Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S.\textsuperscript{1}

Robert Rosner and Stephen Goldberg
Energy Policy Institute at Chicago
The Harris School of Public Policy Studies

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1.0 Introduction

We have written extensively on the subject of the prospects of nuclear energy in the United States and around the world. With the extraordinary events unfolding at the Fukushima Daiichi nuclear power plants, events that are being assessed by the technical and regulatory experts both in the United States and across the world, it is increasingly clear that the analysis and conclusions in our research may require updates based on the lessons-learned from these events.

In the fall of 2009, Professor Lester of MIT and one of us\textsuperscript{2} reported that many countries around the world are taking a fresh look at nuclear power, in what has come to be called the global nuclear renaissance. An important cause of the global

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nuclear renaissance is the prospect of severe disruptions to the earth’s climate brought about by continued increases in greenhouse gas emissions, primarily from the combustion of fossil fuels. 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. In this paper, 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 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; therefore, the investment community would need to price nuclear investments in the range of conventional energy investments. In the report, “Nuclear Reactors: Generation to Generation,”3 the authors 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 expounded upon on the extraordinary nuclear activity in China and, given the degree that manufacturing and design work has gone off-shore for the current generation of reactors, the opportunities the United States holds to be the leader in the design and deployment of small modular light-water reactors. 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) requested Argonne National Laboratory (ANL) to update The Economic Future of Nuclear Power (August 2004). This white paper reports on the progress we have made on the updated study. Our partners on the updated study include: Dr. Geoffrey Rothwell, Senior Lecturer at Stanford University, and Joe Hezir and Ed Davis, EOP Foundation, Inc. The updated study focuses on key economic parameters and policy options for both gigawatt-level (GW-level) and 50-300 megawatt-level (MW-level) module

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 units and compared the results to investment parameters used in building larger units; the study team used simulated learning curves and a theoretical configuration of units for later plants. There is however still additional research that is required to sharpen the analysis, especially in the areas of the degree of learning for individual cost centers pertaining to early SMR units as well as on the details on the appropriate capacity and capacity additions for later SMRs that are sited and built when the vast preponderance of learning on early plants has been achieved. We plan to expand our work on two key modeling sensitivities: (1) how individual and collective uncertainty influences the 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 is currently in peer review. Preliminary work was reported at the Harris School of Public Policy Studies in February 2011. Based on the peer review comments, we plan to perform a more detailed analysis of uncertainty and validate some of our preliminary results with more detailed database and more robust modeling tools.

2.0 SMRs have a High Potential for Generating Competitive Electricity, with the U.S. being a Technology Leader

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 that 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

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4 [http://harrisschool.uchicago.edu/centers/hepi/workshops.asp](http://harrisschool.uchicago.edu/centers/hepi/workshops.asp)
seeking to transplant portions of its supply chain in the U.S. from current foreign sources, the SMR industry offers the potential to establish a large domestic manufacturing base building upon current U.S. manufacturing infrastructure and capability, including the Naval shipbuilding and idle domestic nuclear component and equipment facilities. 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 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. All of this 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 Nuclear Regulatory Commission (NRC) filing in the 2012 time frame, and detailed engineering is about 10-20% complete. At the time of our analysis, limited cost data were publicly available, and current estimates have a significant amount of uncertainty. Our current understanding is that GW-level units are estimated to have roughly two orders of magnitude greater man-hours expended in this early engineering design work as compared with SMRs. The tooling up at the factory dedicated to SMR manufacturing is still in the planning stages, and will likely require significant investment for a dedicated facility to manufacture SMRs for an nth-of-a-kind economy.

**3.0 Lessons-learned from Economic Analysis of GW-level Reactors**

**3.1 Overnight Cost Estimates**

Since the 2004 Study, we have 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+ cost estimates in the United States have increased considerably (i.e., from about $2000/kW to a consensus estimate of
about \$4400/kW\(^5\). Key contributors to this increase include: (1) commodity price increases for critical nuclear components, structures, and materials; (2) a more detailed scope for the basis estimates, particularly including more realistic owner’s costs in the overnight cost estimates; and (3) the increased use of “pancaking” 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. We also learned that amortization of nonrecurring design and engineering costs, the so-called “first-of-a-kind” costs, was considerably uncertain.

We 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) units 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. 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. Our view is that these DD&E activities for the SMR program would have to be more expansive than the scope for the NP-2010 FOAKE program. DD&E completion would also have the impact of reducing the tendency to “pancake” contingencies, so that fixed/firm cost estimates are established and, more importantly, supporting follow-on fabrication and construction activities for SMRs are enabled and carried out.

### 3.2 Risk Premium and the Resulting Cost Comparison with Natural Gas-fired Electricity

In both the 2004 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 baseload power.\(^6\) In the absence of carbon pricing and relatively weak production regulation, natural gas-fired generation is cheaper than all other

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\(^5\) All point estimates for costs quoted here are associated with error bounds, which we here do not quote in the interests of economy of presentation; the full study now under peer review provides a more detailed description of these uncertainties.

\(^6\) In the 2004 Study, limited analysis was done on the comparison between the economic competitiveness of nuclear energy and natural gas with variable cost of capital scenarios.
sources of generation at the moment. In our opinion, 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 speculation in the gas markets perceiving significant shortfalls in supply.

In our recent work, the uncertainty of future natural gas prices was captured by the anticipation of outcomes of the levelized cost of electricity. We 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. We further understand that this is priced into the weighted-average-cost-of capital (WACC). In this study, a variable risk premium was used for comparing GW-level units with natural gas-fired units. The goal is to price the cost of “size risk”. Figure 1 provides a simplified illustration of risk by comparing the size of a nuclear investment with other conventional baseload investments, in the context of the average annual revenues of investor-owned nuclear utilities.

In the case of unsubsidized financing, particularly relevant in merchant markets, preliminary results show that only decision makers that have significant aversion to risk of future natural gas spikes (i.e., gas prices rising to about $7/MBtu or one standard deviation above the average behavior of natural gas prices) would view these units as cost-competitive. When subsidized units and units in regulated territories were included, GW-level units look more promising. 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.” As identified in Figure 1, on average, investor-owned U.S. utilities, representing 70 percent of nuclear generation, have about $13 billion in average annual revenues. A twin-unit GW-scale nuclear investment of $11 billion would represent about 90% of their annual revenues compared to the size of the project – thus

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7 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 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, as 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.

8 For example, on average, investor-owned U.S. utilities, representing 70 percent of nuclear generation, have about $13 billion in net investment. A twin-unit GW-level nuclear investment of $11 billion would represent about 90% of their annual revenues assigned to cover this project
suggesting that the risk premium 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 units, the study team has performed an initial set of calculations for a variety of WACC outcomes. We are learning that “bet the company” risk has significant potential to be mitigated\(^9\) 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 units.

4.0 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 of government support programs. This scoping analysis does support a competitive position for \(n^{th}\)-of-a-kind SMRs, based on best achievable overnight cost estimates. However, one of the limitations at this stage of the analysis is our reliance on

\[^9\] Private communication from Fitch Ratings
theoretical estimates for earlier plants. In our opinion, we need to adopt the ‘lessons learned’ from the NP-2010 program: We should avoid prematurely down-selecting a reference design, and it will be important to support detailed design and engineering work for at least two designs to arrive at firmer estimates for these earlier plants, as well as fully exercise the NRC licensing process (this will be discussed in further depth below).

The theoretical make-up of an SMR project 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 study team also analyzed a so-called 50% LEAD\(^{10}\), or a plant with three modules, representing 300 MW of capacity. The overall best achievable overnight cost estimate for the \(n^{\text{th}}\)-of-a-kind module was found to be $4600/kW. The overall total capital investment for this project, using these overnight cost estimates, is about $3 billion, or essentially in the range of investments that electricity generators make for fossil-fired generation. The ongoing peer review comments are providing the study team additional perspectives on the size of a minimal \(n^{\text{th}}\)-of-a-kind project that can be competitive with GW-scale units in regulated or subsidized markets, as well as with natural gas-fired units, particularly on the key subject of the amortization of fixed costs. Because of the lack of specificity of most of the SMR designs, it is unclear whether “micro capacity” modules are cost competitive with natural gas-fired units, particularly if there is no carbon pricing and natural gas remains relatively plentiful and relatively cheap.

4.1 Learning Process

More detailed research is required on the learning rates for individual cost centers as well as the degree of cost efficiencies that can be gained. The study team used a theoretical overall learning rate for all capital cost centers. Future research needs to elucidate how these individual cost centers would change with variable learning rates. As such, the study team used a fairly conservative learning rate of 10% for capital (fixed) costs and 2-3% learning rate for variable costs (Operations and Maintenance) at this stage of analysis.\(^{11}\) Ten percent learning rates mean that costs

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\(^{10}\) Short hand for the first-of-the-first” SMRs, which can be regarded as commercial-scale pilot plants.

\(^{11}\) 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
will be reduced by 10 percent for every doubling either in the number of modules or plants. The so-called “first-of-the-first” SMRs, known as the LEAD, in our study would have a significantly higher overnight cost estimate, about 75% higher than the $4600/kW we estimate for the n<sup>th</sup>-of-a-kind unit. On a conservative basis, we believe that the LEAD plant is 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 these first set of modules. The next sets of plants, the first-of-a-kind (FOAK) plants, provide the basis for optimizing the supply chain. After the LEAD is designed, licensed and long-lead procurement activities have been completed, the study team projected that a dedicated manufacturing facility could be planned, designed and built. At that time, firm capital and operating costs would be amortized over the FOAK units. Therefore, the LEAD plant, because it is essentially stick-built, is likely to cost substantially more than the FOAK plants. While fixed costs can, in fact, decline with increases in cumulative capacity, estimating this decline is limited to the tools available at the time of the study. Assuming continuous production of 1 module per manufacturer per month for a 4-year campaign (i.e., 2019-2023), the study team assumed that approximately $900 million to$1 billion of costs, including $300 million for the dedicated factory, would be amortized over about 8-9 plants (encompassing FOAK[$200 M/plant] and LEAD [$100 M/plant]).

4.2 Size of the Fleet and Learning after 1.8 GW of Deployment

The study team projected a hypothetical size and configuration for the fleet, chosen to correspond to the assumption that an n<sup>th</sup>-of-a-kind manufacturing facility would be able to produce about one (100 MW) reactor-steam-generation module per month, or 1,200 MW per year, or 24,000 MW over a 20-year facility life (covering the learning plants and the NOAK plants). For this case, at an assumed learning rate of 10 percent, about 19.2 GW would represent the capacity of n<sup>th</sup>-of-a-kind plants and 4.8 GW would represent the capacity of the learning plants.

Learning on the first three projects, representing 18 modules, appears significant. Based on the initial scoping studies, assuming a 10 percent learning rate and after keep engineering teams and construction crews intact, a highly competitive construction industry, and streamlined regulation largely eliminating construction delays.

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12 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.

13 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.
deploying the first 1.8 GW, overnight costs of about $80/MWh is achieved – this overnight cost 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 (about $80/MWh); 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 (about $60-65/MWh). Figure 2 summarizes these costs projections as SMRs mature in the marketplace and become more competitive with natural gas-fired generation.

Figure 2: Levelized Costs of Learning Plants

5.0 Market Transformation Opportunities for SMRs

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. 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.

- 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

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14 This represents 18 modules – equivalent to four doublings in the module learning process.
demand, nor do they allow for agencies to enter into long-term contracts that are “bankable” by suppliers. In addition, federal agencies are required to review and modify electricity purchases to comply with Executive Order 13154 issued by President Obama on October 5, 2009. The Executive Order 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 an excellent source to meet the President’s Executive Order. This study provides a scenario of purchasing the bulk of the power from the LEAD plant.

• 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, in our opinion, substantial upgrades in all facets of infrastructure requirements, particularly in the safety and security areas, would have to be made, and as exemplified by the ongoing efforts in this direction by the UAE (and, in particular, by Abu Dhabi); this is a substantial undertaking for these less developed countries. Assuming these countries are successful in making these upgrades, studies performed by Argonne National Laboratory argue that nth-of-a-kind SMRs would appear to be a feasible power option for countries that have grid capacity of 2000-3000 MW.

• SMRs have the potential to replace existing coal generation that may be retired in light of pending environmental regulations. A number of industry studies as well as recent EIA analysis indicate the potential for retirement of 50-100 GW of existing coal generation units in the U.S.15 These units are older, smaller (i.e., less than 500 MW), and less energy efficient than most of the existing coal plant fleet, and lack the environmental controls needed to meet emerging air quality, water quality, and coal-ash management requirements. Many of these units could be retired by 2020.

In the business case, the study team developed a first-order approximation of the financial support by the Federal Government needed for SMRs to reach full commercialization. The cost assumptions are derived from the economic modeling presented in the previous section. Based on the technical inputs and cost information from the SMR vendors, combined with the learning experience in the shipbuilding industry, the study team developed a five-stage business model for achieving SMR commercialization. The five stages are discrete and provide DOE
opportunities to decide on going forward based on the progress and successes (see Figure 3, below).

- **Stage 1. Detailed Design and Engineering and Licensing**: SMR licensing and design studies for two SMR designs. The study team assumed that DOE will competitively select and cost share licensing and design studies for two SMR technologies. We believe 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, i.e., competing at least two designs against one another mitigates the considerable technology risks carried by premature down-selection.

- **Stage 2. Lead Commercial Deployment**: Construction of LEAD SMR facilities, potentially up to two designs, starting operation in 2019. In the reference case, the study team estimated that the LCOE from the LEAD SMR facility would be about 75% higher than the $65/MWh \( n^{th} \)-of-a-kind project or about $130 per MWh, significantly higher than the target emissions-free electricity price of about $80 per MWh that would be paid by federal facilities. The Government could partner with the commercial sector, such as providing guarantees (through power purchase contracts) for covering the price difference between market conditions and cost of production as well as by posting a performance guarantee through contractual arrangements. The Government’s current purchases of renewable energy as well as power from clean coal projects could serve as a guide.

- **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 facility. Further analysis of the cash flow at the manufacturing facility is needed to ascertain the capital formation requirements that the manufacturer will have to arrange in order to justify development of the requisite 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. We refer to these as FOAK commercial facilities. Conservatively, we estimated that about 4.8 GW of SMR modules will be needed to achieve the full benefits of learning, at a 10% learning rate, with construction during the period 2019-2027. The study team estimated a 2023-2027 deployment schedule for FOAK plants, taking into account that up to one-third (roughly 1.6 GW, or of order two plants) could be exported, and that the
production tax credit (PTC) would expire by 2035, the target date established by the President for the proposed Clean Energy Standard.

- **Stage 5. Fully Commercial, Competitive SMR Industry:** Fully commercial SMR industry, competitive with natural gas-fired generation as a baseload generation technology. If the learning process for the LEAD and FOAK facilities is successful in meeting the cost targets set forth in this plan, there would be no need for any federal incentives for NOAK facilities. Clearly, if a price for carbon is established, this would further enhance the relative competitiveness of NOAK SMR facilities. As suggested earlier, NOAK SMR facilities may have a lower risk premium than large nuclear reactors, possibly obviating the need for loan guarantees or other measures to reduce the WACC.

![Proposed SMR Business Model](image)

**Figure 3: Five-Stage Business Model Identifying Investors and Relative Contributions**

### 6.0 Final Thoughts

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

Going forward, the next two critical steps we propose are: (1) establishing a viable pro-growth jobs strategy for the U.S. SMR industry that would include support from all sectors of the economy, including state and local government support; and (2) establishing quantitative metrics on the progress the U.S. is making in deploying SMR technology and comparing our progress with our competitors, particularly the emerging SMART reactor technology in Korea. Our continued studies on the economics of SMRs will be informed by the peer review process, and will be aimed at securing yet more refined bounds on the costs of the 5 development stages, including especially on the learning phase leading to a NOAK SMR economy.