-up based on detailed engineering. Each phase has a specific and defined budget and ends with a CNSC statement as to the barriers to licensing that have been resolved.

Similarly, the ONR can provide confirmation of a design's acceptance based on a generic design assessment. The process does not supplant a site-specific licensing process, but it does provide a vendor with confidence as to whether a new design will meet regulatory requirements. As with the Canadian process, the generic design assessment proceeds in a step-wise fashion with the issuance of a report at the end of each step. The update identifies any concerns or technical issues, thereby identifying key issues early in the process. If ONR is satisfied at the end of the process, it can issue a design's acceptance confirmation. As part of this process, the ONR is authorized to enter into a limitation of liability agreement with a reactor vendor setting a ceiling on the costs that ONR can charge the applicant.

CNSC's and ONR's approaches present a sensible foundation for the development of a step-wise scheme. However, there would have to be adjustments made to accommodate the differing legal environments, with special consideration of the opportunities now required in the United States for extensive public involvement in licensing matters. Although the current NRC requirements can and should be adapted to provide flexibility like those found in Canada or the United Kingdom, actual experience may reveal the need for legislative or regulatory adjustments.[k] Any new step-wise licensing approach that is adopted should preserve the existing Part 50 and Part 52 processes in order to provide an applicant with various licensing options.

Other Initiatives

In addition to the pursuit of a step-wise licensing process, other changes would facilitate advanced reactor licensing:

- As noted above, the NRC should seek to provide clear and early guidance as to regulatory requirements for advanced reactors. The NRC's current requirements and experience are focused on LWR technology. Those vendors who seek to pursue non-LWR technology require guidance as to the requirements that will be applied to them. DOE has worked with NRC to assist in the development of such guidance,[l] but much remains to be done to develop approaches that are risk-informed and performance-

[k] The existing regulatory framework was developed with a focus on LWRs and includes specific technical requirements to address those designs. Non-LWRs may include the use of fuels, coolants, safety elements, and design features that vary significantly from LWRs and, as a result, may present very different types of risks. Experience may demonstrate that a revised regulatory framework will better accommodate the risks and technological differences associated with non-LWRs.

[l] See, Idaho National Laboratory, Guidance for Developing Principal Design Criteria for Advanced (Non-Light Water) Reactors (Idaho Falls, ID: Idaho National Laboratory, 2014), INL/EXT-14-31179, http://www.nrc.gov/docs/ML1435/ML14353A246.pdf.

based. The NRC recently sought public comments concerning draft design criteria for advanced reactors and should continue this effort.[m] Public meetings, including vendor-specific workshops, should guide the development of such criteria. Moreover, the NRC should develop an internal technical capability to process applications for non-LWR designs.

- DOE should continue to expand its programs pursuing R&D on advanced reactor designs, to assist in the licensing of advanced designs, and to develop codes and data to facilitate the analysis of those designs. In addition, DOE has launched a promising program, the Gateway to Accelerated Innovation in Nuclear (GAIN), to provide the nuclear community with a single point of access to the capabilities—people, facilities, materials, and data—from across the DOE complex and its national laboratories. GAIN is intended to integrate and facilitate efforts by private industry, universities, and government research institutions to test, develop, and demonstrate advanced nuclear technologies—thereby accelerating the licensing and commercialization of these systems.[n]
- Adjustment of current arrangements for fee recovery should be pursued. Under current law, the NRC must recover 90% of its budget from fees charged to licensees and applicants. The 10% Federal component is intended to encompass NRC work that does not directly benefit current licensees and applicants, such as the NRC's international activities and its monitoring of Agreement States. Current licensees understandably do not seek to pay for activities that do not benefit them, and an expansion of work related to advanced technologies may not be of interest. The fees present a particular challenge for applicants with advanced approaches because they may confront substantial fees at a time when their resources must be carefully husbanded.[o] In recognition of this reality, the NRC's Fiscal Year 2017 budget request includes $5 million in non-fee-recoverable activities to develop a strategy of non-LWR licensing. Some cost sharing should be provided on an ongoing basis, perhaps with the level of cost-sharing determined by the stage of the licensing process.
- Some advanced light water designs, particularly those for SMRs, may justify modification of requirements for emergency planning zones, for security requirements, insurance, control room staffing, and perhaps other matters.[p] The NRC should provide early generic resolution of these and related policy issues in order to facilitate the review of applications that promise to be filed in the near future. The NRC recently approved a staff plan for a rulemaking pertaining to emergency preparedness for SMRs.[q]

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[m] See "Solicitation of Public Comments for the Advanced Non-Light Water Reactor Design Criteria," U.S. Nuclear Regulatory Commission, last modified April 8, 2016, http://www.nrc.gov/reactors/advanced/non-lwr-activities/adv-non-lwr-rx-dc.html. The solicitation describes the NRC-DOE effort and cites various NRC documents providing guidance relating to the evaluation of various specific types of advanced reactors.

[n] A DOE web page describes the scope of the program: https://gain.inl.gov/SitePages/Home.aspx.

[o] The AP1000 reactors that are now under construction benefitted from cost sharing of licensing costs with the Federal Government.

[p] Nuclear Regulatory Commission (NRC), "Potential Policy, Licensing and Key Technical Issues for Small Modular Nuclear Reactor Designs," NRC, March 28, 2010, SECY-10-0034, http://www.nrc.gov/docs/ML0932/ML093290268.pdf.

[q] Nuclear Regulatory Commission (NRC), "Staff Requirements Memorandum: Rulemaking Plan on Emergency Preparedness for Small Modular Reactors and Other New Technologies," NRC, June 22, 2016, http://www.nrc.gov/docs/ML1617/ML16174A166.pdf.