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**EPIC** Energy Policy  
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at Chicago

## **Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S.<sup>1,2</sup>**

Robert Rosner and Stephen Goldberg

Energy Policy Institute at Chicago  
The Harris School of Public Policy Studies

Contributor:

Joseph S. Hezir, Principal, EOP Foundation, Inc.

Technical Paper, Revision 1

November, 2011

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<sup>1</sup> The research described in this paper was funded by the U.S. DOE through Argonne National Laboratory, which is operated by UChicago Argonne, LLC under contract No. DE-AC02-06CH1357. This report was prepared as an account of work sponsored by the United States Department of Energy. Neither the United States Government nor any agency thereof, nor the University of Chicago, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or the institutional opinions of the University of Chicago.

<sup>2</sup> This paper is a major update of [an earlier paper](#), July 2011.

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# CONTENTS

KEY DEFINITIONS .....	iv
ABSTRACT.....	1
1.0 INTRODUCTION.....	1
2.0 SAFETY CASE FOR SMRs.....	5
3.0 SMR OPPORTUNITIES AND CHALLENGES .....	7
4.0 ECONOMIC ANALYSIS.....	9
4.1 Overnight Cost Estimates for GW-Scale Reactors.....	9
4.2 Weighted Average Cost of Capital and Risk Premium Analysis.....	10
5.0 MODELING THE SMR ECONOMY .....	15
5.1 Learning Process .....	17
5.1.1 LEAD SMR Plants.....	17
5.1.2 FOAK Plants and the Learning Fleet.....	18
5.2 SMR Manufacturing Throughput.....	22
6.0 GOVERNMENT INCENTIVE PROGRAMS AND OTHER MARKET INCENTIVES.....	23
6.1 Capital Cost and Production Cost Incentives.....	25
6.2 Government Sponsorship of Market Transformation Incentives .....	28
6.2.1 Purchase Power Agreements with Federal Agency Facilities.....	28
6.2.2 Export Sales of FOAK SMR Plants .....	30
6.2.3 Opportunities to Mitigate Early Retirements of Coal Fired Generation .....	31
7.0 SMR STRATEGIC BUSINESS PLAN .....	33
8.0 CONCLUSIONS CONCERNING LICENSING, ECONOMICS, AND BUSINESS CASE.....	37
8.1 Licensing, Design, and Engineering.....	37
8.2 Economics .....	38
8.3 Market Transformation Issues.....	41
9.0 FINAL THOUGHTS AND FUTURE WORK.....	43

## CONTENTS (CONT.)

APPENDIX A: ALTERNATIVE SMR TECHNOLOGIES.....	45
APPENDIX B: LICENSING AND DESIGN ISSUES.....	47
APPENDIX C: ECONOMIC ISSUES.....	55
APPENDIX D: FINANCIAL INCENTIVE AND MARKET TRANSFORMATION OPTIONS.....	63
APPENDIX E: MANAGEMENT MODELS FOR SMR DEPLOYMENT.....	67
APPENDIX F: RELATIONSHIP OF FINANCIAL RISK TO PROJECT SIZE .....	71

## FIGURES

1 Comparison of Size of Investment with Average Annual Revenues of Investor-Owned Nuclear Utilities.....	11
2 Levelized Costs of Learning Plants.....	20
3 Levelized Costs of LEAD and Learning Plants .....	21
4 Cost Differential between SMR Plants/Modules and Gas-Fired Plants.....	23
5 Distribution of Coal Power Plants by Generation Size and Age.....	31
6 Five-Stage Business Model Identifying Investors and Relative Contributions .....	36
C.1 Learning-by-Doing Experience in Navy Shipbuilding .....	56
C.2 Composition of All-in Capital Costs for a Large LWR .....	57
F.1 Firm's Investment in Nuclear Reactor Project for SMRs and GW-LWRs .....	72

## TABLES

1	Moody's Rating Methodology for Electric Utilities .....	13
2	Calculation of Levelized Cost of Electricity for SMRs .....	19
3	Breakdown of Direct Costs .....	20
4	Comparison of Estimated Unsubsidized LCOE for Clean Electricity Technologies.....	29
A.1	Types of Small and Modular Reactor Technologies .....	45
A.2	Design Characteristics of Two Alternative LWR SMRs .....	46
B.1	Summary Comparison of SMR Licensing Issues.....	49
C.1	Relationship of Development Cost to Company Size.....	61
E.1	Alternative SMR Management Models.....	68
E.2	Risk Allocation Issues for Deployment.....	69

## KEY DEFINITIONS

**All-in capital costs:** This term refers to the total plant capital requirements and is sometimes referred to as “total capital costs (TOC).” This estimate expands the estimate of overnight costs to include interest during construction (IDC) costs and escalation costs. For utilities subject to state rate regulation, IDC costs are reported as the allowance for funds used during construction. These funds are accumulated as a capital cost item and included in the rate base for cost recovery purposes after the plant goes into service and has been declared “used and useful.” All-in capital cost estimates are expressed in current year dollars and are significantly higher than overnight cost estimates because of the inclusion of escalation and IDC costs. Thus, all-in costs are project and time dependent, and may not be readily comparable because of differences in assumptions on construction schedules and commercial operation dates.

**Detailed design and engineering (DD&E) costs for SMRs:** This generally consists of the cost of the detailed engineering of the equipment and plant facilities needed to bring the design to completion in order to support construction. It generally is assumed that the detailed engineering needs to be completed only once and can then be used to support the manufacturing of equipment for all subsequent plants. These costs include completion of detailed design; the preparation of construction drawings; the specification of system components; procurement engineering, including the preparation of bid packages for suppliers; a general site layout (that would then be adapted to individual plants); and all nonrecurring design and engineering work at the manufacturing site. DD&E is essential to developing fixed/firm cost estimates and supporting follow-on manufacturing and construction activities for SMRs.

**Engineering, procurement and construction (EPC) costs:** These include direct costs for the NSSS, the turbine generator, and the BOP, as well as indirect costs such as engineering and construction services. EPC costs also include an allowance for contingencies and an allowance for escalation. EPC costs include FOAKE costs. A typical EPC contract may include an amount for escalation set relative to an index rather than a fixed amount. The EPC contract also may contain provisions for risk sharing if costs escalate at a rate that is higher than the agreed-upon escalation index. This report generally reports EPC costs with contingency but without escalation, consistent with the definition of overnight costs, as described below.

**First-of-a-kind engineering (FOAKE) costs:** These costs are associated with the upfront design and engineering design work required to obtain design certification and a combined construction and operation license from the Nuclear Regulatory Commission.

**Gigawatt-scale light water reactor (GW-LWR):** The 1000-MWe light water reactors that are commercially available.

**Learning plants and modules:** The initial set of learning plants and modules in the SMR commercialization effort. The purpose of building a first of a “first-of-a-kind” (FOAK) plant (LEAD) is to show that the design is commercially viable and to facilitate the optimization of the construction of a manufacturing plant dedicated to SMR production. The dedicated manufacturing plant is likely to be built before the completion or near the completion of the

LEAD plant. The FOAK plants provide the basis for optimizing the supply chain. The dedicated manufacturing plant would be amortized over the FOAK plants. Therefore, the LEAD plant is likely to cost substantially more than the FOAK plants.

**Levelized cost of electricity:** This cost includes the overnight cost and total financing costs, as well as the costs of operation, fuel, and maintenance and is expressed in dollars per MWh and cents per kWh.

**Nth-of-a-kind (NOAK) plants:** The estimated costs for these plants do not include major design costs and assume that “lessons learned” have been incorporated in this build generation; thus, that the learning curve has been surmounted.

**Nuclear fleet of SMRs:** A full array of plants and modules, including LEAD, FOAK and NOAK.

**Owner’s costs:** This category includes owner’s agent/engineer costs; licensing and project development costs, project management and oversight; owner’s contingency; administration building and security; site facility transportation upgrades and site improvements; interconnect and switchyard upgrades; spare parts; the initial nuclear fuel core; banking and legal fees’ state permitting; property tax; and sales tax and working capital. Owner’s costs also include site-specific development costs, such as transmission costs, which can vary widely from site to site. Also, owner’s costs can vary in the degree that development costs are capitalized (in which case they are included in owner’s cost) or expensed (in which case they are excluded). Consequently, there can be a significant variation in owner’s cost estimates.

**Overnight costs:** Overnight capital costs include the EPC cost (including contingency) and the owner’s costs, exclusive of escalation and interest. The overnight cost refers to the cost of the plant if it could be constructed overnight. This definition excludes any time-dependent costs such as escalation and interest during construction. In essence, it assumes that the commercial operation date occurs in the year the estimate.

**Risk premium:** This measures the extra financing costs that debt holders and equity holders are expected to be paid for a particular investment.

**Small modular reactor (SMR):** Advanced reactors that are built in modular arrangements at the factory are less than 600 MWe,<sup>3</sup> and shipped to the location of use by truck, rail, or barge.

**Weighted average cost of capital (WACC):** The rate (in percent) that a company is expected to pay on average to all its security holders to finance its assets. It represents the minimum return that a company must earn on an existing asset base to satisfy its creditors, owners, and other providers of capital.

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<sup>3</sup> It should be noted that for the purpose of this analysis, the SMR definition was expanded to encompass plants of 600 MW capacity (note that small reactors are defined by the [International Atomic Energy Agency](http://www.iaea.org/NewsCenter/Press/2011/01/011011.html) as those with an electricity output of less than 300 MW (see <http://www.amacad.org/publications/nuclearReactors.aspx>).

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# **SMALL MODULAR REACTORS – KEY TO FUTURE NUCLEAR POWER GENERATION IN THE U.S.**

Robert Rosner, Stephen Goldberg, and Joseph Hezir

## **ABSTRACT**

The study team has been conducting an extensive analysis of the economics of both gigawatt (GW)-scale reactors and small modular reactors (SMRs). This technical paper provides results to date regarding the SMRs. Topics covered include the safety case; economics; the business case and a business plan; government incentives; licensing, design, and engineering; and future research. Capital cost estimates cover a range of categories, including the plant capital costs for the nuclear steam supply system, turbine building, and balance of plant; costs for engineering and construction services; owner's costs and contingencies; and escalation and financing costs. Ongoing research is focusing on the learning process for SMRs. The study team is also releasing a companion paper on a review of overnight cost estimates for GW-level reactors.

## **1.0 INTRODUCTION**

Two of the authors (Rosner and Goldberg) have written extensively on the subject of the prospects of nuclear energy in the United States and internationally. As the technical and regulatory experts in the United States and across the world are still assessing the aftermath of the extraordinary events at the Fukushima Dai-ichi nuclear power plants, it is increasingly clear that the analysis and conclusions in our research will require updates based on the lessons learned from these events.

Nuclear power occupies a unique position in the debate over global climate change as the only carbon-free energy source that (1) is already contributing to world energy supplies on a large scale, (2) has potential to be expanded if the challenges of safety, nonproliferation, waste management, and economic competitiveness are addressed, and (3) is technologically fully mature. We concluded that any alternative nuclear development pathway (such as additional flexibility in technology approaches and deployment strategies) would need to be evolutionary, rather than a disruptive, radical shift. The urgency of scale-up is such that only technologies that have either already been tested in the marketplace or at least are close to commercial demonstration should be eligible for consideration. We further concluded that (1) small modular light-water reactor (SMR) designs offer such opportunities for scale-up and, therefore, could move us faster to clean energy supplies, but (2) because of the high capital intensity of nuclear energy projects, the cost of nuclear electricity is particularly sensitive to the availability of

financing at competitive rates. In the report *Nuclear Reactors: Generation to Generation*,<sup>4</sup> we described the evolution of nuclear reactor designs from Generation I technology to Generation IV designs, and concluded that the determining factor in establishing the future nuclear marketplace will likely be based on “who wants to invest and where.” We discussed the significant nuclear activity in China and, given the degree that manufacturing and design work has gone off-shore for the current generation of reactors, the United States has an opportunity to be the leader in the design and deployment of SMRs. And we opined that SMRs are the logical choice for smaller countries or countries with limited electrical grid capacity and the attendant safety, security, and nonproliferation benefits, stating that a detailed economic analysis would be done shortly that will address the relative competitiveness of SMRs.

In 2010, the U.S. Department of Energy (U.S. DOE), Office of Nuclear Energy, requested Argonne National Laboratory (ANL) to update *The Economic Future of Nuclear Power* (August 2004). In addition to the follow-on examination of large light water reactor plants, DOE also requested that ANL begin to examine the economics of SMRs. This white paper reports on the progress we have made on the SMR portion of this study. Our partners on the updated study include Dr. Geoffrey Rothwell, Senior Lecturer at Stanford University, and Joseph S. Hezir, the EOP Foundation. This part of the study focuses on key economic parameters and policy options for 50-300 megawatt-level (MW-level) SMRs, and includes a business plan for deploying SMRs by 2020. The study team has used currently best achievable cost estimates for factory-produced modular reactors and compared the results to investment parameters used in building larger reactors; the study team used alternative learning curves for a theoretical configuration of modular reactors for later plants. The original version of this paper (July 2011)<sup>5</sup> discussed the importance of addressing key sensitivities. There is still additional research to be done on specific learning rates at individual cost centers, including consideration of two key modeling sensitivities: (1) the effect of individual and collective uncertainty on relative competitiveness and (2) verification and validation of the economic parameters, particularly the building blocks of the cost center assumptions for SMRs. The detailed report covering these issues is currently being updated, but the preliminary work was reported at the Harris School of Public Policy Studies in February 2011.<sup>6</sup> *We are continuing to perform a more detailed analysis of uncertainty and are validating some of our preliminary results with more detailed modeling tools. This additional work will incorporate operations research modeling tools that can simulate factory-based construction practices.*<sup>7</sup>

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<sup>4</sup> Stephen M. Goldberg and Robert Rosner, *Nuclear Reactors: Generation to Generation*, American Academy of Arts and Sciences, [www.amacad.org/publications/nuclearreactors.aspx](http://www.amacad.org/publications/nuclearreactors.aspx), 2011.

<sup>5</sup> See <http://harrisschool.uchicago.edu/centers/hepi/SMR%20Final%20White%20Paper%207-11.pdf>.

<sup>6</sup> See <http://harrisschool.uchicago.edu/centers/hepi/workshops.asp>.

<sup>7</sup> Prefabrication, preassembly, modularization, and off-site fabrication involve the fabrication or assembly of systems and components at off-site locations and manufacturing plants. Once completed, the systems or components are shipped to a construction job site for installation at the appropriate time. These techniques offer the promise of lower project costs, shorter schedules, improved quality, and more efficient use of labor and materials. Various obstacles stand in the way of the widespread use of such technologies, including updated codes and standards (including adoption by the U.S. Nuclear Regulatory Commission) that impede innovative practices ([http://modular.org/marketing/documents/NRC\\_USConstructionIndustry\\_Report.pdf](http://modular.org/marketing/documents/NRC_USConstructionIndustry_Report.pdf)).

Clearly, today, because of an unanticipated abundance of natural gas in the United States, nuclear energy, in general, is facing tough competition. Natural gas prices are at historic lows. However, natural gas is a commodity that has shown significant price volatility and is likely to exhibit similar patterns in the future. The study team designed a business case for SMRs that is sensitive to various natural gas futures; as such, the study team has designed a serial approach, the most crucial stage being the initial detailed design and engineering phase, with the goal of limiting the U.S. government's financial exposure. The study team anticipates that non-governmental entities, including but not limited to manufacturers, vendors, utilities, and financial institutions, would shoulder a significant portion of the overall financial risk.

Planning and design work on SMR technologies is at a relatively early stage; thus, any cost estimates should be regarded as early stage estimates. It is premature to "lock in" those financial institutions that are responsible for performing due diligence reviews on specific projects until more detailed estimates are available.

Many people have made generous and valuable contributions to this study. Professor Geoff Rothwell, Stanford University, provided the study team with the core and supplemental analyses and very timely and pragmatic advice. Dr. J'Tia Taylor, Argonne National Laboratory, supported Dr. Rothwell in these analyses. Deserving special mention is Allen Sanderson of the Economics Department at the University of Chicago, who provided insightful comments and suggested improvements to the study. Constructive suggestions have been received from Dr. Pete Lyons, DOE Assistant Secretary of Nuclear Energy; Dr. Pete Miller, former DOE Assistant Secretary of Nuclear Energy; John Kelly, DOE Deputy Assistant Secretary for Nuclear Reactor Technologies; Matt Crozat, DOE Special Assistant to the Assistant Secretary for Nuclear Energy; Vic Reis, DOE Senior Advisor to the Under Secretary for Science; and Craig Welling, DOE Deputy Office Director, Advanced Reactor Concepts Office, as well as Tim Beville and the staff of DOE's Advanced Reactor Concepts Office. The study team also would like to acknowledge the comments and useful suggestions the study team received during the peer review process from the nuclear industry, the utility sector, and the financial sector. Reviewers included the following: Rich Singer, VP Fuels, Emissions, and Transportation, MidAmerican Energy Co.; Jeff Kaman, Energy Manager, John Deere; Dorothy R. Davidson, VP Strategic Programs, AREVA; T. J. Kim, Director—Regulatory Affairs & Licensing, Generation mPower, Babcock & Wilcox; Amir Shahkarami, Senior Vice President, Generation, Exelon Corp.; Michael G. Anness, Small Modular Reactor Product Manager, Research & Technology, Westinghouse Electric Co.; Matthew H. Kelley and Clark Mykoff, Decision Analysis, Research & Technology, Westinghouse Electric Co.; George A. Davis, Manager, New Plant Government Programs, Westinghouse Electric Co.; Christofer Mowry, President, Babcock & Wilcox Nuclear Energy, Inc.; Ellen Lapson, Managing Director, Fitch Ratings; Stephen A. Byrne, Executive Vice President, Generation & Transmission Chief Operating Officer, South Carolina Electric & Gas Company; Paul Longsworth, Vice President, New Ventures, Fluor; Ted Feigenbaum, Project Director, Bechtel Corp.; Kennette Benedict, Executive Director, *Bulletin of the Atomic Scientist*; Bruce Landrey, CMO, NuScale; Dick Sandvik, NuScale; and Andrea Sterdis, Senior Manager of Strategic Nuclear Expansion, Tennessee Valley Authority. The authors especially would like to acknowledge the discerning comments from Marilyn Kray, Vice-President at Exelon, throughout the course of the study.

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## 2.0 SAFETY CASE FOR SMRs

While the focus in this paper is on the business case for SMRs, the safety case also is an important element of the case for SMRs. Although SMRs (the designs addressed in this paper) use the same fuel type and the same light water cooling as gigawatt (GW)-scale light water reactors (LWRs), there are significant enhancements in the reactor design that contribute to the upgraded safety case. Appendix A provides a brief overview of the various technology options for SMRs, including the light water SMR designs that are the focus of the present analysis.

Light water SMR designs proposed to date incorporate passive safety features that utilize gravity-driven or natural convection systems – rather than engineered, pump-driven systems – to supply backup cooling in unusual circumstances. These passive systems should also minimize the need for prompt operator actions in any upset condition. The designs rely on natural circulation for both normal operations and accident conditions, requiring no primary system pumps. In addition, these SMR designs utilize integral designs, meaning all major primary components are located in a single, high-strength pressure vessel. That feature is expected to result in a much lower susceptibility to certain potential events, such as a loss of coolant accident, because there is no large external primary piping. In addition, light water SMRs would have a much lower level of decay heat than large plants and, therefore, would require less cooling after reactor shutdown. *Specifically, in a post-Fukushima lessons-learned environment, the study team believes that the current SMR designs have three inherent advantages over the current class of large operating reactors, namely:*

- 1. These designs mitigate and, potentially, eliminate the need for back-up or emergency electrical generators, relying exclusively on robust battery power to maintain minimal safety operations.*
- 2. They improve seismic capability with the containment and reactor vessels in a pool of water underground; this dampens the effects of any earth movement and greatly enhances the ability of the system to withstand earthquakes.*
- 3. They provide large and robust underground pool storage for the spent fuel, drastically reducing the potential of uncovering of these pools.*

These and other attributes of SMR designs present a strong safety case. Differences in the design of SMRs will lead to different approaches for how the Nuclear Regulatory Commission (NRC) requirements will be satisfied. Ongoing efforts by the SMR community, the larger nuclear community, and the NRC staff have identified licensing issues unique to SMR designs and are working collaboratively to develop alternative approaches for reconciling these issues within the established NRC regulatory process. These efforts are summarized in Appendix B; a detailed examination of these issues is beyond the scope of this paper.

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### 3.0 SMR OPPORTUNITIES AND CHALLENGES

There are many opportunities and challenges for United States industry and government to be leaders in SMR technology.

#### *Opportunities*

As stated earlier, SMRs have the potential to achieve significant greenhouse gas emission reductions. They could provide alternative baseload power generation to facilitate the retirement of older, smaller, and less efficient coal generation plants that would, otherwise, not be good candidates for retrofitting carbon capture and storage technology. They could be deployed in regions of the U.S. and the world that have less potential for other forms of carbon-free electricity, such as solar or wind energy. There may be technical or market constraints, such as projected electricity demand growth and transmission capacity, which would support SMR deployment but not GW-scale LWRs. From the on-shore manufacturing perspective, a key point is that the manufacturing base needed for SMRs can be developed domestically. Thus, while the large commercial LWR industry is seeking to transplant portions of its supply chain from current foreign sources to the U.S., the SMR industry offers the potential to establish a large domestic manufacturing base building upon already existing U.S. manufacturing infrastructure and capability, including the Naval shipbuilding and underutilized domestic nuclear component and equipment plants. The study team learned that a number of sustainable domestic jobs could be created – that is, the full panoply of design, manufacturing, supplier, and construction activities – if the U.S. can establish itself as a credible and substantial designer and manufacturer of SMRs. While many SMR technologies are being studied around the world, a strong U.S. commercialization program can enable U.S. industry to be first to market SMRs, thereby serving as a fulcrum for export growth as well as a lever in influencing international decisions on deploying both nuclear reactor and nuclear fuel cycle technology. *A viable U.S.-centric SMR industry would enable the U.S. to recapture technological leadership in commercial nuclear technology, which has been lost to suppliers in France, Japan, Korea, Russia, and, now rapidly emerging, China.*

#### *Challenges*

SMR design, licensing, and detailed engineering activities are in an early stage. Licensing and design certification documents are expected to be ready for NRC filing in the 2013 time frame, and detailed engineering is about 10-20% complete. At the time of this analysis, limited cost data were publicly available, and current estimates have a significant amount of uncertainty. The study team estimates that GW-level reactors have roughly two orders of magnitude greater man-hours already expended in this early engineering design work as compared with design work carried out for SMRs to date. *Finally, the tooling up at a factory dedicated to SMR manufacturing is still in the planning stages and will likely require significant investment for a dedicated plant to manufacture SMRs for an n<sup>th</sup>-of-a-kind (NOAK) economy.*

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## 4.0 ECONOMIC ANALYSIS

### 4.1 OVERNIGHT COST ESTIMATES FOR GW-SCALE REACTORS

Since the 2004 Chicago Study,<sup>8</sup> the study team has learned that overnight costs (the capital cost of the plant without financing and escalation costs) for the Generation III (Advanced Boiling Water Reactor) and Generation III+ (e.g., AP1000) reactors in the United States have increased considerably (i.e., from about \$2000/kW to a consensus estimate of about \$4220/kW).<sup>9,10</sup> Key contributors to this increase include (1) commodity price increases for critical nuclear components, structures, and materials; (2) more detailed engineering and better definition of the scope for the basis estimates, particularly including more realistic owner's costs; and (3) greater reliance on fixed/firm supplier contracts, with increased use of "pancaking"<sup>11</sup> contingency estimates as a key risk management tool, i.e., inclusion of contingency as multiple adders to the individual estimates by all sectors – the design team, the manufacturers, the suppliers, and the owners. Financial risk management was analyzed separately and will be discussed in more detail below. Note that that amortization of nonrecurring design and engineering costs, the so-called "first-of-a-kind" engineering (FOAKE) costs, was uncertain because of the uncertain rate and duration of the FOAKE costs that will be imposed on the cost of future GW-level plants. The results appear in a companion white paper.

The study team learned during the study, which included comments received from the utilities and vendors who participated in the DOE Nuclear Power 2010 (NP-2010) program, that further delineation of the design and engineering for large (GW-scale) reactors would have likely resulted in firmer overnight cost quotes and, potentially, more expedited licensing approvals. This lesson – if learned – argues strongly that a key initial step for a robust SMR reprogram is to support the completion of detailed design and engineering (DD&E) work that is more expansive than the FOAKE effort. The scope of such a DD&E effort would include the preparation of construction drawings; the specification of system components; procurement engineering, including the preparation of bid packages for suppliers; a general site layout (that would then be adapted to individual plants); and all nonrecurring design and engineering work at the manufacturing site. These DD&E activities for the SMR program may have to be more expansive than the scope for the NP2010 FOAKE program. More robust engineering design work could facilitate the NRC design certification (DC) process, and additional design and engineering activity will be needed to integrate the design of SMR modules with site and manufacturing facility specifications. A more robust DD&E process also may reduce the tendency to "pancake" contingencies, so that fixed/firm cost estimates are established and, more

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<sup>8</sup> University of Chicago, *The Economic Future of Nuclear Power*, Chicago: University of Chicago with Argonne National Laboratory, August 2004.

<sup>9</sup> All point estimates for costs quoted in this paper are associated with error bounds, which are not given here in the interest of economy of presentation; the full study now under peer review provides a more detailed description of these uncertainties.

<sup>10</sup> It should be noted that commodity prices have softened recently, and the dollar has strengthened. If these trends continue, future overnight costs could alter the trend line of ever rising estimates.

<sup>11</sup> Pancaking is a term used by the industry to represent additive contingencies that are accounted for in the EPC bid packages.

importantly, supporting follow-on manufacturing and construction activities for SMRs are carried out.

Estimates of DD&E costs for SMRs are being closely held by the vendors for obvious reasons having to do with business competitiveness. Based on general discussions with the vendors, the study team estimates that the total DD&E cost for each SMR technology is approximately \$1.0 billion. This amount includes the cost for bringing the design to the point where it can satisfy NRC requirements (either under the Code of Federal Regulations, Part 50 or Part 52), support firm/fixed-cost estimates for construction of the initial SMR plant (which designate as the “LEAD” plant), and provide design and cost estimates for the construction of an SMR module manufacturing facility. The DD&E estimate is somewhat more conservative than the experience with Gen III+ reactors, which the study team estimates at about \$800 million for the licensing/DC/FOAKE activities. This conservatism reflects the additional work needed to integrate the SMR design with the design of the manufacturing facility, as well as a judgment as to the need for and benefits of a more robust upfront design effort. Planned follow-on research will ascertain the key cost drivers and trade-offs that determine these DD&E estimates.

## **4.2 WEIGHTED AVERAGE COST OF CAPITAL AND RISK PREMIUM ANALYSIS**

In both the 2004 Chicago Study and the current work, the future behavior of natural gas prices is the dominant factor when assessing the relative competitiveness of nuclear energy for base load power.<sup>12</sup> In the absence of carbon pricing and increasingly stringent air and water quality and waste management regulation, natural gas-fired generation is cheaper than all other sources of generation at the moment. While the current outlook calls for domestic natural gas supplies to be robust and prices to remain relatively stable, natural gas markets remain subject to volatility. Two perturbations could occur that might cause natural gas prices to spike – pricing natural gas to its oil equivalent due to an emerging export market for natural gas and shortfalls in the realization of expected supply additions from shale gas. The study team plans to address these issues in greater detail in a future paper. Note that the natural gas market has experienced at least four price spikes in the last 10 years.<sup>13</sup>

In recent work of Dr. Rothwell (Stanford University), the uncertainty of future natural gas prices was captured in the range of estimates of the levelized cost of electricity.<sup>14</sup> Dr. Rothwell found that there are opportunities for nuclear energy competitiveness – when decision makers require high confidence that their investments are competitive relative to other supply options. The study team further understands that this is priced into the weighted-average cost of capital (WACC). In Dr. Rothwell’s work, a variable risk premium was used for comparing GW-scale plants with

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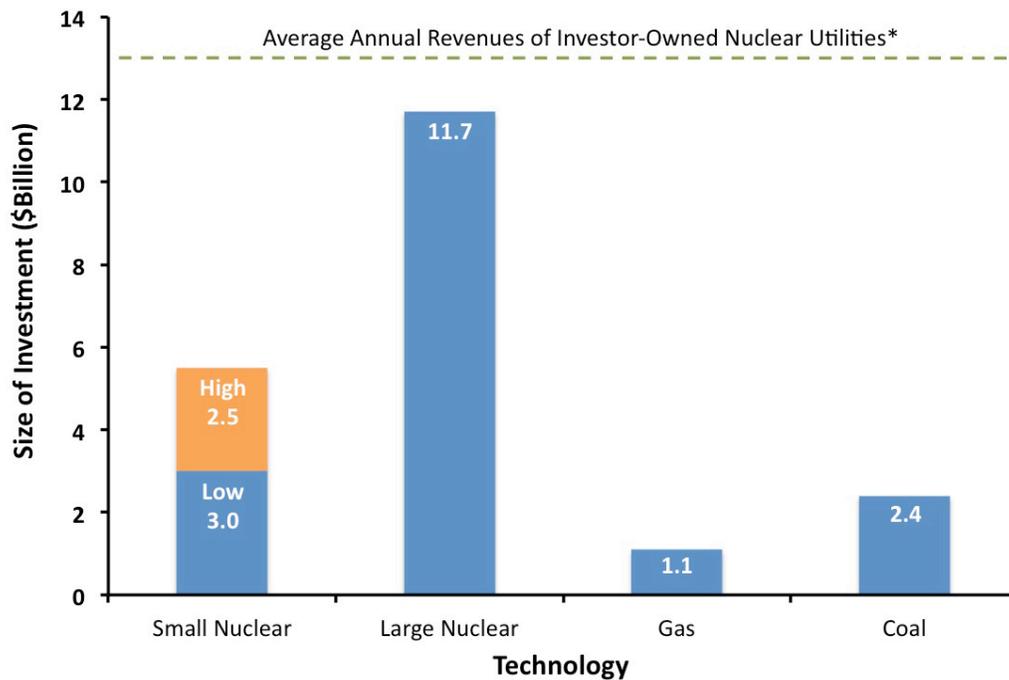
<sup>12</sup> In the 2004 Chicago Study, limited analysis was done on the comparison between the economic competitiveness of nuclear energy and natural gas with variable cost of capital scenarios.

<sup>13</sup> See natural gas price data at <http://research.stlouisfed.org/fred2/series/GASPRICE/downloaddata?cid=98>.

<sup>14</sup> See G. Rothwell, “The Economics of Future Nuclear Power,” an update of *The Economic Future of Nuclear Power*, a study conducted at the University of Chicago, March 17, 2011. See <http://harrisschool.uchicago.edu/centers/hepi/workshops.asp>.

natural gas-fired plants.<sup>15</sup> The goal was to relate the risk premium to “size risk.” The conceptual basis for this approach is described further in Appendix F.

Figure 1 provides a simplified illustration of risk by comparing the size of a nuclear investment with other conventional base load investments; for comparison, the average annual revenue of investor-owned nuclear utilities is shown. This analysis, which puts significant weight on the size of the investment to measure WACC, is consistent with Moody’s Investor Service opinion that “we view nuclear generation plans as a ‘bet the farm’ endeavor for most companies, due to the size of the investment and length of time needed to build a nuclear power facility.”<sup>16</sup>



\* Before the announced mergers of: (1) Exelon and Constellation; and (2) Duke and Progress.

**FIGURE 1 Comparison of Size of Investment (i.e., Overnight Cost) with Average Annual Revenues of Investor-Owned Nuclear Utilities<sup>17</sup>**

<sup>15</sup> The DOE Title XVII Loan Guarantee Program changed the structure and the level of the risk premium. Such loans are priced at the cost of Treasury borrowing of comparable maturities, plus a premium. Even with the Federal Financing Bank (FFB) premium, the cost of debt is generally below rates offered by commercial lenders. The availability of the loan guarantee changes the risk premium in three significant ways: (1) it allows a capital structure with greater leveraging (i.e., higher debt/equity ratio); (2) it lowers the cost of debt financing, because of the availability of a direct loan from the FFB; and (3) it lowers the return on equity as well. The risk protection afforded by the loan guarantee lessens the basis for investors to otherwise command a risk premium, and the terms of the loan guarantee place tighter constraints on the ability of investors to take out equity unless minimum debt service coverage and reserve requirements are met.

<sup>16</sup> In the authors’ opinion, Moody’s statement is a financial statement and, in all probability, does not reflect a technology assessment regarding nuclear energy.

<sup>17</sup> Specific examples of current annual revenues are the following: Ameron – \$7.6 billion; Constellation Energy – \$13.9 billion; and Exelon – \$19.4 billion.

As indicated in Figure 1, on average, investor-owned U.S. utilities, representing 70% of nuclear generation, have about \$13 billion in average annual revenue. A twin-unit GW-scale nuclear investment of \$11 billion would represent about 90% of their annual revenues – suggesting that a larger size project presents a risk premium due to size alone that cannot be ignored and may well be substantial. However, more work needs to be done to understand the sensitivity of the risk premium in this area. For SMR plants, the study team has performed an initial set of calculations for a variety of WACC outcomes. The team found that the risk premium associated with project size has significant potential to be mitigated<sup>18</sup> because lower upfront investments potentially shorten the pre-completion period and, therefore, lower pre-completion risk; all of these factors would result in a lower risk premium and, in turn, a lower WACC. If lower WACC is achieved, the opportunity to compete with natural gas-fired generation in both regulated and unregulated territories would be larger than for GW-scale plants, thus further enhancing the future competitiveness of SMRs. Also, Moody’s estimates that (i) financial strength metrics for both regulated and unregulated utilities (such as cash-to-debt flow ratios) and (ii) cash flow predictability for unregulated utilities are significant factors in its rating methodology (see Table 1). In the opinion of the authors, the temporal nature of cash flow predictability is an important indicator when assessing the debt quality for nuclear power plants.

According to a recent study issued by the Texas Institute, the historical record of commercial nuclear power plant construction by U.S. investor-owned utilities showed an almost 70% probability that the utility would experience a rating downgrade of uncertain magnitude.<sup>19,20</sup> It should be noted that this study was based upon the corporate finance structures that were in place in the 1980s and 1990s. These structures are not representative of today’s financing vehicles that are based on limited recourse arrangements. The study team developed a conceptual model to examine the impacts of size risk on WACC (described in Appendix F). The study team compared the WACC for conventional investments versus large nuclear investments, based on the size risk, implicit to the financial strength, as measured by Moody’s. The model indicates that investments in large nuclear projects (approximately \$6-7 billion) exhibit significantly higher WACC as compared with conventional energy investments (approximately \$2-3 billion).<sup>21</sup> According to a Congressional Budget Office (CBO) report,

Moody’s recently reported that it was considering taking a more negative view of bond issuers who were seeking to finance the construction of new nuclear plants. A primary concern cited by Moody’s was whether the proposed plants were economically viable, especially given uncertainties about the effects of energy

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<sup>18</sup> Private communication from Fitch Ratings (2011).

<sup>19</sup> “Impact of Nuclear Power Projects on Credit Ratings and Credit Recoveries Following Default of Investor Owned Utilities Sponsoring Nuclear Projects,” [www.TexasInstitute.org](http://www.TexasInstitute.org), September 2011.

<sup>20</sup> Another study, performed by the Congressional Budget Office, also found that “...most utilities that undertook nuclear projects suffered ratings downgrades – sometimes several downgrades – during the construction phase.” Congressional Budget Office, *Federal Loan Guarantees for the Construction of Nuclear Power Plants*, citation in footnote 22 below.

<sup>21</sup> See G. Rothwell, “The Economics of Future Nuclear Power,” a 2011 update of *The Economic Future of Nuclear Power* (2004), a study conducted at the University of Chicago. See <http://harrisschool.uchicago.edu/centers/hepi/workshops.asp>.

**TABLE 1 Moody's Rating Methodology for Electric Utilities**

<b>Rating Factor Weighting – Regulated Electric Utilities</b>			
<b>Broad Rating Factors</b>	<b>Broad Factor Weighting</b>	<b>Rating Sub-Factor</b>	<b>Sub-Factor Weighting</b>
Regulatory Framework	25%		25%
Ability to Recover Costs and Earn Returns	25%		25%
Diversification	10%	Market Position	5%
		Generation and Fuel Diversity	5%
Financial Strength, Liquidity and Key Financial Metrics	40%	Liquidity	10%
		CFO pre-WC/Debt	7.50%
		CFO pre-WC + Interest/Interest	7.50%
		CFO pre-WC - Dividends/Debt	7.50%
		Debt/Capitalization or Debt/Regulated Asset Value	7.50%
<b>Rating Factor Weighting – Unregulated Electric Utilities</b>			
Market Assessment, Scale and Competitive Position	25%	Size and scale	15%
		Competitive position and market structure	10%
Cash Flow Predictability of Business Model	25%	Fuel strategy and mix	5%
		Degree of integration and hedging strategy	5%
		Capital requirements and operational performance	5%
		Contribution from low-risk/high-risk business	10%
Financial Policy	10%		
Financial Strength Metrics	40%	Cash Flow/Debt	12.5%
		Cash Flow Interest Coverage	10%
		Retained Cash/Debt	12.5%
		Free Cash Flow/Debt	5%

efficiency programs and national clean electricity standards on the demand for new nuclear generating capacity, the availability of capital in such projects, and the effect of such investment on the sponsoring utilities' balance sheets.<sup>22</sup>

Furthermore, CBO discussed the market risk associated with GW-scale plants:

Market risk is the component of risk that investors cannot protect themselves against by diversifying their portfolios. Investors require compensation for market risk because investments exposed to such risk are more likely to have low returns when the economy as a whole is weak and resources are more highly valued... In the case of nuclear construction guarantees provided to investor-owned utilities or merchant power providers, for example, plant construction may be more likely to

<sup>22</sup> Congressional Budget Office, *Federal Loan Guarantees for the Construction of Nuclear Power Plants*, <http://www.cbo.gov/ftpdocs/122xx/doc12238/08-03-NuclearLoans.pdf>, August 2011.

be slowed or canceled when the demand for electricity is depressed by a weak economy.<sup>23,24</sup>

SMRs could potentially mitigate such a risk in several ways. First, SMRs have lower pre-completion risk due to shorter construction schedules (24-36 months as compared with 48 months). Second, because of their smaller size, SMRs have lower market risk because there is significantly less power than needs to be sold as compared with GW-level plants. Finally, the modular nature of SMRs affords the flexibility to build capacity on an as-needed basis.

In the case of unsubsidized financing, particularly relevant to merchant markets, utility decision makers that have significant aversion to risk of future natural gas spikes (i.e., gas prices rising to about \$7/Mcf or one standard deviation above the recent average behavior of natural gas prices) would possibly view alternatives to gas-fired generation as attractive options, particularly if the investment requirements are comparable – SMRs could potentially “fit the bill.”

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<sup>23</sup> Ibid.

<sup>24</sup> This point has been substantiated by Fitch Ratings (private communication, 2011).

## 5.0 MODELING THE SMR ECONOMY

The goal of this stage of the study was a scoping analysis sufficient to develop a business case for future programmatic and policy decisions, including options for government incentives. This scoping analysis does support a competitive position for n<sup>th</sup>-of-a-kind (NOAK) SMRs, based on best achievable overnight cost estimates. However, one of the limitations at this stage of the analysis is reliance on projections of best achievable costs for the NOAK SMRs based on limited engineering design work. The study team recommends that the “lessons learned” be adopted from the NP2010 program. Detailed design and engineering work should be supported for at least several designs to promote competition and arrive at more robust design solutions, with firmer cost estimates, for the earlier SMR plants, as well as to fully exercise the NRC licensing process (this will be discussed in Appendix B).

Modeling the SMR economy requires particular focus on three important parameters: (1) the shift of SMR manufacturing from on-site construction to factories, (2) the achievement of scale in the rate of factory manufacturing of SMRs, and (3) the ability to achieve manufacturing cost saving through learning. The present modeling effort is designed to illustrate the role of these factors in the economic feasibility of an SMR commercial deployment program. The SMR community refers to this architecture as the “economics of mass manufacturing,” in contrast to the “economics of scale,” which is the major driver for GW-scale nuclear power plants.

The LWR-based SMR vendors offer different size SMR modules as well as different size commercial plant configurations. Not wanting to single out a particular vendor offering, the study team developed a hypothetical SMR configuration that would illustrate the economics of SMR mass manufacturing and deployment. The hypothetical SMR module was assumed to be 100 MW, and the make-up of a complete SMR plant was sized at six 100-MW modules, represented by six reactor-turbine-generator sets for a total of 600 MW of build-out capacity. The hypothetical module size represents a middle position between actual SMR module designs ranging from 45 MW to 300 MW. A hypothetical six-module SMR plant also represents a middle position between designs ranging from one SMR module per plant to up to 12 SMR modules per plant.

Capital cost estimates for SMRs are in early stage development, and little detailed information is currently in the public domain. Adapting the limited information currently available from SMR vendors to the hypothetical configuration, the study team estimated the “best achievable” overnight cost estimate for the NOAK SMR plant to be about \$4700/kW when configured as a fully operational 600 MW plant.<sup>25</sup> Limited information is currently available to allow for

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<sup>25</sup> The overnight capital costs are composed of the following cost centers:

- (1) *DIR*, direct construction costs (Account 10, including pre-construction costs, assigned to “owners’ costs”) and Account 20 (direct construction costs);
- (2) *INDIR*, (Account 30, including the indirect costs of plant construction, including capitalized indirect costs);
- (3) *OWN*, owners’ costs (Account 40, not including off-site, “beyond the busbar,” transmission costs);
- (4) Supplemental costs (Account 50, primarily first-core costs); and
- (5) Contingency.

Direct construction costs in Account 20 are separated into (1) balance-of-plant (BOP) structures and improvement costs (Series 21) and (2) power unit costs (Series 22 + 23 + 24 + 25 + 26).

deconstruction of this estimate into its major cost center components. The study team is doing additional analysis using operations research models that include a more robust analysis of specific cost centers. This analysis will be available in subsequent reports.

The overall total capital investment for this project, using these overnight cost estimates, is about \$3 billion. Note that a total capital investment of this scale is comparable to the capital investment requirement for a new 1,000 MW advanced pulverized coal power plant.<sup>26</sup>

Peer reviewers of the initial analysis suggested that a spectrum of outcomes be considered for natural gas-fired electricity to provide additional perspective on the relative competitiveness of SMRs with natural gas-fired combined cycle generation plants. Because of the uncertainties (and potential volatility) in natural gas prices, the study team chose not to adopt any single natural gas price projection, but instead developed a broad range of costs for natural gas combined-cycle electricity based on historical data. The historical record reveals an average wellhead price for natural gas of \$5.45/MMBTU, with a standard deviation of \$2.53/MMBTU. The study team decided to use the historical averages as the basis for developing cost estimates for natural gas combined-cycle electricity generation. The team concluded that any set of single-point price projections would not adequately capture the degree of uncertainty facing investors in new power generation facilities. The use of statistical historical averages represents one approach to address this uncertainty; future analyses may consider other methodological approaches as well.<sup>27</sup>

Based on the historical data, the study team developed estimates of natural gas combined-cycle electricity costs ranging from about \$60 per MWh to \$80 per MWh (6 to 8¢/kWh), where the low end of the range reflected the historical average natural gas price and the upper end of the range reflected one standard deviation in the historical average.<sup>28</sup> Although the low end estimate is based on a natural gas price that is currently above market price, it is within the range of projected natural gas prices in the post-2020 timeframe, when SMR plants could be ready for deployment. In a separate paper, the study team will further analyze the issues surrounding natural gas price projections, including issues pertaining to shale gas.

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<sup>26</sup> Based on an estimated unit overnight capital cost for new advanced pulverized coal plants of \$2.8-3.2 million per MW, as reported by the Energy Information Administration (EIA) in “Updated Capital Cost Estimates for Electricity Generation Plants,” November 2010.

<sup>27</sup> One other possibility would be to perform a Monte Carlo simulation based on one or more price projections.

<sup>28</sup> See G. Rothwell, “The Economics of Future Nuclear Power,” a 2011 update of *The Economic Future of Nuclear Power* (2004), a study conducted at the University of Chicago. See <http://harrisschool.uchicago.edu/centers/hepi/workshops.asp>.

## 5.1 LEARNING PROCESS

Preliminarily, the study team used a conservative learning rate of 10% for capital (fixed) costs and a 2-3% learning rate for variable costs (operations and maintenance).<sup>29</sup> Ten percent learning rates mean that costs will be reduced by 10% for every doubling either in the number of modules or plants.<sup>30</sup> The learning rate was drawn from the 2004 study, and was influenced by the learning experience drawn from Navy shipbuilding. The study team applied the same learning rate to all capital cost centers. Further research will be required to elucidate the learning rates for each of the cost centers.

### 5.1.1 LEAD SMR Plants

For modeling purposes, the so-called “first-of-the-first” SMR deployment was characterized as the LEAD SMR plant. The LEAD plant likely would be custom-built, but based on the design that ultimately would be built in a factory. Consequently, the overnight capital cost for the LEAD plant was expected to be significantly higher than a NOAK SMR plant that incorporated the benefits of the learning process in a factory setting. The overnight cost of the LEAD plant was projected to be in the range of \$7,000-11,500/kW, significantly higher than the estimated overnight cost of \$4,700/kW for the NOAK plant. The LEAD plant is assumed to be fully populated with six modules. The cost estimate for the LEAD plant is conservative, emblematic of the inability, at the start of this enterprise, to establish the best procurement, manufacturing, and delivery system at the time of the construction of this first set of modules. This estimate may pose a challenge to potential “first movers” in the industry, but it is not insurmountable. This barrier can be overcome by means of a combination of vendor pricing schemes, equity sharing, power purchase and sales arrangements, state and local government incentives, and private sector incentives. Some of these possibilities are discussed later in this paper.

The study team also performed economic analyses with a half-scale LEAD (or “LEAD/2”) SMR plant consisting of three 100-MW modules, or 300 MW total. The LEAD/2 option would have even higher overnight capital costs, because the fixed cost for plant infrastructure assets would be amortized over fewer modules; however, total capital costs would be lower. It may be desirable to deploy a LEAD/2 as the initial SMR commercial plant, particularly if multiple SMR designs are supported, to reduce total capital cost expenditures for these initial plants.

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<sup>29</sup> The Chicago Study (2004, p. 4-1) states, “A plausible range for future learning rates in the U.S. nuclear construction industry is between 3 and 10 percent. Three percent is consistent with a scenario involving low capacity growth, reactor orders of a variety of designs spaced widely enough apart in time that engineering and construction personnel cannot maintain continuity, some construction delays, and a construction industry that can retain internally a considerable proportion of learning benefits. A medium learning rate of 5 percent is appropriate for a scenario with more or less continuous construction, with occasional, but not frequent, cases of sequential units built at a single facility, a narrower range of reactor designs built by a more competitive construction industry, with delays uncommon. A 10 percent learning rate is aggressive. It would necessitate a continuous stream of orders that keep engineering teams and construction crews intact, a highly competitive construction industry, and streamlined regulation largely eliminating construction delays.”

<sup>30</sup> For fixed capital costs (costs that do not change with capacity), doubling is based on the number of plants; for variable capital costs (costs that are amortized by the number of modules at the site), doubling is based on the number of modules.

### 5.1.2 FOAK Plants and the Learning Fleet

The next sets of plants, the FOAK SMR plants, provide the basis for optimizing the supply chain and demonstrating the learning process. After the LEAD is designed and licensed, and after long-lead procurement activities have been completed, the study team projected that a dedicated manufacturing plant could be planned, designed, and built. At that time, firm capital and operating costs would be amortized over the FOAK plants.

The study team's learning model is based on an assumption of an SMR multi-module manufacturing facility with the capacity to produce 12 modules per year.<sup>31</sup> Assuming continuous production of one module per manufacturer per month for a 4-year campaign, the size of the FOAK learning fleet was estimated to be 48 SMR modules, which would outfit eight FOAK plants, depending upon whether the plants were fully populated with such modules. The study team also assumed that all front-end development costs would be amortized and recovered over the LEAD and FOAK learning fleet. This would enable the private sector to amortize its share of DD&E costs (i.e., not cost shared by the federal government and/or other public entities).<sup>32</sup> The private sector share of the front-end development costs was estimated to be up to \$500 million.<sup>33</sup> These initial cost estimates will be better understood as the SMR designs mature, and, in particular, a more precise picture of the requisite manufacturing requirements is defined.

Based on an assumed learning rate of 10%, the study team estimated that significant learning would be achieved after deployment of the LEAD and FOAK-1 plants (12 SMR modules total), with the full effects of learning achieved after manufacturing of 54 SMR modules. It should be noted that learning on the first three projects, representing 18 modules, appears significant. Based on the initial scoping studies, assuming a 10% learning rate and deployment of the first 18 modules (or 1.8 GW), an LCOE of about \$80/MWh (8¢/kWh)<sup>34</sup> would be achieved. This milestone represents (1) about 100% of the so-called "journey" that is required to achieve a competitive position with the upper end of the projected levelized cost for natural gas-fired generation (i.e., about \$80/MWh or 8¢/kWh), and (2) about two-thirds of the journey to compete head-to-head with the low end of the projected cost for natural gas-fired generation (i.e., about \$60-65/MWh or 6-6.5¢/kWh). The follow-on research will focus on the learning process that occurs in such a dedicated factory.

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<sup>31</sup> This case was established during the team's visit to Huntington Ingalls Industries' Newport News shipbuilding facilities. The learning experience from naval shipbuilding is discussed further in Appendix C, which also describes in more detail the economics of the learning process.

<sup>32</sup> Note the prudence of the investment in the module manufacturing facility also requires that a substantial order book for SMRs has been established prior to placing the investment.

<sup>33</sup> The study team estimated total DD&E costs per design of approximately \$1 billion and assumed that the government cost shares approximately \$500 million of these costs on a 50-50 basis, resulting in a total non-federal residual cost of \$500 million to be amortized by the SMR vendor team. The initial capital cost for outfitting an SMR multi-module manufacturing facility is on the order of \$300 million, which also would be amortized in the cost of the FOAK learning plants.

<sup>34</sup> \$10/MWh = 1 cent/kWh.

Tables 2 and 3 present the estimates by major cost centers for the LEAD/2, LEAD, FOAK-4,<sup>35</sup> and NOAK plants. Figure 2 summarizes these cost projections as SMRs mature in the marketplace and become more competitive with natural gas-fired generation. Note that these estimates assume a real WACC of 5.2%, which represents the low end of the range and reflects a relatively low risk premium.

**TABLE 2 Calculation of Levelized Cost of Electricity for SMRs (\$2011, WACC = 5.2%)**

	Units	NOAK	FOAK-4	LEAD	LEAD/2
Net Electrical Capacity	MWe	600 <sup>a</sup>	600 <sup>a</sup>	600 <sup>a</sup>	300 <sup>b</sup>
Direct Costs (see Table 3)	\$ M	2,000	2,229	2,837	1,808
Indirect Costs (10% of direct costs)	\$ M	200	223	284	181
First Core Costs	\$ M	93	93	93	93
DD&E Expenses <sup>c</sup>	\$ M	0	50	100	100
Owner's Cost	\$ M	200 <sup>d</sup>	200 <sup>d</sup>	200 <sup>d</sup>	200 <sup>d</sup>
<b>Overnight Cost</b>	<b>\$ M</b>	<b>2,493</b>	<b>2,795</b>	<b>3,515</b>	<b>2,382</b>
Contingency	%	15	26	35	35
Total Overnight Cost	\$ M	2,867	3,529	4,745	3,215
Total Overnight Cost per kW	\$/kW	4,778	5,882	7,908	10,717
Interest During Construction Factor	%	8.69	8.69	8.69	8.69
<b>All-in Capital Costs</b>	<b>\$ M</b>	<b>3,084</b>	<b>3,771</b>	<b>5,050</b>	<b>3,422</b>
Levelized Capital Cost + D&D Cost	\$/MWh	40.36	49.36	66.09	89.58
Levelized O&M Costs	\$/MWh	12.05	13.26	16.54	25.49
Levelized Fuel Cost	\$/MWh	8.53	8.53	8.53	8.53
<b>Levelized Cost (real 2011\$)</b>	<b>\$/MWh</b>	<b>60.95</b>	<b>71.15</b>	<b>91.17</b>	<b>123.60</b>

a. Six reactors of 100 MWe each. Capacity factor of 90%.

b. Three reactors of 100 MWe each. Capacity factor of 90%.

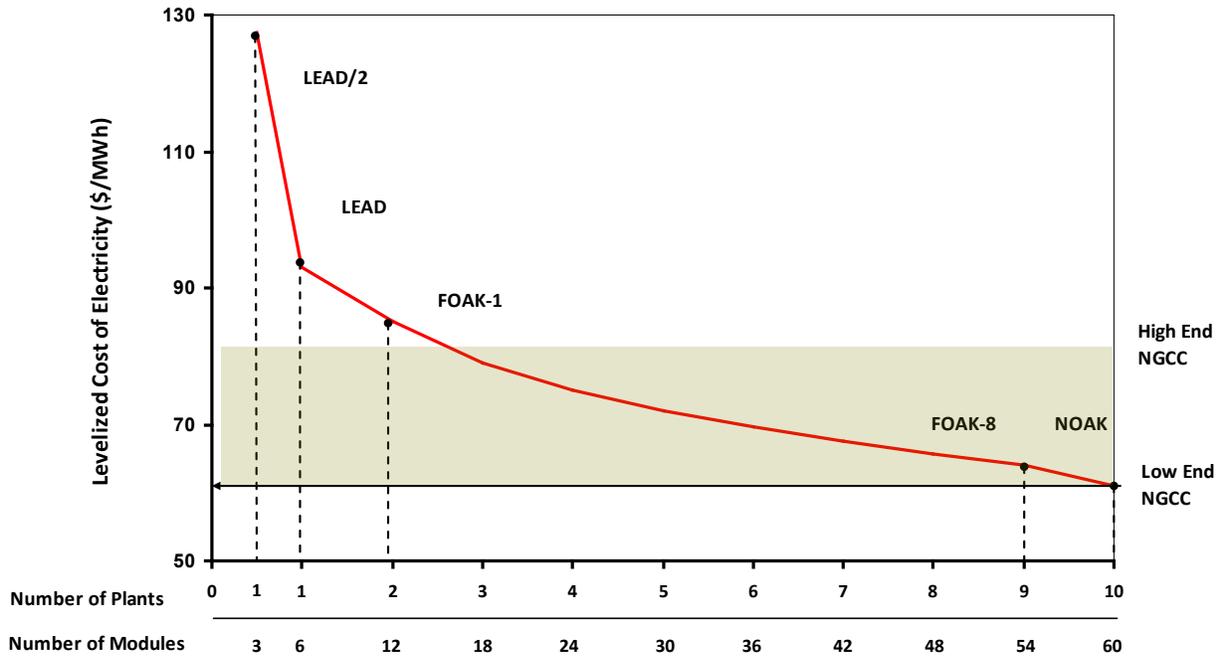
c. It is assumed that DD&E costs would be 50/50 cost-shared between the federal government and private sector; other scenarios that increase the private sector's share should be considered.

d. Further analysis is required for this cost center.

<sup>35</sup> This plant represents the mid-range of the family of FOAK plants.

**TABLE 3 Breakdown of Direct Costs (\$2011)**

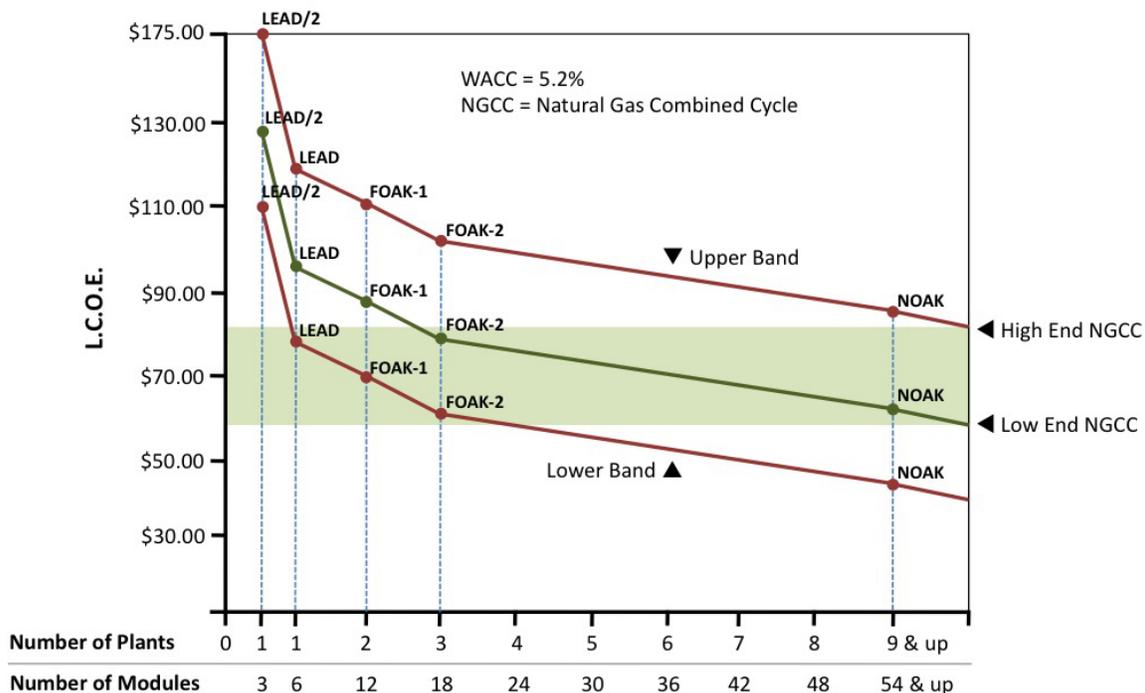
	Units	NOAK	FOAK-4	LEAD	LEAD/2
Balance of Plant Structures	\$ M	80	88	110	\$110
Reactor Building	\$ M	200	220	274	274
Non-reactor Structures	\$ M	120	132	165	165
<b>Total Site Improvements and Structures</b>	<b>\$ M</b>	<b>400</b>	<b>440</b>	<b>549</b>	<b>549</b>
Reactor and Steam Generator	\$ M	1,000	1,118	1,430	\$787
Turbine Generator and Condenser	\$ M	300	\$335	\$429	\$236
Transformer and Elec. Equipment	\$ M	200	\$224	\$286	\$157
Cooling System and Misc. Equip.	\$ M	100	\$112	\$143	\$79
<b>Power Unit Equipment</b>	<b>\$ M</b>	<b>1,600</b>	<b>1,789</b>	<b>2,288</b>	<b>1,259</b>
<b>Direct Costs</b>	<b>\$ M</b>	<b>2,000</b>	<b>2,229</b>	<b>2,837</b>	<b>1,808</b>



**FIGURE 2 Levelized Costs of Learning Plants (NOAK overnight costs, \$4,770/kW)**

The study team performed a sensitivity analysis of the effects of alternative cost estimates on the learning fleet of FOAK plants. Figure 3 provides a region (in the form of bounding analysis) for a 10% learning rate and is based on a range of cost estimates for the LEAD and NOAK plants. The upper band of estimates assumes a cost estimate for the LEAD plant of about \$11,000/kW with a more aggressive learning rate for the subsequent FOAK plants; the lower band of cost estimates assumes a LEAD plant cost estimate of about \$6,700/kW with a lower learning rate for subsequent FOAK plants. At the low end of the range of cost estimates, the LEAD plant is competitive at the \$80/MWh (8¢/kWh) LCOE level, and the learning process reaches the low end of the competitive range (i.e., \$60-65/MWh or 6-6.5¢/kWh) after deployment of 18 SMR modules total (the LEAD plus two FOAK SMR plants).<sup>36</sup>

The learning rate analysis is conservatively based on an extrapolation from the analysis of learning in the 2004 Chicago Study, combined with information on the experience of Navy shipbuilding programs. It is consistent with, but perhaps a bit more conservative than, public statements from SMR vendors.<sup>37</sup> The study team believes that the learning analysis would



**FIGURE 3 Levelized Costs of LEAD and Learning Plants (\$/MWh)**

<sup>36</sup> Assumptions for the so-called band width (the spread between the upper and lower band) will be further elucidated in the upcoming research.

<sup>37</sup> By comparison, senior executives from SMR vendor companies testified before the Senate Energy and Water Appropriations Subcommittee on July 14, 2011, that they believed that sufficient learning could be demonstrated by the time of the 10<sup>th</sup> SMR module to enable SMRs to compete with alternative electric generation technologies without the need for special federal subsidies. As the sensitivity analysis here shows, this result could be achieved through a combination of more robust designs with lower LEAD cost estimates and a higher learning rate than assumed in the business case analysis.

benefit from an examination of learning experience in other industries as well. In addition, the team is conducting more research using modeling tools that would improve the simulation of learning rates and bounding analysis.

## **5.2 SMR MANUFACTURING THROUGHPUT**

Once learning was achieved, the study team projected a reference case for the size and configuration for the fleet of NOAK SMR plants. This projection represents an extension of the SMR manufacturing assumptions incorporated into the learning model. As discussed earlier, an SMR module manufacturing plant was assumed to be able to produce about one (100 MW) SMR steam-generation module per month, or 12 SMR modules per year. A total of 240 SMR modules (both FOAK and NOAK plants) would be manufactured over an assumed 20-year manufacturing plant useful life. For the hypothetical SMR design (i.e., 100 MW modules), this represents a total of 24 GW of SMR generation capacity, of which the initial 5.4 GW represents the LEAD and FOAK plants, and the remaining 18.6 GW represents NOAK plants.<sup>38</sup>

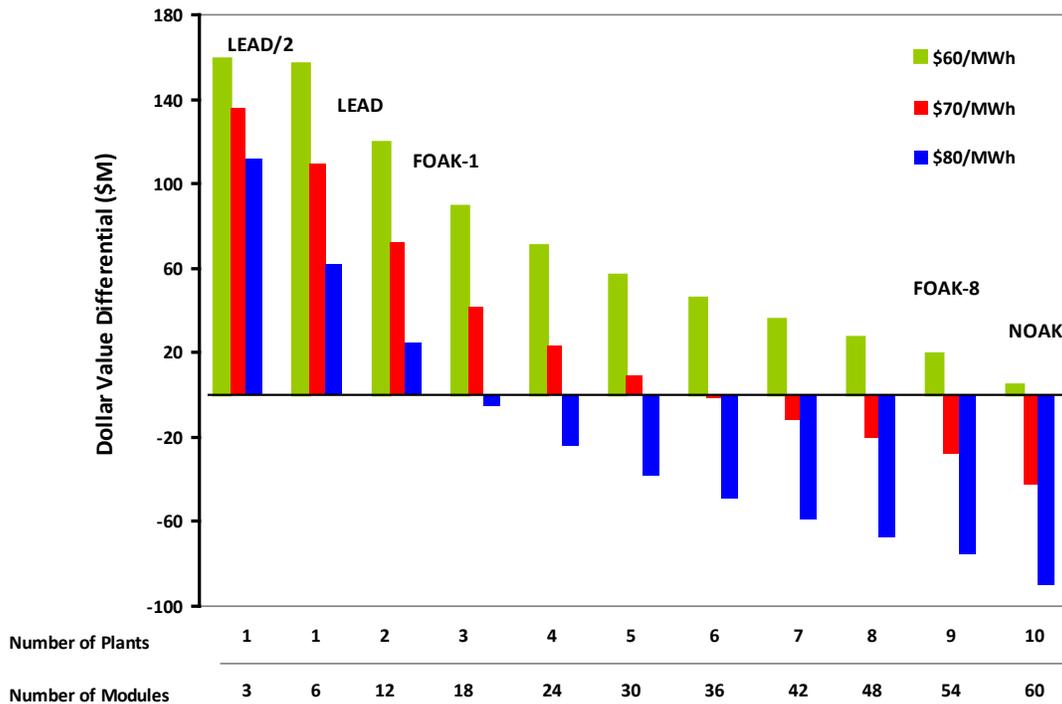
This estimate of 240 SMR modules over a 20-year manufacturing run represents the reference case. The study team believes that this aggregate estimate would support a viable commercial SMR module manufacturing plant. The actual size of the NOAK SMR fleet could be significantly larger, and would be determined on the basis of market demand. Additional research will be required to ascertain the financial requirements for a viable factory operation, including projected costs, revenues, and financial cost parameters.

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<sup>38</sup> It is assumed that the first-of-the-first plants (LEAD) would exercise some of the learning potential; the remaining plants (FOAK) would exercise the full automation capabilities at the factory site.

## 6.0 GOVERNMENT INCENTIVE PROGRAMS AND OTHER MARKET INCENTIVES

As illustrated in the previous discussion, until significant learning benefits are achieved, the LEAD SMR plant and some number of FOAK SMR plants may not be competitive with new natural gas combined-cycle generation. Estimates of the number of SMR modules that may not be competitive and the magnitude of the difference in cost are subject to significant uncertainty. The estimates are dependent upon at least three key variables: the initial cost estimates<sup>39</sup> for the LEAD SMR design, the learning rate, and the future price of natural gas.<sup>40</sup> The potential range of uncertainty is illustrated in Figure 4, which identifies the generation cost differential (\$/MWh) between the family of SMR plants (LEAD, FOAK, and NOAK) and gas-fired plants for a variety of natural gas price scenarios. This analysis adopts the 10% learning assumption and the overnight cost estimate of \$4,700/kW.



**FIGURE 4 Cost Differential between SMR Plants/Modules and Gas-Fired Plants**

<sup>39</sup> These cost estimates assume the real WACC of 5.2%, which represents a relatively low risk premium.

<sup>40</sup> If natural gas prices remain indefinitely depressed, these scenarios are unlikely to materialize, and the gaps will be significantly higher for the entire family of SMR plants.

Assuming that early SMR deployments will carry cost premiums (until the benefits of learning are achieved), the issue is whether federal government incentives are needed to help overcome this barrier. Some may argue that commercial deployment will occur, albeit at a slower pace, as the cost of alternatives increases to a level that makes initial SMR deployments competitive. Others may argue that SMR vendors should market initial modules at market prices and absorb any losses until a sufficient number of modules are sold that will begin to generate a profit. However, the combination of the large upfront capital investment, the long period before a return on capital may be achieved, and the large uncertainty in the potential level of return on investment make it unlikely that SMRs will be commercialized without some form of government incentive.

The present analysis assumes that government incentives will be essential to bridging this gap and accelerating private sector investment (see Appendix D). It is the study team's understanding that DOE has proposed to share the cost of certain SMR design and licensing study activities. This section analyzes possible options for government incentives for early deployments (LEAD and FOAK plants) in addition to federal cost sharing for the design and licensing effort. The present analysis considers several alternative approaches to providing such incentives, either in the form of direct or indirect government financial incentives, or through market transformation actions that will spur demand for FOAK plants in competitive applications. The study team's approach is to identify targeted, least-cost incentives that could form the basis for further dialogue between stakeholders and policy makers.

Possible financial incentives need to be designed and evaluated relative to a particular management model for deployment of LEAD and FOAK plants. The study team's management model assumes that these initial SMR plants will be managed and financed by the private sector, consisting of a possible consortium of the SMR vendor, the reactor module manufacturer, other major vendors, a host-site utility company, and one or more other electricity generation or vertically integrated utilities. The types of incentives that could be structured for this type of management model are discussed in the subsections that follow.

Other management models were considered by the team. These alternative models would have a greater direct government role in the ownership, financing, and marketing of the SMR plant. Under a build-own-operate-transfer (BOOT) model, for example, the federal government would license, build, finance, and operate an SMR plant, and upon successful operation, seek to transfer ownership to the private sector. Another model would provide for the federal government to lease a privately developed SMR plant and take full responsibility for operation of the plant and marketing of the power generation. The various possible management models are described and contrasted further in Appendix E.

## 6.1 CAPITAL COST AND PRODUCTION COST INCENTIVES

Several forms of government support programs could assist the learning modules in reducing the cost differential, assuming competitive market conditions:

- **Capital Cost Incentive:** A capital cost incentive would reduce the effective overnight capital cost through either direct government cost sharing or through an investment tax credit.<sup>41</sup> There are policy precedents for both. DOE provides direct cost sharing for demonstration projects involving FOAK coal generation technology under the Clean Coal Power Initiative (CCPI). Congress provided a capital cost incentive for renewable energy projects in the form of an Investment Tax Credit (ITC), which currently can be converted to an upfront cash grant.<sup>42</sup> Capital cost incentives help “buy down” the initial capital cost of SMR deployments, thus reducing the capital recovery requirements that would otherwise be reflected in the LCOE. A direct buy-down of the capital cost protects project sponsors against construction risk for SMRs by shifting a portion of that risk to the government. It also shifts performance risk from the project sponsor to the federal government, i.e., the federal government pays the capital cost incentive regardless of whether the project performs as planned or not. In the case of SMRs, shifting a portion of performance risk from the SMR community to the government also may adversely impact the risk-reward structure guiding the learning process. For example, a capital cost incentive for SMRs would be fixed, regardless of whether the investment achieved the estimated learning performance. Consequently, capital cost incentives were not incorporated into the business case analysis for SMRs.
- **Production Cost Incentive:** A production cost incentive is a performance-based incentive. With a production cost incentive, the government incentive would be triggered only when the project successfully operates. The project sponsors would assume full responsibility for the upfront capital cost and would assume the full risk for project construction. *The production cost incentive would establish a target price, a so-called “market-based benchmark.” Any savings in energy generation costs over the target price would accrue to the generator. Thus, a production cost incentive would provide a strong motivation for cost control and learning improvements, since any gains greater than target levels would enhance project net cash flow.* Initial SMR deployments, without the benefits of learning, will have significantly higher costs than fully commercialized SMR plants and thus would benefit from production cost incentives. Because any production cost differential would decline rapidly due to the combined effect of module manufacturing rates and learning experience, the financial incentive could be set at a declining rate, and the level would be determined on a plant-by-plant basis, based on the

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<sup>41</sup> Another form of capital cost incentive is the provision for accelerated depreciation, which does not reduce capital cost requirements, but enables project sponsors to recover capital costs more quickly.

<sup>42</sup> Renewable energy generation technologies are eligible to receive a production tax credit, which can be converted to either an investment tax credit or a cash grant. However, only projects that have initiated construction by December 31, 2011, are eligible for the cash grant option.

achievement of cost reduction targets.<sup>43</sup> The key design parameters for the incentive include the following:

1. The magnitude of the deployment incentive should decline with the number of SMR modules and should phase out after the fleet of LEAD and FOAK plants has been deployed.
2. The incentive should be market-based rather than cost-based; the incentive should take into account not only the cost of SMRs but also the cost of competing technologies and be set accordingly.
3. The deployment incentive could take several forms, including a direct payment to offset a portion of production costs or a production tax credit.

The Energy Policy Act of 2005 authorized a production tax credit of \$18/MWh (1.8¢/kWh) for up to 6,000 MW of new nuclear power plant capacity. To qualify, a project must commence operations by 2021. Treasury Department guidelines further required that a qualifying project initiate construction, defined as the pouring of safety-related concrete, by 2014. Currently, two GW-scale projects totaling 4,600 MW are in early construction; consequently, as much as 1,400 MW in credits is available for other nuclear projects, including SMRs.

The budgetary cost of providing the production cost incentive depends on the learning rate and the market price of electricity generated from the SMR project. Higher learning rates and higher market prices would decrease the magnitude of the incentive; lower rates and lower market prices would increase the need for production incentives. Using two scenarios (with market prices based on the cost of natural gas combined-cycle generation) yields the following range of estimates of the size of production incentives required for the FOAK plants described earlier. For a 10% learning rate,

- Based on a market price of \$60/MWh<sup>44</sup> (6¢/kWh), the LEAD plant and the subsequent eight FOAK plants would need, on average, a production credit of \$13.60/MWh (1.4¢/kWh), 24% less than the \$18 credit currently available to renewable and GW-scale nuclear technologies. (The actual credit would be on a sliding scale, with the credit for the LEAD plant at approximately \$31/MWh, or 3.1¢/kWh, declining to a credit of about \$6/MWh, or 0.6¢/kWh, by the time of deployment of FOAK-8). The total cost of the credit would be about \$600 million per year (once all plants were built and operating).
- If the market price were about \$70/MWh (7¢/kWh), the LEAD and only four subsequent FOAK plants would require a production incentive. In this case, the

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<sup>43</sup> A possible model would be performance-based rate regulation, where regulators set revenue caps for regulated utilities that will allow for an expected return on equity if certain cost reduction targets are met. If those reduction targets are not met, the utility's return on equity could be diminished.

<sup>44</sup> Note that if gas prices fall to an average of \$4/MMBtu, the market price for the gas-fired electricity would be significantly lower, and the PTC would likely be an insufficient subsidy.

average incentive would be \$8.40/MWh (0.8¢/kWh), with a total cost of about \$200 million per year.

Higher learning rates would drive down the size of the production incentive. For example, at a 12% learning rate,

- At a market price of \$60/MWh (6¢/kWh), the LEAD and the subsequent five FOAK plants would require a production incentive, with an average incentive level of about \$15/MWh (1.5¢/kWh). Total annual cost (after all plants are in full operation) would be about \$450 million per year.
- At a market price of \$70/MWh (7¢/kWh), the LEAD and three FOAK plants would require a production incentive averaging \$9.00/MWh (0.9¢/kWh, half of the current statutory incentive), with a total annual cost of about \$170 million per year.

The range of costs for the production incentive illustrates the sensitivity of the incentive level to the learning rate and the market price of electricity. Thus, efforts to achieve higher learning rates, including fully optimized engineering designs for the SMRs and the manufacturing plant, as well as specially targeted market introduction opportunities that enable SMRs to sell electricity for higher priced and higher value applications, can have a critical impact on the requirements for production incentives. The potential size of the incentive should be subject to further analysis as higher quality cost estimates become available.

- **Loan Guarantees:** Loan guarantees do not directly impact project capital costs, but guarantees facilitate the ability of the project sponsors to access capital at lower cost. The effect of the guarantee is to broaden the pool of potential equity and debt investors, and thus to lower the WACC of the project. The lower WACC is then reflected in a lower LCOE. Loan guarantees can be particularly effective in mitigating the risk premium typically associated with the financing of FOAK technology deployments. For example, federal loan guarantees are viewed as having a key role in mitigating the risk premium and lowering the WACC early-mover, GW-scale nuclear plants. As discussed earlier, the smaller investment requirements for the first-of-a-kind SMR plant (both the LEAD and one or more early FOAK plants) significantly reduce the risk premium that may otherwise be sought by private equity and debt holders; this reduced risk premium would obviate the need for loan guarantees. Appendix F discusses the relationship between size of investment relative to the size of the sponsor and its potential effect on risk premium. The business case analysis assumes that a robust SMR DD&E effort will mitigate the risk premium sufficiently so that loan guarantees will not be part of the incentive program. However, it is possible that a federal loan guarantee may be appropriate for the LEAD and the FOAK-1 plant.<sup>45</sup>

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<sup>45</sup> The DOE Loan Guarantee Program Office currently has available approximately \$10 billion in uncommitted loan guarantee for new nuclear power generation plants. The statutory language of Title XVII of the Energy Policy Act of 2005, as well as the DOE Part 609 implementing regulations, would allow SMRs to be eligible for this loan guarantee authority. DOE would need to issue a new solicitation for applications, since the initial solicitation for nuclear power plant projects is now closed.

## **6.2 GOVERNMENT SPONSORSHIP OF MARKET TRANSFORMATION INCENTIVES**

Similar to other important energy technologies, such as energy storage and renewables, “market pull” activities coupled with the traditional “technology push” activities would significantly increase the likelihood of timely and successful commercialization.

Market transformation incentives serve two important objectives. They facilitate demand for the off-take of SMR plants, thus reducing market risk and helping to attract private investment without high risk premiums. In addition, if such market transformation opportunities could be targeted to higher price electricity markets or higher value electricity applications, they would significantly reduce the cost of any companion production incentives.

There are three special market opportunities that may provide the additional market pull needed to successfully commercialize SMRs: the federal government, international applications, and the need for replacement of existing coal generation plants.

### **6.2.1 Purchase Power Agreements with Federal Agency Facilities**

Federal facilities could be the initial customer for the output of the LEAD or FOAK SMR plants. The federal government is the largest single consumer of electricity in the U.S., but its use of electricity is widely dispersed geographically and highly fragmented institutionally (i.e., many suppliers and customers). Current federal electricity procurement policies do not encourage aggregation of demand, nor do they allow for agencies to enter into long-term contracts that are “bankable” by suppliers.

President Obama has sought to place federal agencies in the vanguard of efforts to adopt clean energy technologies and reduce greenhouse gas emissions. Executive Order 13514, issued on October 5, 2009, calls for reductions in greenhouse gases by all federal agencies, with DOE establishing a target of a 28% reduction by 2020, including greenhouse gases associated with purchased electricity. SMRs provide one potential option to meet the President’s Executive Order. One or more federal agency facilities that can be cost effectively connected to an SMR plant could agree to contract to purchase the bulk of the power output from a privately developed and financed LEAD plant.<sup>46</sup> A LEAD plant, even without the benefits of learning, could offer electricity to federal facilities at prices competitive with the unsubsidized significant cost of other clean energy technologies.

Table 4 shows that the LCOE estimates for the LEAD and FOAK-1 plants are in the range of the unsubsidized national LCOE estimates for other clean electricity generation technologies (based on the current state of maturity of the other technologies). All of these technologies should

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<sup>46</sup> One idea identified in the course of the study team’s initial study, but not yet assessed, is to utilize the federal agency preference power program of the federal power marketing agencies (PMAs) as a means to market SMR electricity to various federal agency facilities. The federal PMAs market federal hydropower to both government- and customer-owned electricity distributors. The PMAs also market federal hydropower to federal facilities. Expansion of these distribution arrangements to include SMR electricity likely would require legislation.

experience additional learning improvements over time. However, as presented earlier in the learning model analysis, the study team anticipates significantly greater learning improvements in SMR technology that would improve the competitive position of SMRs over time. Additional competitive market opportunities can be identified on a region-specific, technology-specific basis. For example, the Southeast U.S. has limited wind resources. While the region has abundant biomass resources, the estimated unsubsidized cost of biomass electricity is in the range of \$90-130 per MWh (9-13¢/kWh), making LEAD and FOAK plants very competitive (prior to consideration of subsidies).<sup>47</sup>

Competitive pricing is an important, but not the sole, element to successful SMR deployment. A bankable contractual arrangement also is required, and this provides an important opportunity for federal facilities to enter into the necessary purchase power arrangements. However, to provide a “bankable” arrangement to enable the SMR project sponsor to obtain private sector financing, the federal agency purchase agreement may need to provide a guaranteed payment for aggregate

**TABLE 4 Comparison of Estimated Unsubsidized LCOE for Clean Electricity Technologies**

	LCOE	
	\$/MWh	¢/kWh
<b>SMR Technology<sup>a</sup></b>		
SMR LEAD Plant	90	9
SMR FOAK-1	84	8.4
SMR FOAK-4	71	7.1
<b>Clean Technology<sup>b,c</sup></b>		
Wind (On-shore)	90	9
Solar PV	180	18
Solar Thermal	250	25
Biomass	90-180	9-18

- a. The LCOE estimates for clean electricity technology are from the EIA Annual Energy Outlook for 2011 (see [http://www.eia.doe.gov/oiaf/aeo/electricity\\_generation.html](http://www.eia.doe.gov/oiaf/aeo/electricity_generation.html)) and Georgia Institute of Technology, Ivan Allen College School of Public Policy, “Estimates of the Cost of New Electricity Generation in the South,” Working Paper #54, 2010 (see <http://www.spp.gatech.edu/faculty/workingpapers/wp54.pdf>).
- b. SMR LCOE estimates are in 2010\$; other clean electricity LCOE estimates are in 2009\$.
- c. Clean electricity technology LCOE estimates are for commercial deployment in 2016 (the current clean electricity tax credit incentives expire December 31, 2016).

<sup>47</sup> “Estimates of the Cost of New Electricity Generation in the South,” Working Paper #54, Georgia Institute of Technology, Ivan Allen College School of Public Policy, March 26, 2010.

output, regardless of actual generation output.<sup>48</sup> Another challenge is to establish a mechanism to aggregate demand among federal electricity consumers if no single federal facility customer has a large enough demand for the output of an SMR module. The study team believes that high-level federal leadership, such as that exemplified in E.O. 13514, can surmount these challenges and provide critical initial markets for SMR plants.

### 6.2.2 Export Sales of FOAK SMR Plants

Previous studies have documented the potential for a significant export market for U.S. SMRs, mainly in lesser developed countries that do not have the demand or infrastructure to accommodate GW-scale LWRs. Clearly, the economics of SMR deployment depends not only on the cost of SMR modules, but also on the substantial upgrades in all facets of infrastructure requirements, particularly in the safety and security areas, that would have to be made, and as exemplified by the ongoing efforts in this direction by the United Arab Emirates (and, in particular, by Abu Dhabi). This is a substantial undertaking for these less developed countries. Thus, such applications may be an attractive market opportunity for FOAK SMR plants, even if the cost of such plants may not have yet achieved all of the learning benefits.

The Department of Commerce has launched the Civil Nuclear Trade Initiative, which seeks to identify the key trade policy challenges and the most significant commercial opportunities. The Initiative encompasses all aspects of the U.S. nuclear industry, and, as part of this effort, the Department identified 27 countries as “markets of interest” for new nuclear expansion. A recent Commerce Department report identified that “SMRs can be a solution for certain markets that have smaller and less robust electricity grids and limited investment capacity.” Studies performed by Argonne National Laboratory suggest that SMRs would appear to be a feasible power option for countries that have grid capacity of 2,000-3,000 MW. *Exports of SMR technology also could play an important role in furthering non-proliferation policy objectives. The design of SMR nuclear fuel management systems, such as encapsulation of the fuel, may have non-proliferation benefits that merit further assessment. Also, the development of an SMR export industry would be step toward a U.S.-centric, bundled reliable fuel services.*

Exports of FOAK plants help achieve learning without the need for a full array of production incentives required for domestic FOAK deployments. Projected, unsubsidized, electricity market prices will likely be higher in selected foreign markets, particularly when the electricity pricing

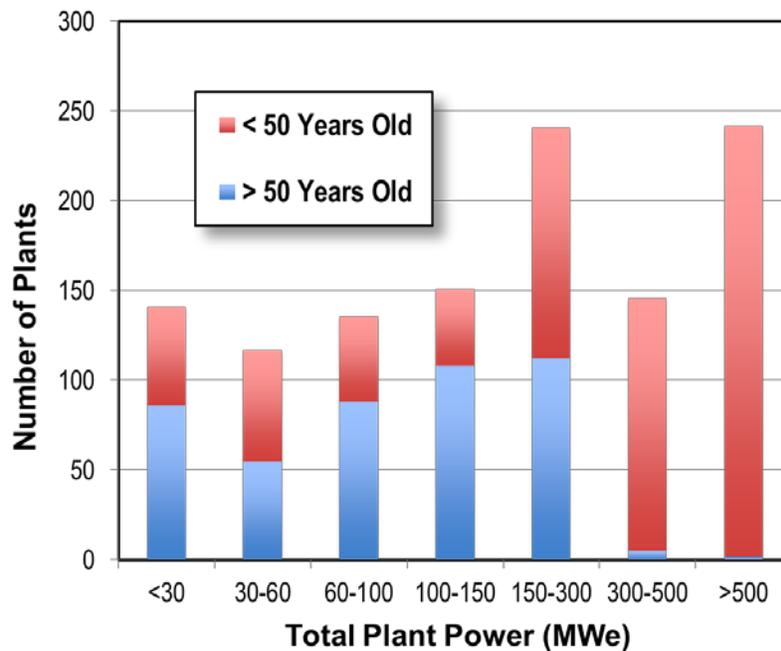
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<sup>48</sup> This arrangement is known as a “take-or-pay” contract and is sometimes employed in energy market transactions as a means to provide certainty in project revenues for purposes of meeting debt repayment obligations. A take-or-pay contract would provide revenue certainty to the SMR project sponsors based on an agreed-upon price and output level. It would shift the risk of production and sales levels from the project sponsor to the federal purchaser. However, it would not shield sponsors from project cost risk in the event that the cost of generation exceeded the levels initially assumed in the price agreement.

is based on liquefied natural gas import prices.<sup>49</sup> This situation would enable SMRs to be in a more favorable competitive position. SMR exports would qualify, if needed, for export credit assistance under current U.S. government programs, but this assistance would not require the need for new federal funding.

### 6.2.3 Opportunities to Mitigate Early Retirements of Coal Fired Generation

The study team anticipates more rigorous environmental constraints on the current fleet of approximately 300 GW of legacy coal-fired generation. Early retirement of legacy coal plants with upwards of 70 GW of capacity is widely expected.<sup>50</sup> These plants are older, smaller (i.e., less than 500 MW), and less energy efficient than most of the existing coal plant fleet. Figure 5 represents the distribution of existing coal-fired power plants by size and age. There are a significant number of older plants (about 200) in the 300 MW class or less that could be candidates for replacement. The alternative of investing in “clean coal” technologies to bring



**FIGURE 5 Distribution of Coal Power Plants by Generation Size and Age (2030)<sup>51</sup>**

<sup>49</sup> Generation costs vary substantially among countries, depending upon availability of indigenous energy resources; generation costs often bear no relationship to retail prices due to government tax and subsidy policies. For example, the price of electricity to industrial customers in Morocco is about \$123 per MWh (12.3¢/kWh), four times the price of \$32 per MWh (3.2¢/kWh) in Egypt. Countries that do not have ample indigenous energy resources and are thus dependent upon imports of fuel or electricity to meet growing electricity demand present good opportunities for SMR FOAK plant deployments.

<sup>50</sup> A compilation estimates of potential early retirements can be found in a Memorandum by the staff of the House Energy and Commerce Subcommittee on Energy and Power, “Hearing on the ‘The American Energy Initiative’,” September 12, 2011.

<sup>51</sup> “SMR Interests and Activities in the United States,” Briefing for Brazil, Craig Welling, Deputy for Advanced Reactor Concepts, Office of Nuclear Energy, Department of Energy.

these (typically 40 years old or more) small coal plants up to the anticipated environmental emission standards is widely considered to be a challenging research, development, and deployment endeavor.<sup>52</sup> Thus, the cost of compliance may make these plants uncompetitive, and many could be retired by 2020.<sup>53</sup>

Analyses by the Federal Energy Regulatory Commission staff<sup>54</sup> and the National Electricity Reliability Corporation<sup>55</sup> point out these early retirements, if forced to occur quickly and without appropriate regional coordination, could increase risk to electricity reliability. Increases in the marginal cost of coal-fired electricity, coupled with the potential risk to reliability, may create opportunities for early deployment of FOAK plants under conditions where the cost premium associated with FOAK plants could be acceptable. If so, the 250-300 MW footprint for a typical older coal-fired plant would be comparable to a replacement SMR plant. Scheduling represents another challenge. The proposed new regulations could lead to retirements in the 2015-2020 timeframe, substantially earlier than the schedule for deployment of FOAK plants. However, at the time of completion of this paper, the U.S. House of Representatives was considering legislation that would extend certain compliance deadlines.<sup>56</sup> *Further analysis of the existing coal fleet would be needed to begin to identify the potential scale and timeframe of the opportunity to replace certain coal-fired plants with SMRs.*

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<sup>52</sup> MIT, *The Future of Coal*, [http://web.mit.edu/coal/The\\_Future\\_of\\_Coal\\_Chapters\\_6-8.pdf](http://web.mit.edu/coal/The_Future_of_Coal_Chapters_6-8.pdf), 2007.

<sup>53</sup> Even if the cost of retrofits is competitive, some companies may decide to pay a premium to replace a coal plant with a SMR FOAK plant as a possible hedge against future carbon prices.

<sup>54</sup> Federal Energy Regulatory Commission, Letter to the Honorable Lisa Murkowski, Ranking Member, Committee on Energy and Natural Resources, August 1, 2011.

<sup>55</sup> National Electricity Reliability Corporation, "2010 Special Reliability Scenario Assessment: Potential Resource Adequacy Impacts of U.S. Environmental Regulations," [http://www.nerc.com/files/EPA\\_Scenario\\_Final.pdf](http://www.nerc.com/files/EPA_Scenario_Final.pdf), 2010.

<sup>56</sup> As an additional incentive, it has been suggested that the EPA allow for extended compliance deadlines in cases where an existing coal-fired power plant would be retired in favor of a FOAK SMR plant.

## 7.0 SMR STRATEGIC BUSINESS PLAN

The study team synthesized the knowledge gained from analysis of the SMR learning process, economics, and market transformation opportunities into a five-stage business model for achieving SMR commercialization. Figure 6 shows a schematic of the model, highlighting the source of financing for each stage. The five stages are discrete and provide DOE stage-gated decision-making opportunities on going forward based on the performance of each preceding stage. Specific performance objectives can be established for each stage to enable policy-makers and private sector stakeholders to assess performance and determine whether continued implementation is justified.

- **Stage 1. Detailed Design and Engineering (DD&E) and Licensing:** This stage encompasses the full range of technical and regulatory work required to achieve NRC approval of SMR designs, site licenses, and preparations to commence site construction. The development of a design certification package for submission to the NRC is the critical component of this effort, but as discussed earlier, the full scope of DD&E activities is much more expansive than preparation of the certified design documents. The study team estimates that the total cost of DD&E for each SMR technology option is up to \$1 billion, including the necessary engineering work to integrate the SMR design with the design of the SMR manufacturing facility. As discussed further in Appendix C, the front-end development costs for bringing SMR technology to the point of initial deployment are relatively large. When judging the ability of the U.S. nuclear vendor community to shoulder the financial risk, the study team found that the size of the SMR investment would be a significant hurdle for these companies. The study team believes that a federal government role to cost share DD&E activities is appropriate. The study team identified four possible LWR-derived SMR designs that appear promising, but has not yet completed sufficient analysis to support a decision on federal support. In view of the current budgetary constraints on federal funding, the study team believes that the federal government can invest its resources most effectively by supporting a competition among multiple SMR technology teams. The competition could be structured in phases, with an early, relatively low-cost phase supporting a larger number of SMR teams, with a subsequent phase (leading to final design and licensing approvals by the NRC) limited to no more than two teams. The down-selection process may become self-selection, as further DD&E reveals the relative differences among the SMR options. The study team believes that the achievement of both the design certification and the combined operating license by at least two design teams is a necessary condition to move ahead to the next stage; comparing at least two designs against one another mitigates the considerable technology risks carried by premature selection.<sup>57</sup> The business plan model assumes that the cost for funding this stage would be shared on a 50-50 basis between the federal government and the SMR vendors. Given current budget constraints, the government could lower its investment by limiting the scope of activities eligible for cost sharing, or reducing the cost share, or both. For example, the costs for detailed engineering,

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<sup>57</sup> "...The U.S. government will have to figure out how to incubate early movers while not locking in one technology prematurely" (Ernest Moniz, "Why We Still Need Nuclear Power," *Foreign Affairs*, November/December 2011).

necessary to support construction planning but not directly needed to support NRC certification, could be excluded; site specific licensing costs, such as the COL, also could be excluded from cost sharing. The business plan does not contain specific recommendations on the scope of included and excluded costs; these decisions are better left to negotiations between the SMR design teams and DOE, based on the available level of federal government funding. In any event, the government also may want to consider placing a firm cap on the level of federal assistance to be provided at this stage. *Success at this stage would be measured on the basis of successful licensing and completion of detailed engineering that meets specific technical and cost targets.*

- **Stage 2. LEAD Commercial Deployment:** Construction of LEAD plants, potentially up to two designs, starting operation in 2020. In the reference case, the study team estimated that the LCOE from the LEAD plant would be in at the high end of the range \$90-100/MWh (9-10¢/kWh), or about 50-60% higher than the \$60/MWh (6.1¢/kWh) NOAK project. The business strategy assumes that this gap can be closed in one of several ways, as described earlier in the paper. One approach is to target the output of the LEAD plant to higher priced clean electricity applications, such as new federal agency purchases of clean electricity under E.O. 13514. This will reduce but may not fully close the gap. The second approach is to provide a production incentive in the form of a production tax credit. The credit would be modeled after the current \$18 per MWh (1.8¢/kWh) incentive available for new renewable energy and GW-scale nuclear power plants, but the actual level would be tailored to the final estimated LCOE for the LEAD plant and the projected residual market gap based on the final off-take arrangements.<sup>58</sup> The study team business model assumes that a LEAD facility is deployed for only one SMR design. However, based on the final outcome of the DD&E work, and the potential market demand at that time, the federal government may wish to consider deploying LEAD plants for two different SMR designs.<sup>59</sup> Depending upon federal budgetary constraints, it may be desirable to deploy LEAD/2 plants, especially if two designs are supported, to reduce the total government costs (both purchase costs for SMR LEAD plant electricity as well as production cost incentives) for this stage of the business model. *Success at this stage would be determined on the basis of the installed cost and performance of the LEAD plant.*
- **Stage 3. SMR Module Manufacturing Capability:** Development of an order book for additional SMR plants (of a single SMR technology) in a sufficient quantity to justify the deployment of an SMR manufacturing plant. Further analysis of the technical design and cash flow at the manufacturing plant is needed to ascertain the capital formation requirements that the manufacturer will have to arrange in order to justify development of the requisite manufacturing plant. The initial analysis suggests that if the vendors, perhaps with government policy encouragement, develop a sufficient order book, it

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<sup>58</sup> The study team's analysis of financial incentives focuses only on possible federal incentives. It is possible that state and local governments, as well as private sector consortium partners, also could provide financial incentives that would improve the financial feasibility of the LEAD (and FOAK) plants.

<sup>59</sup> The study team is of the opinion that federal incentives for FOAK plants, discussed below, should be focused on only one SMR technology, in order to assure that sufficient aggregation of demand necessary to support the SMR fabrication facility is achieved.

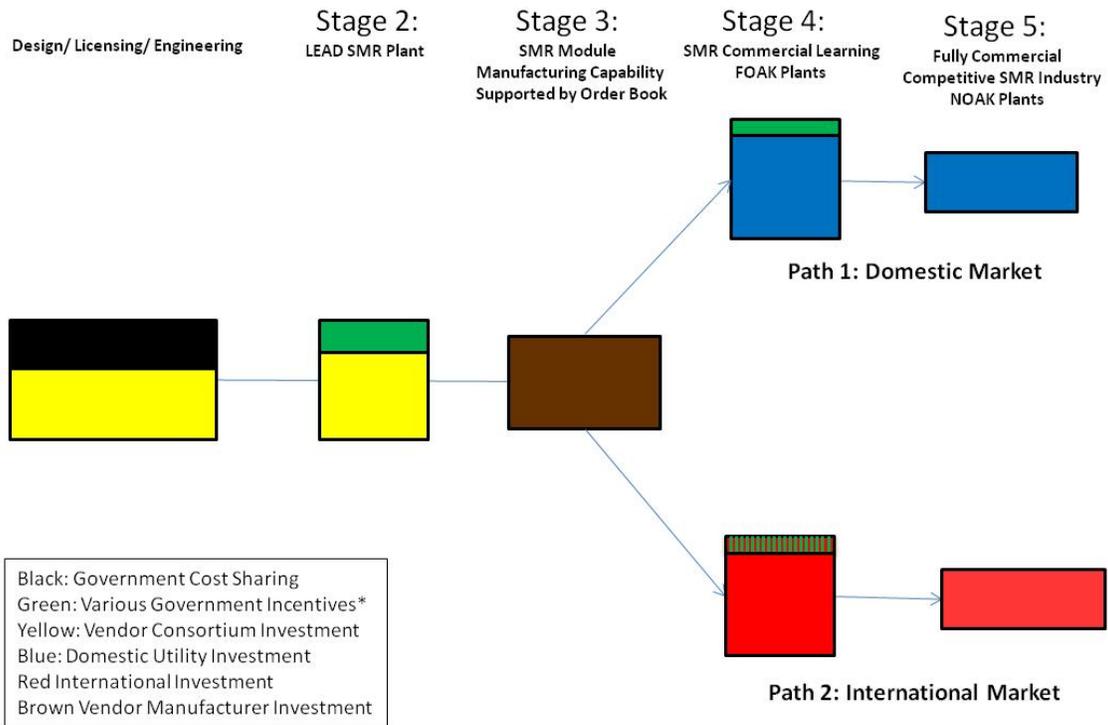
would provide the basis to secure private financing of the manufacturing plant without the need for special federal financial incentives. *Success at this stage would be determined by achievement of an order book sufficient for private investment in the module manufacturing facility.*

- **Stage 4. SMR Commercial Learning:** Deployment of additional SMR plants and modules in sufficient quantity to achieve the benefits of learning in manufacturing. Based on a hypothetical SMR plant configuration (consisting of six 100-MW modules per plant), the study team estimated that up to nine SMR plants (a LEAD plant and up to eight FOAK plants) will be needed to achieve the full benefits of learning, at a 10% learning rate. The present analysis suggests that the estimated LCOE from several of the early FOAK plants would be higher than market competitive costs. As discussed earlier, closing this gap will require some combination of innovative business arrangements, carefully targeted markets, possible federal market transformation efforts (such as clean electricity purchases), and production cost incentives. The size of any production cost incentive would be determined case by case based on learning rate targets and would diminish as FOAK plants move down the learning curve. In the aggregate, the average magnitude of the incentive would be less than the current \$18/MWh (1.8¢/kWh) credit currently available for new renewable and GW-scale nuclear electric generation plants.

The study team believes that perhaps several FOAK plants could be exported for deployment in foreign markets, contributing to the learning process while avoiding the cost of domestic production incentives. Electricity market prices are higher in many countries that may be interested in SMR plants than those in the U.S., creating an opportunity for early FOAK plants to be cost competitive. Any FOAK plants for export would need to be targeted to countries that have established nuclear energy infrastructures and regulatory regimes, particularly in the areas of nuclear safety and nuclear nonproliferation; these infrastructures and regimes would also need to have been reviewed thoroughly by international organizations. The FOAK plants exported to foreign markets might qualify under existing federal export credit assistance programs, especially in instances where U.S. companies are in competition with state-owned or state-aligned enterprises with access to financing on favorable terms.

*Success at this stage would be determined by the actual rate of learning in FOAK modules and the ability to successfully deploy SMR plants within cost, performance, and incentive target levels.*

- **Stage 5. Fully Commercial, Competitive SMR Industry:** Fully commercial SMR industry, competitive with natural gas-fired generation as a base-load generation technology. *If the learning process for the LEAD and FOAK plants is successful in meeting the cost parameters identified in the present analysis, there would be no need for any federal incentives for NOAK plants.* If a price for carbon is established, this would further enhance the competitiveness of NOAK SMR plants relative to fossil fuel generation alternatives.



\*Potential incentives could include production tax credits, purchase power agreements and export credit assistance.

**FIGURE 6 Five-Stage Business Model Identifying Investors and Relative Contributions**

## **8.0 CONCLUSIONS CONCERNING LICENSING, ECONOMICS, AND BUSINESS CASE**

Based on its work to date, the study team drew the following conclusions with respect to the licensing, economics, and business case for SMRs.

### **8.1 LICENSING, DESIGN, AND ENGINEERING**

- There appears to be a consensus that the current GW-LWR licensing framework – design certification (DC), early site permit (ESP), and combined construction and operating license (COL) – should be adaptable to SMRs. The process to adapt the current regulations and guidelines is in the planning stage, so the magnitude of the challenges has yet to be fully defined. Also, to streamline the licensing reviews, the applicable industry codes and standards will need to be updated and expanded to consider the benefits of modular construction practices, potentially different operating conditions, and changes in safety and security requirements.
- Cost estimate targets announced by SMR vendors are based on several important assumptions regarding the regulatory framework that will be used by the NRC to approve SMR designs and licenses. Consequently, the vendor technical and cost assumptions are subject to uncertainty and could change based on the outcome of the NRC process. A significant amount of effort is underway to resolve SMR licensing issues. The NRC staff, the American Nuclear Society (ANS), the Nuclear Energy Institute (NEI), and others have been analyzing the current licensing structure for GW-LWRs (i.e., DC, ESP, and COL) to identify issues and alternatives for adapting this licensing framework to SMRs. The previous work by the NRC staff on the Next Generation Nuclear Plant (NGNP) and other Generation-IV (Gen-IV) initiatives is serving as a forerunner for SMR licensing discussions.
- There currently are differing views among SMR vendors as to the most efficient and effective process for licensing initial SMR plants. One SMR vendor (NuScale) apparently supports an approach to initiate the DC and COL process under the current Part 52 NRC regulations, and then to identify and address issues requiring variances or waivers as they emerge from the review process. Another SMR team, Tennessee Valley Authority (TVA) and mPower, has proposed to the NRC that the initial SMR plant be licensed under the Part 50 two-part licensing framework with a separate construction permit and operating license. Deployment of additional SMRs would be licensed under the Part 52 DC/COL framework. Each of these design teams assert that their approach is the more cost-effective; given the iterative nature of the detailed design and engineering effort, the most important factor is early decision by the NRC on key safety approaches when assessing which is more cost effective. The sooner that firm design specifications are established, the more likely the overall costs for a family of standardized SMRs can be minimized.

- The current state of the licensing framework for SMRs is less mature than that in place for GW-LWRs at the time of initiation of the NP2010 program. At that time, the NRC licensing process was fully developed on paper, and the objective of the program was to demonstrate the process through the development of lead COL applications. As a consequence, there remain considerable uncertainties regarding the economic impact of the licensing process, especially in regard to the next three points.
- Additional licensing issues may arise as SMR design and license applications are further developed. Although the ANS, NEI, and NRC efforts have developed systematic inventories of SMR licensing issues, SMR engineering design efforts are at a very early stage, and new issues may arise. The precise level of engineering design is “business proprietary.” Based on informal discussions with SMR industry representatives, the study team believes that current SMR designs are very preliminary in their evolution (i.e., less than 20% complete). By comparison, engineering design for GW-scale Gen III+ reactors was estimated to be about 30% complete at the time of submission of design certification applications to the NRC. Even at this level, NP2010 participants advised the study team that the review process for NRC design certification would have been more efficient if additional engineering had been completed prior to submission of DC applications to the NRC.
- Uncertainties in the regulatory process could lead to delays in the schedule for final action on design certification and site licensing. Regulatory uncertainty is a significant government risk to SMR developers. The NRC staff process to resolve licensing issues has its own schedule risk, and the outcomes are uncertain.
- *The SMR cost estimates discussed in Section 5 assume favorable NRC approvals of a number of innovative design concepts, including consolidated operator control rooms, alternative approaches to physical security and aircraft impact mitigation, below-ground pool storage of spent fuel, and a smaller source term. These innovative concepts attempt to meet or exceed NRC requirements for GW-scale plants in a more cost-effective manner without diminishing safety and security risks. However, the NRC ultimately must make this determination. If these innovative features are not adopted, SMR cost estimates will be higher than given below.*

## 8.2 ECONOMICS

- The economics for SMRs directly challenges two of the well-established pillars of large LWRs: the economies of scale and the economies of large nuclear fleet operations (i.e., large skilled workforce at each plant site). The SMR community postulates an alternative cost model based on the “economies of mass manufacturing.” The key aspect of this concept is that significant cost savings can be realized through more productive use of highly skilled craft labor in the manufacture of the SMR modules and portions of the nuclear island. The labor cost savings are achievable through fabrication of the modules in manufacturing plants combined with the potential to achieve significant productivity

improvements through “learning by doing” in the manufacturing of a large number of reactor modules.

- The favorability of SMR economics is strongly dependent on the degree of cost savings achievable through off-site factory manufacturing of the reactors and the subsequent learning-by-doing achieved after production of multiple modules. This phenomenon has been well demonstrated in a variety of manufacturing enterprises, including shipbuilding, and initial analysis suggests that this type of learning experience is applicable to the manufacturing of SMR modules. In addition, the shipbuilding experience also shows that achievement of significant cost savings in the manufacturing process could require additional upfront investment in engineering to improve the ease of manufacturing of the design. The economics of the manufacturing learning process is addressed in more detail in Appendix C.2. Based on this experience, the study team believes that a more robust DD&E effort can improve the economics of SMR manufacturing through more cost-efficient design enhancements. The achievement of a high learning rate is a key precursor to a viable SMR industry. The study team is planning to perform additional research in this area.
- U.S. SMR vendors have privately financed the initial stages of SMR design and licensing studies without direct federal assistance. As the level of design, licensing, and engineering activity increases, it is not clear whether the SMR vendors will be able to continue to garner the private sector investment capital needed to bring initial commercial SMR plants into the market in the 2020 timeframe. While the market potential for SMRs is significant (as discussed in Section 8.3), the size of the upfront capital investment relative to the financial capabilities of the nascent SMR industry is challenging. *To put the financial challenge into perspective, the cost for commercialization of an SMR technology is about the same as the cost to bring a new pharmaceutical to market, but for a large drug company such as Pfizer or Merck, this represents less than 1% of market capitalization, while for an “illustrative SMR vendor” (see Table C.1), this represents 30% of its market capitalization – posing a significant financial barrier.* Additional data are presented in Appendix C.
- SMR technology has certain attributes that are attractive to venture capital investment, including the potentially disruptive nature of the technology and the possibility of initial commercial deployment within 10 years. Significant economic returns on investment, however, depend upon the rate of market penetration, are probably two decades away, and are subject to significant uncertainties, such as the potential impact of licensing on cost and schedule. Third party financing, such as venture capital, may be inadequate to support SMR technology development through full commercialization.
- SMR customers, e.g., the electric power generation companies, while interested in SMR deployment, have limited incentive to invest in SMR technology development activities. Regulated utilities are restricted by State Commissions in their ability to recover R&D costs in customer rates, and merchant generators in competitive markets are subject to strong competitive market pressures to minimize costs. In sum, the higher costs

associated with the LEAD and FOAK SMR plants may discourage potential “first movers.”

- The uncertainty over possible future carbon pricing also poses a challenge to private investment in SMR commercialization. A price per ton on carbon production would provide economic incentive for the deployment of all forms of carbon-free generation technology, but the prospect for enactment of a national policy of carbon reduction is highly uncertain.<sup>60</sup>
- Successful commercialization of SMRs will require not merely a successful prototype deployment, but also the development of an “order book” for an initial commercial deployment program. *An “order book” of a substantial number of modules will be needed to support the private sector investment in module manufacturing facilities so that SMR vendors can manufacture sufficient modules to realize the benefits of learning.*<sup>61</sup> Thus, the traditional energy technology commercialization strategy of building a one-of-a-kind demonstration is necessary but not sufficient: it must be closely linked to a follow-on “order book” for additional SMRs in order to lead to a commercially viable NOAK SMR cost structure.
- Because of the significant role of learning in SMR commercialization, there are significant disincentives to be an “early mover.” “Late adopters” can garner the benefits of the learning experience of early movers. Absent a government role, there is no market mechanism to align risks and benefits between the early movers and the late adopters.
- Successful commercialization of SMRs will require a “level playing field” in terms of federal financial incentives relative to other clean energy generation technologies. Wind and solar energy currently qualify for a production tax credit (PTC), which can be converted into either an investment tax credit (ITC), or monetized in the form of a cash grant from the U.S. Treasury.<sup>62</sup> Large commercial LWRs also can qualify for a PTC, which is capped at 6,000 MW of capacity. Early SMR deployments (LEAD or FOAK plants) potentially could meet the statutory 2021 commercial operations date (COD) to

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<sup>60</sup> According to John Rowe, “Absent a carbon price of at least \$25 per ton, natural gas combined cycle (NGCC) generation would be a more attractive generation option than new nuclear (at natural gas prices below \$8 per thousand cubic feet),” <http://pacevirginia.org/2010/09/14/exelons-rowe-says-gas-prices-may-slow-new-reactors>, 2010.

<sup>61</sup> The DD&E cost estimate of \$1 billion per SMR technology includes an allowance for design studies of an SMR module manufacturing facility, including some analysis of the technical and cost integration issues between the SMR module design and manufacturability issues. The study team did not conduct an analysis of the cost to outfit an SMR module manufacturing facility. Based on general discussions with potential manufacturers and rough parametric approaches, the study team “guesstimated” that the cost for outfitting an SMR factory may be on the order of \$300 million. Further analysis is planned as part of the follow-on work to enhance the analysis of the learning model.

<sup>62</sup> To be eligible for the cash grant, a project must initiate construction by December 31, 2011.

qualify for the existing PTC, but would not otherwise meet the current Department of Treasury administrative criteria, including the 2014 date for start of construction.<sup>63</sup>

- Acceleration of SMR deployment activities to serve national energy policies will require government incentives. Absent government incentives, there is no assurance that current privately funded efforts will be carried to fruition, and even if so, on what schedule.
- *The events at the Fukushima nuclear plant in the aftermath of the March 2011 Japanese earthquake, while not yet fully assessed, may prove to be a mixed blessing for SMRs. On the one hand, the experience at Fukushima could underscore the benefits of SMR technology: smaller source terms, easier decay heat removal, passive cooling, and below-grade construction. On the other hand, heightened public concerns about nuclear safety in general could be a disincentive for private capital investment in SMR development.*

### 8.3 MARKET TRANSFORMATION ISSUES

- “Market pull” can supplement the traditional “technology push” in a manner that significantly increases the likelihood of timely and successful commercialization. There are three special market opportunities that may provide the additional market pull needed to successfully commercialize SMRs: availability of federal government support and incentives, international applications, and replacement of existing coal generation plants.
- The federal government is the largest single consumer of electricity in the U.S. economy, but its usage is widely dispersed geographically and highly fragmented institutionally (i.e., many suppliers and customers). Current federal electricity procurement policies do not encourage aggregation of demand, nor do they allow for agencies to enter into long-term contracts that are “bankable” by suppliers.
- The size of an SMR may limit the number of federal agency facilities that could fully utilize its power output. In addition, operational considerations may suggest the need for a portfolio of generating plants, further limiting direct SMR deployments for federal plants. Aggregating electricity demand from multiple federal facilities offers greater opportunities, but the desirability of pursuing this approach may be tempered by the challenges of federal electricity procurement practices.
- The Department of Commerce has recently reported the potential for a significant export market for U.S. SMRs, mainly in lesser developed countries that do not have the demand

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<sup>63</sup> In addition to tax incentives, all technologies are also eligible to receive federal loan guarantees under the Title XVII loan guarantee program of the DOE. SMRs likely would qualify as an “innovative technology” under Title XVII, but this would require DOE to issue a solicitation for SMR projects and set aside a specific amount of loan guarantee authority for this purpose (which is not currently budgeted).

or infrastructure to accommodate GW-LWRs.<sup>64</sup> Countries will be making decisions on new capacity additions over the next two decades. A concerted U.S. SMR export initiative, perhaps combined with an international nuclear fuel assurance program, could create additional opportunities for early deployment of FOAK SMR plants.

- SMRs have the potential to replace existing coal generation that may be retired in light of pending environmental regulations. Several industry studies indicate the potential for retirements of up to 70 GW of existing coal generation plants in the U.S. These plants are old, small (i.e., less than 500 MW), and energy inefficient. They also lack the environmental controls needed to meet emerging requirements for air quality, water quality, and coal ash management. Many of these plants could be retired by 2020. Current regulatory proposals would require utilities to make planning decisions on replacement capacity in the next few years, lending further impetus to the need for a robust SMR commercialization effort. The study team plans to further investigate the potential for SMR deployment as a Clean Air Act compliance strategy in follow-up work.

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<sup>64</sup> U.S. Department of Commerce, “The Commercial Outlook for U.S. Small Modular Nuclear Reactors,” <http://trade.gov/publications/pdfs/the-commercial-outlook-for-us-small-modular-nuclear-reactors.pdf>, February, 2011.

## 9.0 FINAL THOUGHTS AND FUTURE WORK

Clearly, a robust U.S. commercial SMR industry is highly advantageous to many sectors in the United States. It would be a huge stimulus for high-valued job growth, restore U.S. leadership in nuclear reactor technology, and, most importantly, strengthen U.S. leadership in a post-Fukushima world, on matters of nuclear safety, nuclear security, nonproliferation, and nuclear waste management.

*The ability to manufacture at scale a series of SMRs is a critical step to demonstrate the commercial viability. As such, the study team is expanding the research described in this paper to analyze further SMR-product architecture. The upcoming research will address the learning issue, focusing on (1) standardization of the design and the related codes and standards, (2) regulatory standardization, (3) component standardization, (4) standardized operations and maintenance practices, and (5) standardized project management.<sup>65</sup> New approaches in industrial modeling applicable to modularization practices will also be analyzed in this research.<sup>66,67</sup>*

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<sup>65</sup> Karl Ulrich, “The Role of Product Architecture in the Manufacturing Firm,” *Research Policy*, **24**: 419-440, 1995. See <http://opim.wharton.upenn.edu/~ulrich/documents/ulrich-architecture.pdf>.

<sup>66</sup> E. Hong and G. Park, “Modular Design Method using the Independence Axiom and Design Structure Matrix in the Conceptual and Detailed Design Stage,” *Proceedings of ICAD2011 Sixth International Conference on Axiomatic Design*, Daejeon, March 30-31, 2011, <http://designweek2011.kaist.ac.kr/icad/Proceedings%20of%20the%206th%20ICAD/ICAD-2011-Paper19-Hong-and-Park.pdf>.

<sup>67</sup> A. Tripathy and S. D. Eppinger, “Organizing Global Product Development for Complex Engineered Systems,” *IEEE Trans. Eng. Manage.*, **58** (3), [http://web.mit.edu/eppinger/www/pdf/Tripathy\\_IEEE\\_GPD\\_2011.pdf](http://web.mit.edu/eppinger/www/pdf/Tripathy_IEEE_GPD_2011.pdf), August 2011.

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## APPENDIX A: ALTERNATIVE SMR TECHNOLOGIES

SMRs refer generically to a wide variety of reactor technologies and nuclear fuels. The alternative SMR technologies, organized both by reactor technology and by coolant, are listed in Table A.1. Of these options, the SMRs based on LWR technology, using uranium oxide fuels, are considered ready for commercialization at the time of publication of this paper. These are the NuScale, Babcock & Wilcox (B&W), Westinghouse, and Holtec designs.

For purposes of the present analysis, the study team assumed that additional R&D is not necessary to support licensing and commercialization of the integral LWR SMRs. As with any technology though, additional R&D efforts, such as simulation and modeling, could result in further enhancements to the designs to improve performance or reduce costs.

**TABLE A.1 Types of Small and Modular Reactor Technologies**

<p><b>Integral Light Water Reactors (LWR)</b></p> <ul style="list-style-type: none"> <li>○ Babcock &amp; Wilcox – mPower Reactor (160 MW)</li> <li>○ NuScale Power Inc. – NuScale Reactor (45 MW)</li> <li>○ Westinghouse – AP 1000 derived SMR (200 MW)</li> <li>○ Holtec – Inherently Safe Modular Underground Reactor (HI-SMUR 140) (140 MW)</li> </ul>
<p><b>High Temperature Gas-Cooled Reactors</b></p> <ul style="list-style-type: none"> <li>○ AREVA – Antares</li> <li>○ General Atomics – Gas Turbine Modular Helium Reactor (GT-MHR)</li> <li>○ Pebble Bed Modular Reactor Ltd. – Pebble Bed Modular Reactor (PBMR)</li> </ul>
<p><b>Liquid Metal-Cooled and Fast Reactor</b></p> <ul style="list-style-type: none"> <li>○ GE Hitachi – Nuclear Power Reactor Innovative Small Module (PRISM) (311 MW)</li> <li>○ Hyperion Power Generation – Hyperion Power Module (HPG) (70 MW)</li> <li>○ Toshiba – Toshiba 4S (Super Small, Safe and Simple) (10 MW)</li> </ul>

The other SMR technologies are less mature and may require additional R&D and testing. While the more advanced technologies may offer potential advantages over integral LWRs, these advantages are largely on paper. This should not be a reason to delay commercialization of the integral LWR SMRs. As Admiral Rickover pointed out, there are significant differences between an existing reactor design and one that exists only on paper.<sup>68</sup>

<sup>68</sup> On June 5, 1953 Admiral Rickover wrote a memorandum describing the differences between academic and practical reactor concepts. He wrote that: “An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built quickly. (6) It is very flexible in purpose (‘omnibus reactor’). (7) Very little development is required. It will use mostly ‘off-the-shelf’ components. (8) The reactor is in the study phase. It is not being built now. On the other hand, a practical reactor plant can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem. (4) It is very expensive. (5) It takes a long time to build because of the engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated.”

The major design characteristics of the B&W mPower and NuScale SMR technologies are illustrated in Table A.2. Full details of the Westinghouse and Holtec concepts are not currently available.

**TABLE A.2 Design Characteristics of Two Alternative LWR SMRs**

	<b>mPower (B&amp;W)</b>	<b>NuScale</b>	<b>Assumptions for Hypothetical Learning Model</b>
Module Size	160 MW	45 MW	100 MW
Modules per Plant	2 minimum (4 full)	6 minimum (12 full)	6 (Full)
Fully Built-out Plant	320-640 MW	270-540 MW	600 MW

## **APPENDIX B: LICENSING AND DESIGN ISSUES**

### **B.1 INTRODUCTION**

The framework for SMR licensing is evolving. There are a number of licensing issues, including potential permutations and combinations of changes in the licensing framework and process. The key challenge is that significant changes will be needed in the NRC licensing process, and that a major effort, on an accelerated schedule, is needed to meet this challenge.

On September 1, 2010, the NRC announced an initiative for the staff to produce a plan within six months using risk insights into pre-application activities and the potential review of SMR applications. This announcement has the potential to begin the transformation.

In this section, the discussion of licensing issues is divided into two parts: (1) a brief discussion of the substantive licensing issues, followed by (2) a discussion of process issues for how a new licensing regime can be established.

### **B.2 LICENSING ISSUES**

#### **B.2.1 Inventory of Licensing Issues**

The NRC staff work on SMR licensing issues has been underway since 2008. The impetus for the NRC process was the need to develop a licensing framework for the proposed Next Generation Nuclear Plant (NGNP), but the NRC staff established a broader scope to address all types of advanced reactors. While this broader scope allows the NRC to apply the lessons learned from addressing NGNP issues to SMRs, it also may restrict the ability of the NRC staff to view SMR licensing issues from the perspective of business planning attributes unique to SMRs.

An ongoing dialogue between the SMR vendors and the NRC staff over the past two years has resulted in a list of issues where there is consensus on the need for new or modified licensing requirements as they pertain to SMRs. This list was codified in SECY 10-0034 (NRC 2010), which was adopted by the Commission on March 28, 2010.

The Electric Power Research Institute (EPRI) also has been involved in identifying issues from the perspective of the nuclear operating utilities. EPRI initially developed a Utility Requirements Document, followed by the establishment of a Technical Advisory Group of SMR stakeholders. EPRI is in the process of developing technical papers on a series of topics such as fuel qualification; mechanistic source term; licensing bases event selection; classification of structures, systems, and components; and high temperature materials.<sup>69</sup>

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<sup>69</sup> Presentation by Tom J. Mulford, "EPRI Advanced Nuclear Technology Program Activities Related to SMRs," at the NRC Regulatory Information Conference, 2010.

Recognizing "...the potential for SMRs to change the social and energy supply paradigms," the American Nuclear Society (ANS), under the direction of ANS President Tom Sanders, established the President's Special Committee on SMR Generic Licensing Issues. The Committee issued its interim report in July 2010, and the white papers contained in that report covered the same topical areas as the NRC staff agenda.<sup>70</sup>

Finally, the Nuclear Energy Institute (NEI) formed an SMR working group that will be developing its own white papers for consideration by the NRC staff. The NEI agenda is similar to the NRC staff and ANS agendas.

Thus, the inventory and scope of licensing issues currently appear to be well-defined. The list can be categorized as general process issues, engineering design issues, and operational issues affecting design and financial issues. An annotated list of the SMR issues is provided in Table B.1.

### **B.2.2 Licensing Basis**

A key determinant of the licensing process is the licensing basis. The NRC generally relies upon a deterministic basis, although there has been an ongoing debate about incorporating risk-informed and probabilistic risk assessment approaches. The NRC has not formally indicated the licensing basis that will be used for SMR licensing.

In the development of the licensing strategy for the NGNP, the NRC concluded that the "...best approach to establish the licensing and safety basis for the NGNP will be to develop a risk-informed and performance-based technical approach that adapts existing NRC LWR technical licensing requirements in establishing NGNP design-specific technical licensing requirements. This approach uses deterministic engineering judgment and analysis, complemented by probabilistic risk assessment (PRA) information and insights, to establish the NGNP licensing basis and requirements."<sup>71</sup>

The NRC SECY document notes that the staff plans to follow a similar approach to review design and license applications for integral PWR SMR designs as recommended for the NGNP. However, the SECY document indicates that the NRC does plan to be reactive rather than proactive. Specifically, with respect to the use of PRA, the staff concludes that "...resolution of this issued need not occur until after design or licensing applications are submitted that propose a review approach be used by the NRC staff that places greater emphasis on a design-specific PRA to establish the licensing basis and requirements."

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<sup>70</sup> The ANS White Papers can be found at <http://www.ans.org/pi/smr/ans-smr-report.pdf>.

<sup>71</sup> Nuclear Regulatory Commission, *Next Generation Nuclear Plant Licensing Strategy: A Report to Congress*, August 2008.

**TABLE B.1 Summary Comparison of SMR Licensing Issues**

<b>NRC Staff (SECY-10-0034)</b>	<b>ANS</b>	<b>NEI</b>
<b>Framework and Process Issues</b>		
Manufacturing licenses (FY 2013 or beyond)	Manufacturing Licenses	N/A
License structure for multi-module plants (FY 2013 or beyond)	Applicability of LWR licensing to SMR licenses	Modularity (Q4 2010)
N/A	N/A	Form and content of application (Q4 2010)
Licenses for prototype reactors (FY 2013 or beyond)	N/A	N/A
<b>General Design Issues</b>		
Use of probabilistic risk assessment (FY 2013 or later)	Risk informed and performance-based regulation	Risk metrics (Q4 2011)
Defense-in-depth (FY 2011)	N/A	Defense-in-depth (Q4 2011)
Source term, dose, and siting (FY 2011)	N/A	N/A
N/A	Incorporation of process of inspection, tests, analyses, and acceptance criteria into operating licenses and manufacturing plants	N/A
<b>Specific Technical Design Issues</b>		
Key component and system design issues: <ul style="list-style-type: none"> <li>• Core composition and source term</li> <li>• Accident selection</li> <li>• Redundancy of passive residual heat removal system</li> <li>• Classification of structures, systems, and components</li> <li>• Containment functional capability for SMRs</li> </ul>	N/A	N/A
<b>NRC Staff (SECY-10-0034)</b>		
<b>Operational Issues</b>		
Security and safeguards (FY 2011)	Security and safeguards (FY 2011)	Security and safeguards (FY 2011)
Emergency planning (FY 2012 or beyond)	Emergency planning (FY 2012 or beyond)	Emergency planning (FY 2012 or beyond)
Installation of reactor modules during operation of multi-module plants (FY 2013 or beyond)	Installation of reactor modules during operation of multi-module plants (FY 2013 or beyond)	Installation of reactor modules during operation of multi-module plants (FY 2013 or beyond)
<b>Financial Issues</b>		
Annual fees (FY 2011)	Annual fees (FY 2011)	Annual fees (FY 2011)
Insurance and liability (FY 2011)	Insurance and liability (FY 2011)	Insurance and liability (FY 2011)
Decommissioning funding (FY 2013 or later)	Decommissioning funding (FY 2013 or later)	Decommissioning funding (FY 2013 or later)
<b>Other</b>		
Industrial plants using nuclear-generated process heat (FY2013 or beyond)	Industrial plants using nuclear-generated process heat (FY2013 or beyond)	Industrial plants using nuclear-generated process heat (FY2013 or beyond)

### **B.2.3 Design Certification (DC)**

Currently, each reactor vendor has the ability to petition the NRC for a rulemaking to obtain a DC rule that addresses the criteria necessary for design and construction of the plant. Once a DC rule is issued, each project sponsor seeking a license can reference the DC rule, and would be subject to acceptance criteria [or Inspection, Tests, Analyses and Acceptance Criteria (ITAAC)] to demonstrate that the plant has been constructed and will operate in conformance with the DC. The NRC staff assumes that the current DC regulatory process will be retained, with modifications to design requirements and ITAAC appropriate to SMRs.

The two lead SMR vendors are currently preparing DC documents for submittal to the NRC in 2012 for certification under the DC process. Since SMR commercialization efforts are being driven by the reactor vendors, it would appear that early DC would be a key milestone in the commercialization process.

However, there are several alternative approaches to DC. One of the recent ANS white papers proposed an alternative structure, which is to license the SMR manufacturing plant instead. The paper recommended that the manufacturing license (ML) "...with or without a standard design approval, should enable small modular reactor vendors to file one application that approves the reactor design, as alternate to a Design Certification (DC), and permits manufacture and transport of the reactor to a licensed site anywhere in the U.S., with separate export licenses required for export overseas."<sup>72</sup> The NRC SECY document acknowledges that the MLs could be incorporated into the SMR licensing regime, but appears to downplay this regulatory structure in favor of reliance on the existing structure and process for DC and combined construction and operating license (COL).

Another alternative would be a developer-led process that would emphasize early development and submittal of a COL application (COLA), with the DC lagging the COL process. However, this scenario might be appropriate only if the SMR commercialization effort was led by the host utility seeking to deploy an SMR.

### **B.2.4 Licensing**

The NRC staff currently sees the 10 CFR Part 52 COL as the framework for dealing with the inventory of SMR licensing issues. The concept of a COL for new large LWRs was first recommended in 1986 and has been the focus of NRC regulatory development for two decades. The NRC staff believes that the utility industry is familiar with and supports this framework, so it makes sense to adapt the Part 52 requirements as necessary to SMRs.

Some in industry, led by TVA, believe that it would be better to license SMRs under 10 CFR Part 50, which would require a two-part licensing framework: a construction permit (CP), followed by an operating license (OL). This framework could enable a quicker start on SMR

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<sup>72</sup> American Nuclear Society, "Utilization of NRC Manufacturing License for Small Modular Reactors," in *Interim Report of the American Nuclear Society President's Special Committee on Small and Medium Sized Reactor (SMR) Generic Licensing Issues*, July 2010.

construction, since the requirements for a CP are relatively limited. The more difficult issues would be addressed in the OL process, which would provide the NRC and industry additional time to resolve while the first wave of SMR plants is constructed. The OL process also would benefit from the experience gained during design and construction of the initial SMR deployments. The experience with the initial CP/OL framework could subsequently be transferred to a COL structure. However, utilizing a two-part licensing process, as was the case with the initial round of commercial nuclear power plant deployments, poses a significant risk to the project sponsor that the plant could be constructed and not operated, if for any reason it is not successful in obtaining an OL.

While use of the 10 CFR Part 50 process may lead to an earlier start for the first SMR plant, it is likely not the most efficient process to sustain widespread commercialization of SMRs over the longer term. So, even if the initial TVA-sponsored SMR is licensed under 10 CFR Part 50, it is likely that the experience from the initial licensing effort ultimately will be transferred to the Part 52 process.

#### ***B.2.4.1 Generic Regulatory Modifications vs. Case-by-Case Exemptions***

The NRC SECY document and the ANS issue papers highlight different approaches to implementing the SMR regulatory modifications.

The NRC SECY document implies that the various SMR licensing issues will be resolved through the technical paper process, leading to NRC actions to modify requirements so that SMRs can proceed through the normal 10 CFR Part 52 DC/COL process with the benefit of modified requirements. In many cases, adoption of the changes in requirements would require NRC rulemakings. Others could potentially be implemented informally, such as through the issuance of new regulatory guides (RGs).

The ANS papers note that SMR vendors and project sponsors may need to request exemptions to existing requirements as the vehicle to achieve changes in NRC licensing requirements. Both the Part 50 two-part license and the Part 52 COL process allow for project-specific exemptions.<sup>73</sup> Presumably, exemptions granted for the initial SMR deployments would become precedent for all subsequent projects.

A variant on this approach would be for the NRC to adopt a modified exemption process specifically for SMR licensing issues that would facilitate the review and adoption of exemptions in SMR licensing. Another variant would be a hybrid approach that would allow for case-by-case exemptions to be considered by the NRC in parallel with permanent changes in NRC regulatory requirements. These variants would likely allow for earlier licensing for the initial SMR deployments, because they would not be dependent upon the schedule for formal regulatory modifications.

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<sup>73</sup> The exemption process is discussed in the ANS report, “Applicability of the NRC Light Water Reactor Licensing Process to SMRs,” in *Interim Report of the American Nuclear Society President’s Special Committee on Small and Medium Sized Reactor (SMR) Generic License Issues*, July 2010.

Another possibility would be the concept of a risk-informed and performance-based licensing process defined through a joint applicant-NRC licensing review basis (LRB) document. The LRB has been proposed as "...an interim means for conducting risk-informed and performance-based SMR design review that is consistent with both the industry's targeted development timeframes and the NRC's regulatory goals."<sup>74</sup>

#### ***B.2.4.2 Setting Priorities and Schedule for Implementation of Licensing Process Modifications***

The NRC staff planning process for resolving SMR licensing issues appears to be transparent and methodical, with provision for participation by interested parties. However, a more focused, prioritized, and accelerated process likely will be needed to achieve the goal of a commercial U.S. SMR industry in the 2020 timeframe.

For example, by seeking to address a very broad scope of issues affecting not only SMRs but also other advanced reactors, the NRC staff may not be able to give appropriate attention or priority to those issues of greatest importance to near-term SMR commercialization. In addition, the proposed sequencing of the white papers does not reflect any specific set of regulatory or SMR business priorities. Finally, the NRC staff plans would defer consideration of SMR issues affecting engineering design and economics, such as off-site emergency planning, decommissioning funding, and use of probabilistic risk assessment, until the stage of project-specific COLAs. Another key SMR licensing issue, namely, the determination of the need for and value of licensing an SMR manufacturing plant, would be postponed until FY 2013 or later.

The current NRC staff schedule would not permit full resolution of the inventory of SMR licensing issues in a timeframe to support SMR vendor development schedules. For example, both SMR vendors anticipate submitting DC documents to the NRC late in 2013, with the submission of COLAs as early as 2013. Preparation of NRC staff white papers in FY 2010 or FY 2013 would not provide the needed guidance to the vendors on a timely basis. Thus, meeting the objectives set forth in this strategic business plan will require some combination of an accelerated schedule, and a modified process that, as described above, will allow for case-by-case exemptions absent new regulations and guidance.

#### ***B.2.4.3 Detailed Design and Engineering (DD&E) Issues***

The key pacing element is the rate at which SMR engineering design is completed and ready to move to construction. While DC documentation is an important milestone from the perspective of licensing, the completion of the engineering design is the critical milestone to attract customers and move to construction. Here, the term "detailed design and engineering" (DD&E) is used in a broad context (see [Key Definitions](#) section), since there are no sharp boundaries between what constitutes a design certification package that forms the basis for NRC regulatory

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<sup>74</sup> This concept is discussed in the ANS report, "Risk-Informed and Performance-Based Licensing for SMRs," in *Interim Report of the American Nuclear Society President's Special Committee on Small and Medium Sized Reactor (SMR) Generic License Issues*, July 2010.

approvals and the detailed engineering package that forms the basis for construction bid packages. The SMR vendors have indicated that the pace of the engineering design (or DD&E) process was funding constrained. DOE can accelerate this effort and provide a measure of assurance to the SMR market through a cost-shared program

Accelerating SMR DD&E efforts will provide a higher confidence factor to prospective customers on the cost, performance, and schedule parameters of SMRs. One of the principal factors contributing to cost growth in the initial round of nuclear builds was the tendency of utilities and their vendors to initiate construction before detailed engineering was completed.<sup>75</sup> The lessons from this experience were unfortunately not accounted for in the AREVA Olkiluoto 3 project.<sup>76</sup> The DOE Loan Guarantee Program Office is now working to ensure that substantial completion of detailed engineering will be a prerequisite (or condition precedent) for initiation of construction of any new GW-scale LWR project supported with a DOE Title XVII loan guarantee.

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<sup>75</sup> For a further discussion of the factors contributing to cost growth in the initial round of new commercial nuclear power plant construction, see the NEI report, *Credit Subsidy Costs for New Nuclear Power Projects Receiving Department of Energy (DOE) Loan Guarantees: An Analysis of DOE's Methodology and Major Assumptions*, September 2010.

<sup>76</sup> Standard & Poor's, "Construction Track Records for New Nuclear Plants Around the World So Far are Mixed," S&P Credit Research, August 16, 2010.

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## **APPENDIX C: ECONOMIC ISSUES**

### **C.1 CHANGING THE CONCEPT OF ECONOMIC OF SCALE**

The economics of commercial nuclear power has depended heavily upon the concept of economies of scale. During the first commercial build cycle, the initial commercial reactors (e.g., Fermi 1 and Indian Point Unit #1) were on the order of 100-150 MW. Commercial reactors were quickly scaled up to 500 MW, and ultimately to 1,000 MW, which became the norm for later builds.

The economy of scale concept continues to the current day, as vendors and their customers have found that further scale-up is needed to achieve favorable economics. This concept is reflected in the current technologies of choice for new builds, including the Toshiba/Westinghouse AP-1000 (an 1,150 MWe reactor scaled-up from an initial AP-600 design), the Unistar EPR (1,650 MWe), and the Mitsubishi APWR (1,700 MWe). Even the Toshiba ABWR is being considered for uprating in order to improve the economics of the proposed deployment at the South Texas Project.

The economics of SMRs has been postulated as being fundamentally different, often referred to as the “economies of mass manufacturing,” where scale is achieved in the capacity and throughput at a dedicated SMR manufacturing facility rather than in the size of the fully deployed reactor site.

### **C.2 EFFECTS OF MASS MANUFACTURING AND LEARNING**

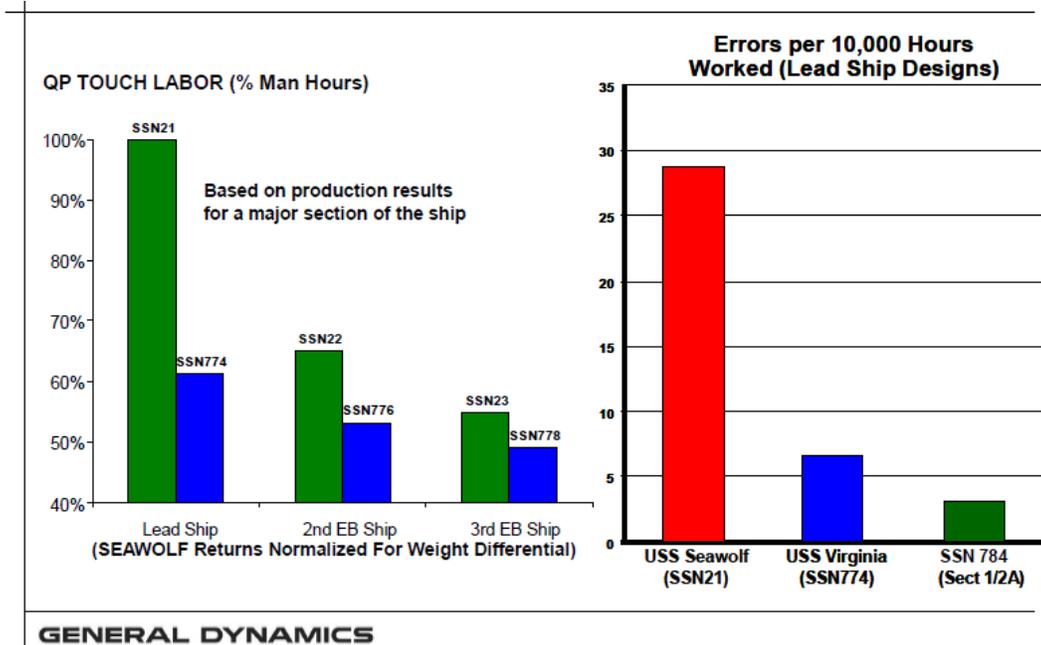
The SMR community (developers, suppliers, and potential customers) have quoted estimates that the plant cost of SMRs (all-in capital costs) would be in the range of \$6,000 per kW, comparable to the unit cost of large LWRs. Achieving significant reductions in these estimates requires the fabrication of many modules on manufacturing plant assembly lines. This would enable manufacturing and assembly processes to be optimized to minimize labor requirements and shorten assembly times.<sup>77</sup> The process of optimization has been referred to as “learning by doing,” whereby lessons are learned from the manufacture and assembly of each module, which can be then passed along in the form of productivity gains or other cost savings in successive modules. Current large LWRs, such as the AP 1000, already incorporate a significant degree of modular construction techniques. Because of the smaller size of components, SMRs provide increased opportunity for modularization and factory manufacturing.

The key issues are (1) the deployment strategy of starting with two LEAD plants, lead modules that would be modeled by the best practices of other DOE or Department of Defense (DOD)

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<sup>77</sup> The proposed new builds of LWRs are moving partly in the direction of off-site assembly through the adoption of modular construction techniques, where segments of the plant will be fabricated in off-site plants and then transported to the construction site. By downsizing the reactors, SMR vendors will be able to more fully utilize off-site fabrication techniques within the setting of a manufacturing plant.

projects, where initial learning on design, regulation, manufacturing, and operation can take place; (2) estimation of the magnitude of savings that can be achieved between the manufacturing of the initial SMR module and manufacturing of the “*n*th” module; and (3) determination of the range of the number of modules that need to be manufactured until the fully optimized NOAK modules have been produced. Analyses of Navy shipbuilding programs have validated this concept and have been able to measure both the magnitude and the length of the production run needed to fully optimize production. A graphical representation of the learning-by-doing process for Navy shipbuilding is shown in Figure C.1.



**FIGURE C.1 Learning-by-Doing Experience in Navy Shipbuilding**

This figure illustrates two important points. First, the graph on the left side shows that significant “learning-by-doing” cost savings can be achieved rapidly – as quickly as the second ship. The graph on the right side shows the improvements achievable even in the first production copy as a result of a more intensive upfront engineering design effort.

Both General Dynamics and Northrup Grumman, the two leading Navy shipbuilding contractors, have assessed the SMR technologies and indicate that the designs lend themselves to similar learning effects.

### C.3 SHOP-BASED MODULAR MANUFACTURING VS. ON-SITE STICK BUILD

Total on-site construction labor can be reduced by installing pre-assembled reactor modules, as well as spreading out the peak construction labor requirements through sequential installation of the modules over time rather than all at once. However, the economics of site deployment are

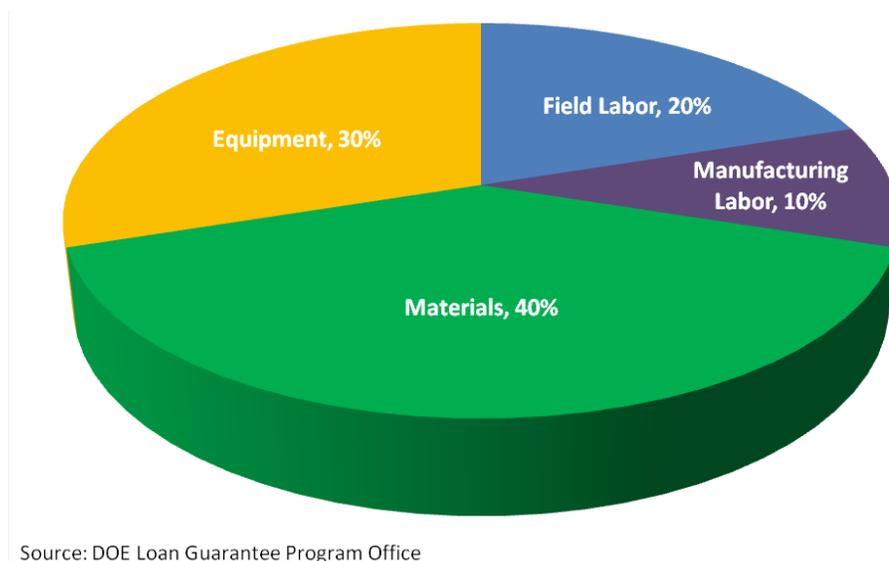
still ultimately linked to full build-out of all modules, since the balance of plant (BOP) will be sized for full module deployment. For example, the reactor building and many ancillary plants will need to be sized for commercial-scale deployment and will need to be constructed upfront along with the deployment of the initial modules.<sup>78</sup> The end result is a form of optimization that increases upfront costs related to certain BOP systems to avoid larger “dis-economies of scale” that would occur if the entire plant were deployed on a modular basis.

Thus, the deployment strategy would preserve the project components where economies of scale are important, while modularizing the reactors (i.e., the nuclear island) to take advantage of manufacturing efficiencies. The one area where there may be some residual “dis-economies of scale” is in the turbine/generator island, where the equipment may need to be scaled to the modular deployment of the nuclear island, and not to the ultimate final capacity of the plant.

The common thread behind these factors is the ability to significantly improve labor productivity and thus reduce labor requirements.

#### C.4 COMPARISON OF COST STRUCTURES BETWEEN LARGE LWRs AND SMRs

The significance of these factors to the overall economics of SMRs can be illustrated by considering the cost structure of large LWRs. For the current round of new builds, the DOE Loan Guarantee Program Office estimates that labor costs, including man-hours and skilled craft labor rate, amount to 30% of the all-in capital costs for large-scale commercial LWRs, as shown in Figure C.2.



**FIGURE C.2 Composition of All-in Capital Costs for a Large LWR**

<sup>78</sup> A current example of this phenomenon is the proposed American Centrifuge Plant being developed by USEC, Inc., where the centrifuge building and feed and withdrawal plants will need to be sized for ultimate deployment, even though the centrifuges can be deployed in modules or cascades.

Thus, savings in labor costs could have a significant impact on all-in capital costs. The savings would have a ripple effect in indirect costs as well, including project management costs, overhead costs, and owner's costs.

## **C.5 METRICS FOR ASSESSING ECONOMIC FEASIBILITY**

Understanding the economics of SMRs, especially the modular nature of SMR deployment and the learning-by-doing effects, may require the application of additional economic metrics for assessing economic feasibility and financial viability. In particular, because the economies of scale are achieved in the manufacturing of small reactor modules, rather than the scale of any particular SMR plant site, the overnight capital cost is a metric that needs to be supplemented by other financial metrics. The trade-offs in the use of various economic metrics are discussed further below.

The most common metric cited for GW-scale LWRs is the total capital expenditure or all-in capital cost. Usually, all-in capital costs are reported in terms of the overnight plant costs on a \$/kW basis. While often cited as a key metric for assessing the cost of GW scale LWRs and comparing nuclear LWR costs with non-nuclear technologies, all-in capital cost comparisons between large LWRs and SMRs can be misleading, for several reasons:

- All-in capital costs do not adequately reflect the significant differences in annual net cash flows that result from the differences in deployment strategies. For example, while the total all-in capital costs for a GW-scale LWR could be comparable, this does not reflect the fact that the SMR deployment strategy would yield revenue sooner than would be achieved by constructing a single large LWR.
- Also, all-in capital cost estimates for SMRs need to be used with caution, because they may have different embedded deployment assumptions. For example, for multi-module SMR designs, the all-in capital costs for an initial deployment could be high because of the upfront costs for the reactor building and ancillary plants that may be assigned to only one or two SMR modules, whereas the all-in capital costs for a fully built-out plant would be much lower on a unit kilowatt basis.
- Finally, the effects of learning by doing could ultimately lead to significant reductions in the all-in capital costs of future modules and thus reduce the “average” all-in cost for the completed plant.

Other metrics often used to evaluate investment opportunities in GW-scale nuclear plants are the net present value (NPV) and/or or the return on equity (ROE). These are two alternative variations on the measurement of value creation. The NPV estimates the net value created by the project for a given discount rate. The ROE represents the return to an equity investor from the initial investment in the project. Both measures capture the full benefits of the project over time but can mask differences in the time sequencing of the revenue stream resulting from staging of module deployments.

Additional metrics that would better capture the differences in economic benefits between SMRs and GW-scale plants is either the measure of the capital cost at risk or the annual net cash flows:

- The capital-at risk metric measures not the total initial all-in capital costs (total \$ or \$/kW) but the amount that has not been repaid (through either amortization of debt or return of equity) at any point in the project implementation. This measure would capture the differences in the sequencing of module deployments and would be dependent upon the risk premiums associated with different staging of module deployment.
- Estimates of annual net cash flow would provide information on annual patterns, including time to initial cash flow as well as the balancing of early revenues from initial module deployments against deployment costs for subsequent modules. It also would provide insights as to causes of cash flow volatility, such as that resulting from volatility in natural gas prices in markets where SMRs are competing with natural gas combined-cycle (NGCC) generation.

The estimated levelized cost of electricity (LCOE) provides a measure of the competitiveness of an SMR plant in the electricity marketplace. It then becomes the starting point for consideration of possible special market mechanisms, such as clean electricity sales or other forms of financial incentives. For SMR plants, the LCOE for an initial deployment of one or two SMR modules could be relatively high, because the full upfront all-in capital costs would be amortized against a revenue stream from only a portion of the final plant capacity. The LCOE estimate would be relatively lower once all all-in capital costs were amortized against the revenues from the full output of the ultimate SMR plant.

Another factor affecting the LCOE for initial commercial deployments of SMRs is the amortization of development costs, including DD&E costs. If the developer seeks to recover these costs in early deployments, the resulting LCOE will be higher. If the development costs are partly offset by federal assistance, or stretched out, the LCOE estimate will be lower.

## **C.6 MARKET COMPETITIVENESS BETWEEN SMRS AND NATURAL GAS**

SMRs have two principal market applications: (1) to meet load growth in areas where electricity demand is projected to erode existing generation reserve margins, but the demand for new generation is smaller than can be economically addressed by large LWRs, and (2) to replace existing coal generation that may be retired as a result of possible new air and water quality and coal-ash regulations (and ultimately carbon dioxide emission caps). In both instances, the principal alternative to SMRs as a base-load generation option is NGCC technology.

Over the past two decades, the use of natural gas for power generation has gone through a boom-and-bust cycle. The deregulation of wholesale electric power markets in the early 1990s led to the growth of independent power producers with NGCC as the generation technology of choice. Since the repeal of the Fuel Use Act in 1987, 164 GW of NGCC capacity has been added to the grid. However, lower-than-anticipated growth in electricity demand and a period of higher gas prices since 2000 led to excess generation reserve capacity in several regional electricity markets

and left a substantial fraction of this NGCC capacity operating at much lower capacity factors than its original design basis. Recent developments in the production of natural gas from shale formations have created new expectations that domestic natural gas supplies will be plentiful and prices will remain relatively low and stable.<sup>79</sup> Consequently, natural gas is now viewed as the benchmark for all alternative electricity generation options.

Thus, the long-term market competitiveness of SMRs, measured as LCOE, will need to be benchmarked to new NGCC capacity. The capital expense cost and performance parameters for NGCC plants are well established. The principal issue affecting the economics of NGCC is future price uncertainty and volatility of natural gas.

### **C.7 FINANCIAL CAPACITY OF VENDORS TO SELF-FINANCE SMR COMMERCIALIZATION**

There are significant federal regulatory barriers to SMR market entry, posing a large burden on the financial capacity of SMR vendors to self-finance the development process. The process for development and regulatory approval of a new nuclear reactor design has parallels with the federal regulatory processes for new commercial aircraft and new pharmaceuticals. Both of these endeavors are also subject to stringent federal regulatory oversight, resulting in development costs and schedules comparable to those facing SMR developers. However, unlike SMR developers, the commercial aircraft and pharmaceutical industries are concentrated in a few large players with large balance sheets that can facilitate private funding for the design and licensing efforts.

Table C.1 illustrates these parameters. In the case of the Boeing 787, the total development cost was large (about \$15 billion), comprising 31% of the September 30, 2011, market capitalization of Boeing and about 23% of 2010 revenues. The estimates for the European Aeronautic Defense & Space (EADS) A380 are even larger, but can be more readily supported by EADS given its European government backing. The total development cost for a new pharmaceutical is about half the estimated development cost for a new SMR technology. However, in the case of pharmaceuticals, development costs are a small fraction of the financial resources of a large pharmaceutical company. The cost to market for an illustrative SMR vendor would roughly be two orders of magnitude higher (measured on the basis of market capitalization) as compared to the burden of financing the development of a new pharmaceutical. In addition, the time to market for SMRs is one-third longer than that for new commercial aircraft or new pharmaceuticals, representing a much longer period before the initiation of revenue generation.

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<sup>79</sup> A further profile of the natural gas generation fleet can be found in the MIT report, *The Future of Natural Gas: An Interdisciplinary MIT Study*, 2010.

**TABLE C.1 Relationship of Development Cost to Company Size**

Developer/Product	Development Cost	Time to Market	Cost as a Percent of:	
			Market Cap (Sept 2011)	Annual Revenues (2010)
Boeing – 787 Dreamliner <sup>a</sup>	\$15B	7 Years	31%	23%
EADS – A380 <sup>b</sup>	\$24B	7 Years	80%	29%
Merck – New Pharmaceutical <sup>c</sup>	\$0.5B	7.5 Years	0.5%	1.0%
Pfizer – New Pharmaceutical <sup>d</sup>	\$0.5B	7.5 Years	0.33%	0.7%
Illustrative SMR Vendor <sup>e,f</sup>	\$1B	10 Years	30%	37%

- a. Development cost represents as spent dollars for R&D, design, and certification; excludes manufacturing costs. Source: Dominic Gates, “Boeing Celebrates 787 Delivery as Program’s Costs Top \$32 Billion,” *The Seattle Times*, September 24, 2011.
- b. Source: Andrea Rothman, “Airbus A380 Order Dearth Risks Double-Decker-Dud-Fate,” *Bloomberg Business Week*, May 7, 2010; article retrieved September 2010 at <http://www.businessweek.com/news/2010-05-05/airbus-a380-order-dearth-risks-double-decker-dud-fate-update1.html>.
- c. Development cost represents the industry average as-spent costs for development of a major new pharmaceutical, including discovery, pre-clinical trials, clinical trials, and approvals; excludes cost of capital and cost of manufacturing. Source: Joseph A. DiMasi, Ronald W. Hansen, and Henry G. Grabowski, “The Price of Innovation: New Estimates of Drug Development Costs,” *Journal of Health Economics* **22** (2003) 151-185. Summary can be found at <http://healthcare-economist.com/2006/04/29/802m/>.
- d. Development cost for new pharmaceutical is the same generic cost cited above, but applied to Pfizer.
- e. Development cost is the estimated generic DD&E cost (in as-spent dollars) for a new SMR technology; excludes SMR module manufacturing costs; also excludes investment cost to outfit an SMR module manufacturing facility.
- f. Two SMR vendors, mPower and NuScale, are single-purpose entities held by consortia. Two other vendors, Westinghouse and Holtec, are privately-held companies with multiple business lines. For purposes of our illustration, we used public data for B&W, a publicly held company with multiple business lines that is the principal sponsor of mPower. The illustration is conservative, because it assumes that all of the financial resources of B&W from all business lines could be drawn upon to support SMR DD&E costs.

In addition, the federal government provides important indirect support for the development and commercial introduction of new commercial aircraft and pharmaceuticals:

- In the case of commercial aircraft, much of the technology is common with military aircraft supported through DOD research, development, and demonstration, and through procurement programs.
- In the area of pharmaceuticals, private investment in the development of new drugs is protected by government-granted exclusivity rights, and marketing is supported through government-approved reimbursements under Medicare/Medicaid programs.

SMR developers currently have no comparable direct or indirect support.

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## APPENDIX D: FINANCIAL INCENTIVE AND MARKET TRANSFORMATION OPTIONS

<b>Technology R&amp;D Financial Incentives</b>	
Licensing and Design Cost Sharing	DOE could provide cost sharing for all or some defined subset of the detailed design and engineering (DD&E) costs. This activity includes the cost of the detailed engineering of the SMR modules and plants as well as the detailed engineering of the SMR manufacturing facility.
R&D Tax Credit	Certain private-sector R&D costs for SMR development activities may be eligible for the existing research and development (R&D) tax credit. The level of the benefit depends upon the determination of eligibility of costs and the tax status of the sponsoring company. DOE could assess the extent to which private sector investment in SMR development qualifies for the existing credit, and determine whether modifications to the credit would be appropriate to address issues such as scope of eligible costs and transferability of the credit.
<b>Technology Deployment Financial Incentives</b>	
Loan Guarantees	A federal loan guarantee is a promise to a Lender of record that if the Lender makes a loan and services a loan under a federal agency's program guidelines and that loan subsequently goes into default, then the federal government will honor the guarantee by buying the defaulted loan. The impact on the Lender is to promote loan making where there might not otherwise be a loan. In addition, loan guarantees facilitate cost efficiency by minimizing or eliminating the risk premium that otherwise would be imposed by commercial lenders. Loan guarantees enable greater leveraging (i.e., higher debt-to-equity ratios), reducing the demands on equity investment. The combination reduces the weighted average cost of capital, and, in turn, the levelized cost of electricity. SMRs are currently eligible for loan guarantees under the statutory language and implementing regulations for the DOE Title XVII loan guarantee program. A new application solicitation would be needed. SMR module manufacturing facilities currently are not eligible for Title XVII loan guarantees.
Investment Tax Credit	An Investment Tax Credit (ITC) reduces the effective capital investment cost of an SMR plant. The ITC would help "buy down" the initial capital cost of a SMR plant, thus reducing capital recovery requirements that would otherwise be reflected in the levelized cost of electricity. The ITC is generated at the time the qualifying facility is placed in service. While the ITC provides a strong incentive to ensure construction of the SMR facility, it does not necessarily incentivize efficiencies in operation. In addition, project sponsors with limited taxable income may not be able to take full advantage of the ITC. Sponsors of renewable energy projects eligible for ITCs may take the ITC benefit in the form of a cash grant; however, this conversion option is currently available only for renewable energy projects that

Investment Tax Credit (Cont.)	commence construction no later than December 31, 2011. The renewable ITC varies depending on the type of renewable energy project; solar, fuel cells, and small wind (< 100 kW) are eligible for credit of 30% of the cost of development, with no maximum credit limit; there is a 10% credit for geothermal, microturbines (< 2 MW) and combined heat and power plants (< 50 MW). Benefits are derived from the ITC over a 6-8 year period. The SMR ITC could be designed to match the renewable ITC.
Production Tax Credit	<p>The production tax credit (PTC) is a performance-based incentive that offsets the cost of operation of SMRs. The PTC would become effective only when the qualified facility is placed into service, and would be based on the level of production. The study team initially designed the level of the PTC to be established based on the difference between estimated production cost and a target price. The PTC could be set at a declining rate to match the learning targets planned for FOAK SMR plants. The key design parameters for the incentive include:</p> <ul style="list-style-type: none"> <li>• The magnitude of the deployment incentive could decline with the succeeding SMR FOAK plants and phase out completely as deployment approaches the NOAK plant.</li> <li>• The incentive could be market-based rather than cost-based; the incentive could take into account not only the cost of SMRs but also the cost of competing technologies and be set accordingly.</li> </ul> <p>The potential size of the incentive could be subject to further analysis as licensing proceeds and better quality cost estimates become available.</p>
<b>Demand Pull Incentives</b>	
Federal Purchases of SMR Electricity	Federal facilities could be the initial customer for the output of LEAD or early FOAK SMR plants. The federal government is the largest single consumer of electricity in the U.S., but its use of electricity is widely dispersed geographically and purchases are highly fragmented. Executive Order 13514 directs federal agencies to promote sustainability and reduce greenhouse gas emissions in electricity consumption; the study team believes that such a potentially large and evolving base for clean energy would enhance the attractiveness and feasibility of SMR electricity supplies. DOE could take the lead to develop a plan for multi-agency aggregation of electricity purchases at multiple locations nationwide that may be suitable for SMR deployment. The study plan could consider supply requirements, schedules, reliability (including back-up power), and contracting opportunities. Implementation of the plan may require regulatory or statutory approvals to enter into firm multi-year contracts in order to provide a “bankable” framework for project sponsors to secure private financing. For example, the contractual arrangements may need to consider some form of “take or pay” requirement that would enable project sponsors to receive a fixed revenue stream regardless of SMR plant generation levels.

U.S. SMR Export Strategy	This activity involves the development of a multi-agency strategic plan to promote exports of SMR FOAK plants. The group could include Department of Commerce, Department of State, Export -Import Bank, Overseas Private Investment Corp., National Security Council, DOD, and Office of Management and Budget. The effort could build upon the current Department of Commerce Civil Nuclear Trade Initiative which has identified 27 countries as “markets of interest” for new nuclear expansion. The SMR export strategy could develop a coordinated “Team USA” plan to promote deployment of SMR FOAK plants, involving a combination of diplomatic efforts, U.S. vendor commitments, and federal export credit assistance. The export strategy could be vendor-neutral and avoid providing a competitive advantage to any single U.S. SMR vendor.
<b>Market Transformation Incentives</b>	
Regulatory Incentives for Coal Plant Replacement	DOE could work with EPA and other federal agencies to assess the environmental regulatory framework affecting the ability of SMRs to replace existing coal power generation that may be retired as a result of pending air quality, water quality, and coal ash regulations. Various estimates show that up to 70 GW of existing coal-fired generation could be retired over the decade. Some of this retired capacity may be suitable for replacement with SMRs. Existing coal generation sites could be attractive for SMRs due to availability of existing rail, road, water, and transmission infrastructure. An interagency group (including DOE, Environment Protection Agency, Federal Energy Regulatory Commission, Council on Environmental Quality, and other agencies) could undertake a comprehensive assessment of the feasibility of deployment of SMR LEAD and FOAK plants in order to assure reliability of the electricity grid and mitigate costs to consumers associated with the retirements. The assessment could identify any regulatory barriers as well determine the feasibility of new environmental regulatory incentives for SMR deployment. In particular, the assessment could determine how federal and state environmental permitting and enforcement programs can provide flexibility to address any schedule or performance uncertainties that may be associated with deployment schedules for SMR LEAD and early FOAK plants. For example, the current EPA authority to allow innovative technology waivers under Section 111 of the Clean Air Act for new source performance standards could serve as one possible model developing new flexibility mechanisms.
Clean Energy Standard	In his January 25, 2011 State of the Union Address, President Obama called for a goal to generate 80% of electricity from clean sources by 2035. Administration officials subsequently indicated that this represents a doubling from current levels (assuming that natural gas generation receives one-half credit as a clean energy source). Staffs within the Administration as well as congressional staff are continuing to study the feasibility of a Clean Energy Standard (CES) and how it might be designed. There are a number of options for assigning the level of CES credits to various technologies and measures under a CES as a way to further policy objectives. Ensuring that SMR plants are

Clean Energy Standard (Cont.)	eligible for inclusion in the CES portfolio, and assigning “bonus” credits, to early adopters of SMR LEAD and FOAK plants, could provide a significant offset to the higher cost (relative to later learning SMR plants) of these plants. Additional bonuses could be assigned if the SMR project also is used as a replacement for a retired fossil fuel generating plant.
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## **APPENDIX E: MANAGEMENT MODELS FOR SMR DEPLOYMENT**

The strategic business plan and business case analysis would assume that the federal government would act primarily in the role of financing SMR commercialization activities that would be managed by one or more private sector entities. The analysis also would assume that the government would act as the customer for LEAD SMR plants. This appendix describes alternative management models for SMR deployments, including alternatives for public-private partnerships and the risk allocation associated with each. Table E.1 provides a description, in chart form, of the variations in ownership, management, financing, and off-take for a range of alternative management models. Whether the federal government participates as a source of financing, an owner/operator, or a customer for SMRs, each has different allocations of risk among the federal government, the SMR vendor, and a private sector electricity provider. The allocation of risk is summarized in Table E.2.

**TABLE E.1 Alternative SMR Management Models**

	<b>INITIAL DEPLOYMENT (with DOE as lead customer)</b>						
	<b>Design, Licensing</b>	<b>Owner</b>	<b>NRC License Holder</b>	<b>Operator</b>	<b>Responsibility for All-in Capital Cost Financing</b>	<b>Responsibility for Operations &amp; Maintenance Expenses</b>	<b>DOE Off-take Agreement</b>
<b>Traditional Regulated Utility Model</b>	DOE cost share	Utility	Utility	Utility	Utility (debt structure depends on the sub-model)	Utility	N/A (PUC-approved rates, paid through annual appropriations)
<b>Merchant Generator / DOE Loan Guarantee</b>	DOE cost share	Merchant generator	Merchant generator	Merchant generator	Merchant generator (debt-leveraged with DOE loan guarantee)	Merchant generator	DOE PPA (could be annual or fully funded appropriation)
<b>Merchant Generator / DOE Purchase Agreement Model</b>	DOE cost share	Merchant generator	Merchant generator	Merchant generator	Merchant generator (debt-leveraged, backed by PPA and possible loan guarantee)	Merchant generator	DOE multi-year PPA (fully funded appropriation)
<b>Government Lease Model</b>	DOE cost share	Utility or merchant generator	Utility or merchant generator	Utility or merchant generator	Private entity (debt-leveraged, backed by lease and possible loan guarantee)	DOE lease payment	N/A (Lease payment covers all costs)
<b>Government Build-Own-Operate-Transfer (BOOT) Model</b>	DOE cost share	DOE initially, then transferred to utility or merchant generator	DOE initially, then transferred to utility or merchant generator	Utility or merchant generator	DOE appropriations or other government financing mechanism	DOE initially, then transferred to utility or merchant generator	N/A (capital and operations & maintenance costs directly funded)

Note: Design/licensing cost includes design certification, initial license (Part 50 or 52), and FOAKE. All DOE loan guarantee options assume legislative relief from current prohibition on loan guarantees in combination with other government grants and contracts.

**TABLE E.2 Risk Allocation Issues for Deployment**

<p><b>Traditional Model – Three Submodels:</b></p> <ol style="list-style-type: none"> <li>1. IOUs</li> <li>2. Government (State, Municipal)</li> <li>3. Federal power – TVA</li> </ol>	<ul style="list-style-type: none"> <li>• Utility takes all risks – all-in capital costs, completion risk, and operation &amp; maintenance expenses (OPEX).</li> <li>• Costs can be passed through to DOE and other customers if deemed prudent by state regulators</li> </ul>
<p><b>DOE Loan Guarantee</b></p>	<ul style="list-style-type: none"> <li>• DOE loan guarantee program takes some all-in capital risk, completion risk, and OPEX risk.</li> <li>• DOE also could have additional risk if multi-year PPA becomes a condition precedent for the loan guarantee.</li> </ul>
<p><b>DOE Multi-year Purchase Power Agreement</b></p>	<ul style="list-style-type: none"> <li>• Merchant generator takes licensing, all-in capital costs, and completion risk.</li> <li>• Merchant generator takes OPEX risk, unless DOE enters into a take-or-pay contract.</li> <li>• DOE risk is limited to the extent of price caps and price escalators in the contract.</li> </ul>
<p><b>Lease</b></p>	<ul style="list-style-type: none"> <li>• Licensing, all-in capital costs, and OPEX cost risk could be shared, depending upon lease terms.</li> <li>• Private owner/operator takes long-term profitability risk for post-lease period.</li> </ul>
<p><b>BOOT</b></p>	<ul style="list-style-type: none"> <li>• DOE takes all license, all-in capital cost completion risk, and OPEX risk. Ownership transfer occurs at the time of the first complete refueling outage. DOE takes the risk of market valuation at the time of transfer.</li> </ul>

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## APPENDIX F: RELATIONSHIP OF FINANCIAL RISK TO PROJECT SIZE

Most financial risk models assess project risk factors independently of project size. For example, the models used by the ratings agencies and in federal credit programs assess the probability of default relative to various technical, managerial, and project economics criteria, and then estimate the expected value of risk based on the probability of default times the loss given default. The loss given default is dependent upon the size of the project.

The study team's analysis of the risk premiums associated with GW-scale LWRs and SMRs led to the view that risk premium, by whatever measure, depends on the size of the project. Thus, all things being equal with respect to technical, managerial and other risk factors, the study team believes that the risk premium for an SMR will be lower than for a GW-scale LWR. Moody's acknowledged this point by relating the size of the project to the size of the project sponsor. According to a Congressional Budget Office (CBO) report,

Moody's recently reported that it was considering taking a more negative view of bond issuers who were seeking to finance the construction of new nuclear plants. A primary concern cited by Moody's was whether the proposed plants were economically viable, especially given uncertainties about the effects of energy-efficiency programs and national clean electricity standards on the demand for new nuclear generating capacity, the availability of capital in such projects, and the effect of such investment on the sponsoring utilities' balance sheets.<sup>80</sup>

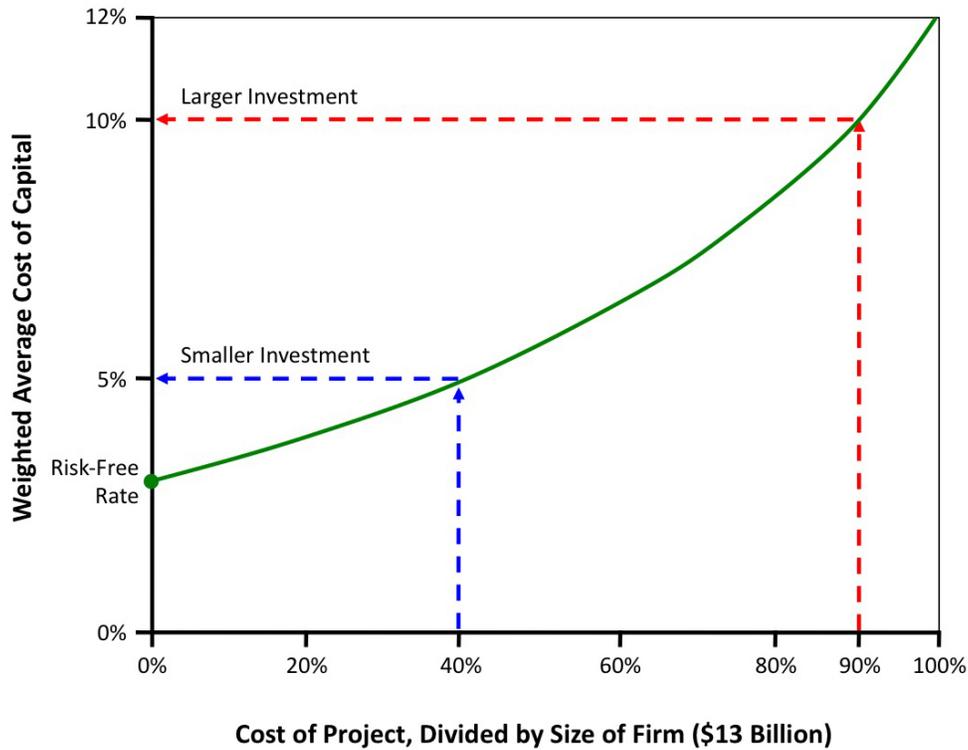
Rothwell has proposed a model for quantifying this relationship. Rothwell hypothesized that the risk premium associated with a project is a function of the wealth of the sponsoring entity: "In particular, the cost of capital in financial markets is a function of the decision maker's pre-project wealth (e.g. net present value) and debt to equity ratio, and the decision maker's anticipated (contingency-adjusted) post-project wealth and debt to equity ratio."<sup>81</sup> Rothwell then developed a mathematical expression for this relationship, which shows risk premium rising at an exponential rate as the size of the project approaches the net present value of the nuclear plant owner. The relationship is illustrated in Figure F.1.

This analysis results suggest that SMRs should be viewed more favorably by utilities and by the investment community as having a lower risk premium than GW-LWRs because of the smaller size of the project relative to the market value of SMR project sponsors. In addition, there may be technical or market constraints, such as electricity demand or transmission, that would support

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<sup>80</sup> Congressional Budget Office, *Federal Loan Guarantees for the Construction of Nuclear Power Plants*, <http://www.cbo.gov/ftpdocs/122xx/doc12238/08-03-NuclearLoans.pdf>, August 2011.

<sup>81</sup> G. Rothwell, "Economics of Nuclear Power," an update of the *Economics of Nuclear Power* (2004), a study conducted at the University of Chicago, March 17, 2011, p. 103. See <http://harrisschool.uchicago.edu/centers/hepi/workshops.asp>



**FIGURE F.1 Firm’s Investment in Nuclear Reactor Project for SMRs and GW-LWRs<sup>82</sup>**

SMR deployment but not large LWRs. The Congressional Budget Office reported that GW-level plants have higher market exposure:

Market risk is the component of risk that investors cannot protect themselves against by diversifying their portfolios. Investors require compensation for market risk because investments exposed to such risk are more likely to have low returns when the economy as a whole is weak and resources are more highly valued... In the case of nuclear construction guarantees provided to investor-owned utilities or merchant power providers, for example, plant construction may be more likely to be slowed or canceled when the demand for electricity is depressed by a weak economy.<sup>83</sup>

This conclusion is consistent with the terms of the various rating agencies, such as Fitch Ratings, that measure debt to capitalization to arrive at a credit worthiness score: “Capital expenditures for projects that take a longer time to completion before producing commercial cash flow and projects that entail material technology risk, completion risk and entry into unfamiliar markets are signs of a more aggressive investment strategy.”

<sup>82</sup> This figure represents a first approximation of data received during 2010 and will be updated in later research.

<sup>83</sup> Congressional Budget Office, op. cit.

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