# NRDC's Perspectives on the Economics of Small Modular Reactors

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# Bottom Lines

- If the government intends to invest $452 million to certify designs and resolve NRC licensing issues, complete this program before offering further government subsidies for SMR development.
- In the US, the capital cost/kW of SMRs are high and the cost of natural gas is low. The market for SMRs would be far more attractive in countries where capital costs are lower and natural gas prices are higher.

# General Observations

➢ Nuclear Power Costs per Kilowatt Increase as Power Decreases:

• Materials cost per kilowatt of a reactor goes up as the size goes down because the reactor surface area per kilowatt of capacity, which dominates materials cost, goes up as reactor size is decreased;

• Cost per kilowatt of secondary containment, as well as independent systems for control, instrumentation, and emergency management, increases as size decreases;

• Cost per kilowatt also increases if each reactor has dedicated and independent systems for control, instrumentation, and emergency management;

➢ First-of-a-Kind (FOAK) SMRs will be Considerably More Expensive than Large Nuclear Plants, which in Turn are Not Competitive with Combined-Cycle Natural Gas Plants at Current Natural Gas Prices.

# Central to the Economic Case for SMRs

1. Substantial cost reduction, via “production learning” must occur primarily due to serial factory manufacturing;

2. There must be sufficient and continuous orders (e.g. one module per month per vendor) to achieve the learning.

# We’ve Heard this Before

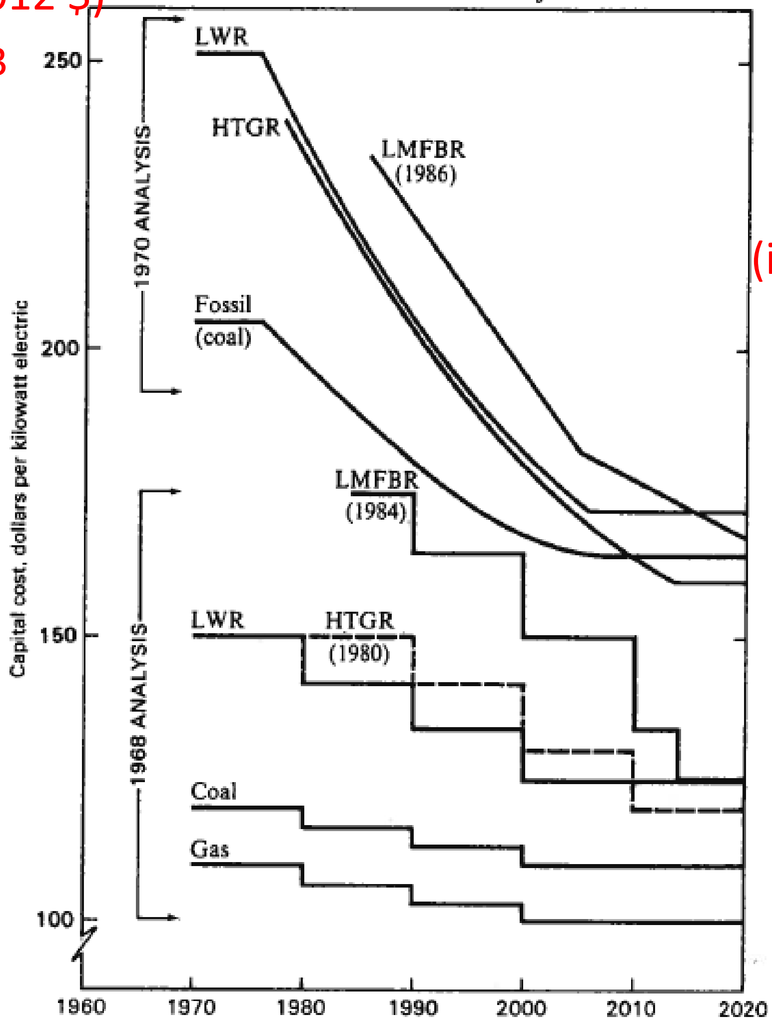
- Similar arguments were made by the Atomic Energy Commission (AEC) to build the case for the Liquid Metal Fast Breeder Reactor (LMFBR) some 40 years ago;
- With respect to each of the most sensitive parameters governing the economics of the breeder, e.g., capital costs, learning rate, cost of uranium, demand for electricity, the AEC chose values that presented the LMFBR in the most favorable light.

# AEC'S "LEARNING CURVE"

$/kW
(in 2012 $)

1,483
1,186
889
593

FIGURE 4. Projected Power Plant Capital Costs Used in AEC's Cost-Benefit Analysis



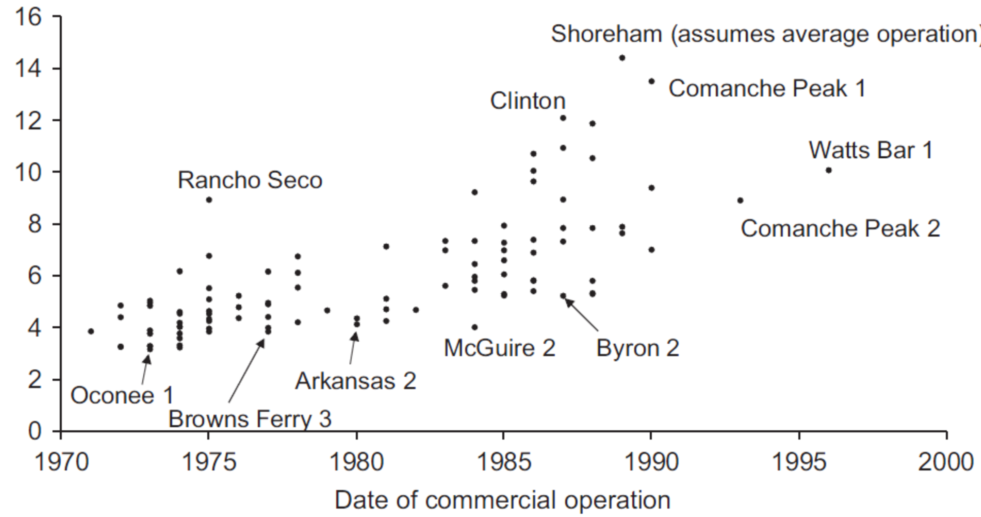

SOURCE: AEC, *Updated (1970) Analysis,* WASH 1184, p. 37.

[Cost-Benefit Analysis of the U.S. Breeder Reactor Program]

*Division of Reactor Development and Technology, U. S. Atomic Energy Commission, January 1972, pg. 37.*

# ACTUAL COST OF U.S. LWRs (total levelized cost)

¢/kWh
(in 2004 $)




[A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005]

Jonathan Koomey, Nathan E. Hultman, *Energy Policy, Volume 35, Issue 11, November 2007, pg. 5636*

# France: "A case of negative learning by doing"

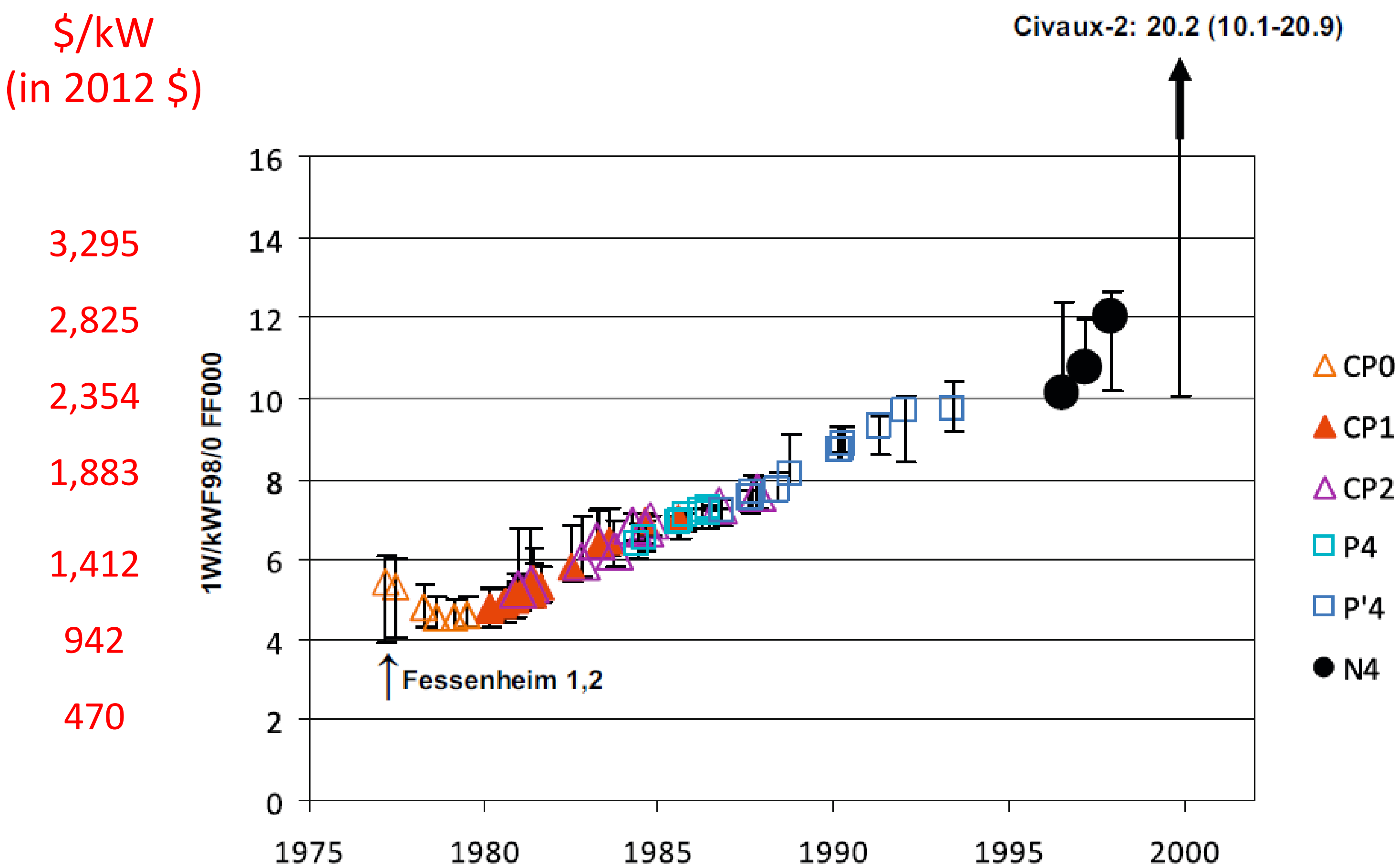



**Fig. 9.** Inferred specific reactor construction costs (1000 FF98/kW) per French PWR reactor sorted by reactor type and completion date (year of first criticality), best guess and min/max – 2 uncertainty ranges of estimates. For numerical data underlying the graph see Appendix Table A2. (For comparison: the exchange rate in 1998 was 5.9 FF/US$.)

[The costs of the French nuclear scale-up: A case of negative learning by doing](#)

Arnulf Grubler, *Energy Policy, Volume 38 (2010) 5174–5188*

# Lessons from U.S. Naval Shipbuilding

**Experience with Seawolf and Virginia Class fast attack submarines has been cited as evidence of "dramatic and rapid impact of learning through the reduction of labor hours in successive ships." The history of the Seawolf and Virginia Class submarines is not fully told in this discussion.**

SEAWOLF CLASS
Seawolf class was proposed to consist of 29 boats, but because the Cold War ended, only three were constructed.

The third member of the Seawolf class, the USS Jimmy Carter, differs significantly from its other two class members. At approximately 100 feet longer, the Carter incorporates an additional hull section to facilitate R&D (research and development) testing on ROV, special operations support, and advanced warfighting capabilities.

At approximately $2 billion apiece, the Seawolf was the most expensive submarine ever constructed.

VIRGINA CLASS
The Virginia Class submarines, which were developed as a cost effective replacement for the Seawolf and Los Angeles classes, have an actual cost per unit price of almost $300k more per submarine than the more capable Seawolf boats ($2.3B vs. $2B.) as a result of a reduced production rate.

**Thus, elements of the SMR business strategy did not occur with these submarines: the number of Seawolf units was slashed, the design was not preserved, and the desired cost reductions did not materialize.**

# University of Chicago EPIC SMR Economic Model

Base Case Results:

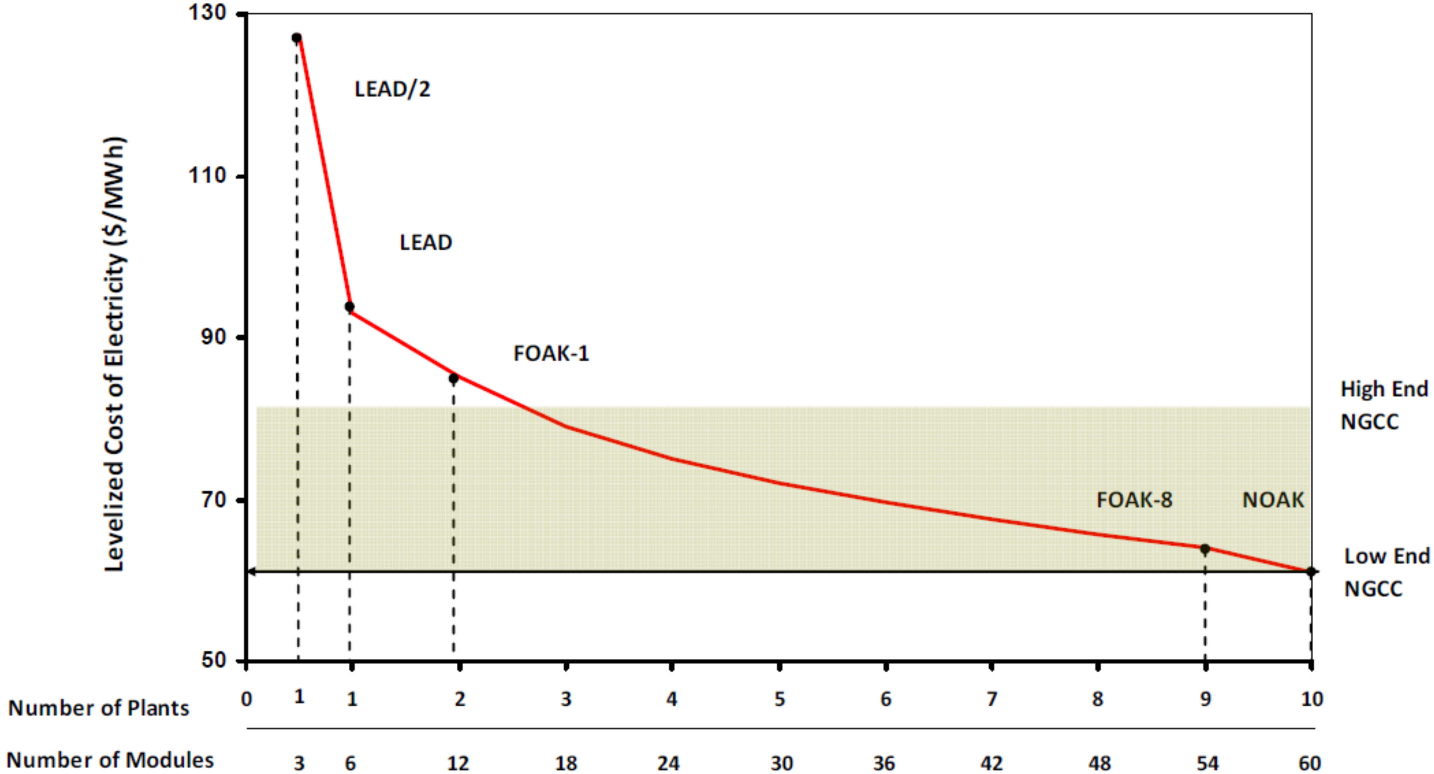



**FIGURE 2 Levelized Costs of Learning Plants (NOAK overnight costs, $4,770/kW)**

Rosner and Goldberg, November 2011

# Key Chicago EPIC Input Assumptions

- Direct Cost of LEAD SMR Plant;
- Contingency for LEAD and FOAK Plants;
- Learning Rate (% cost reduction per doubling of units produced);
- Levelized Cost of natural gas-fired combined cycle generation.

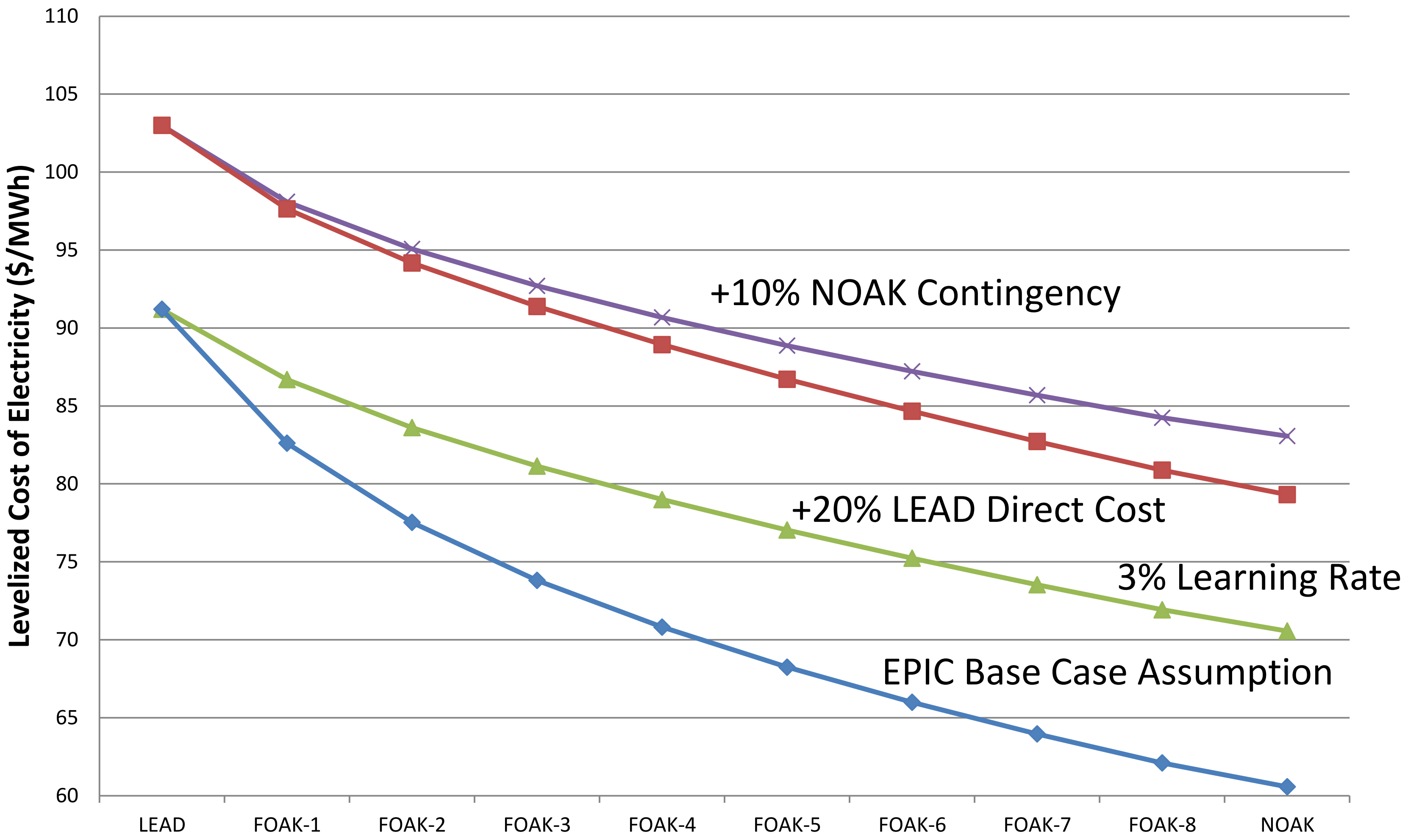
# NRDC Analysis

In order to explore the sensitivity of the U. of Chicago EPIC model results to uncertainties associated with the input assumptions, NRDC has recreated the model in *Analytica,* a commercial Monte-Carlo software package.

# Monte Carlo Calculation: Small Modifications to Key Assumptions

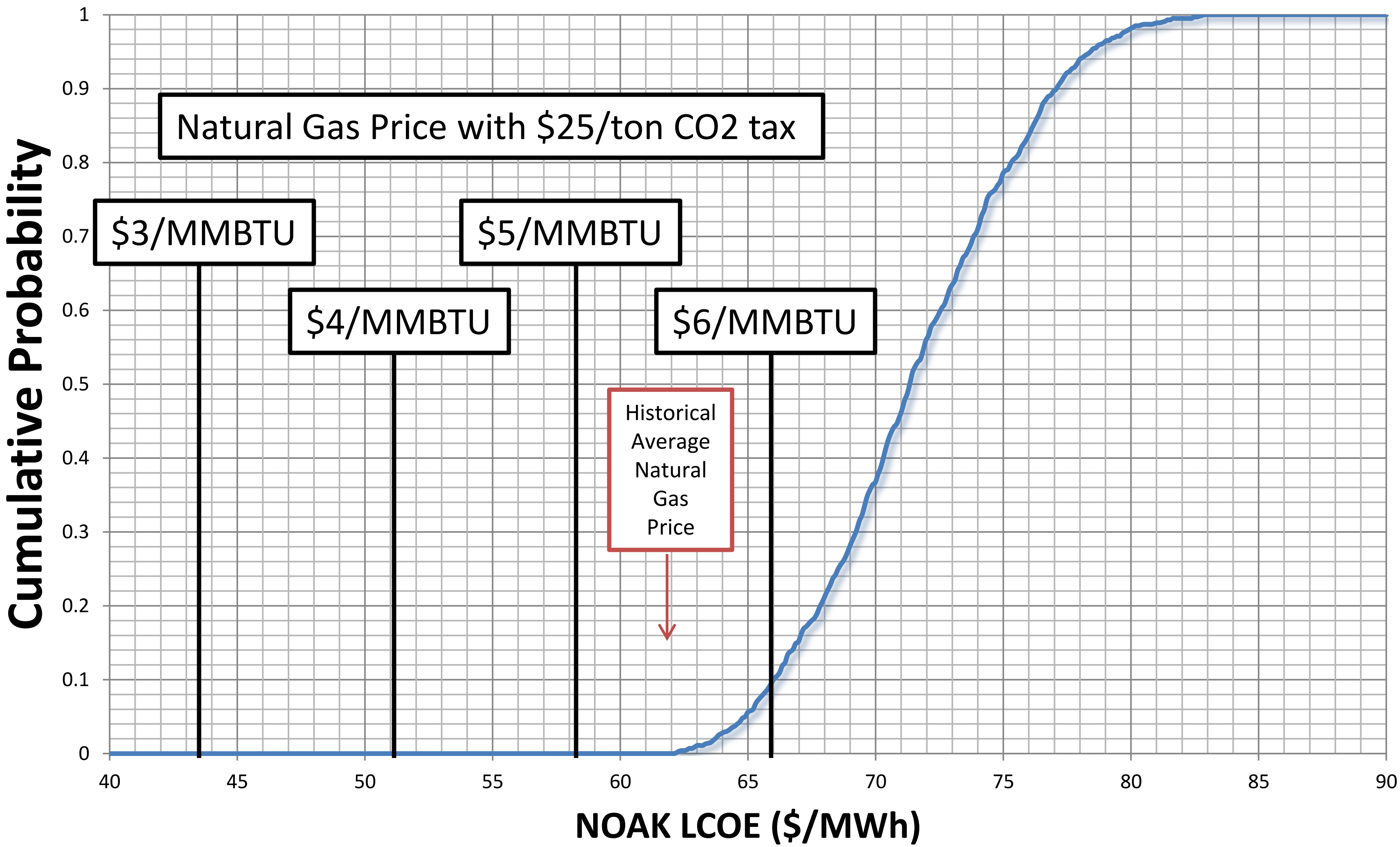
- Learning Rate: 3% to 10% (Base Case – 7%);
- Direct Cost for LEAD Plant: $2,837 M to $3,404 M (Base Case + 20%);
- NOAK Plant Contingency: 15% to 25% (Base Case + 10%);
- Other assumptions, same as in the U. of Chicago EPIC Base Case.

# Small Modification to Key Assumptions within the U. of Chicago EPIC SMR Economy Model:



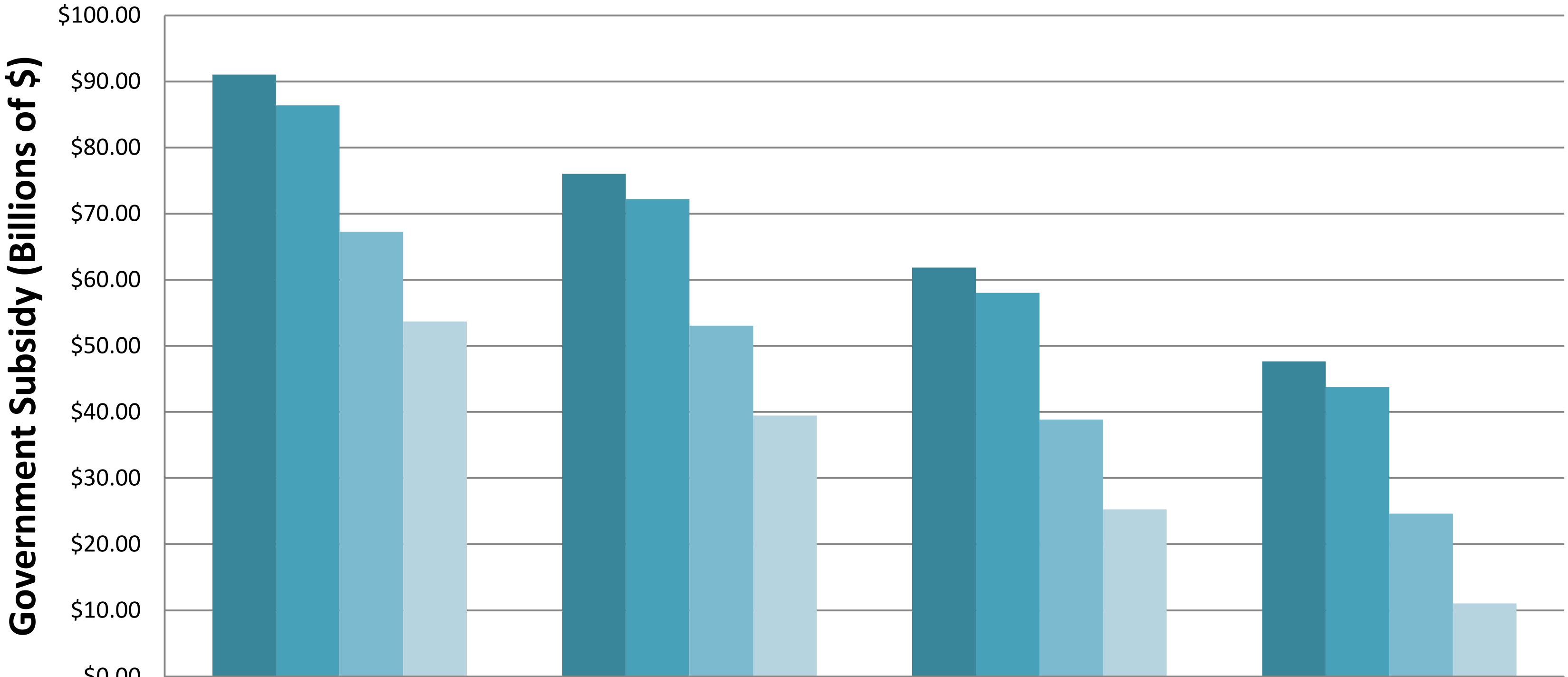
# Cumulative Probability Density for NOAK Levelized Cost of Electricity ($/MWh)

Small Modifications to Key U. of Chicago EPIC Model Assumptions



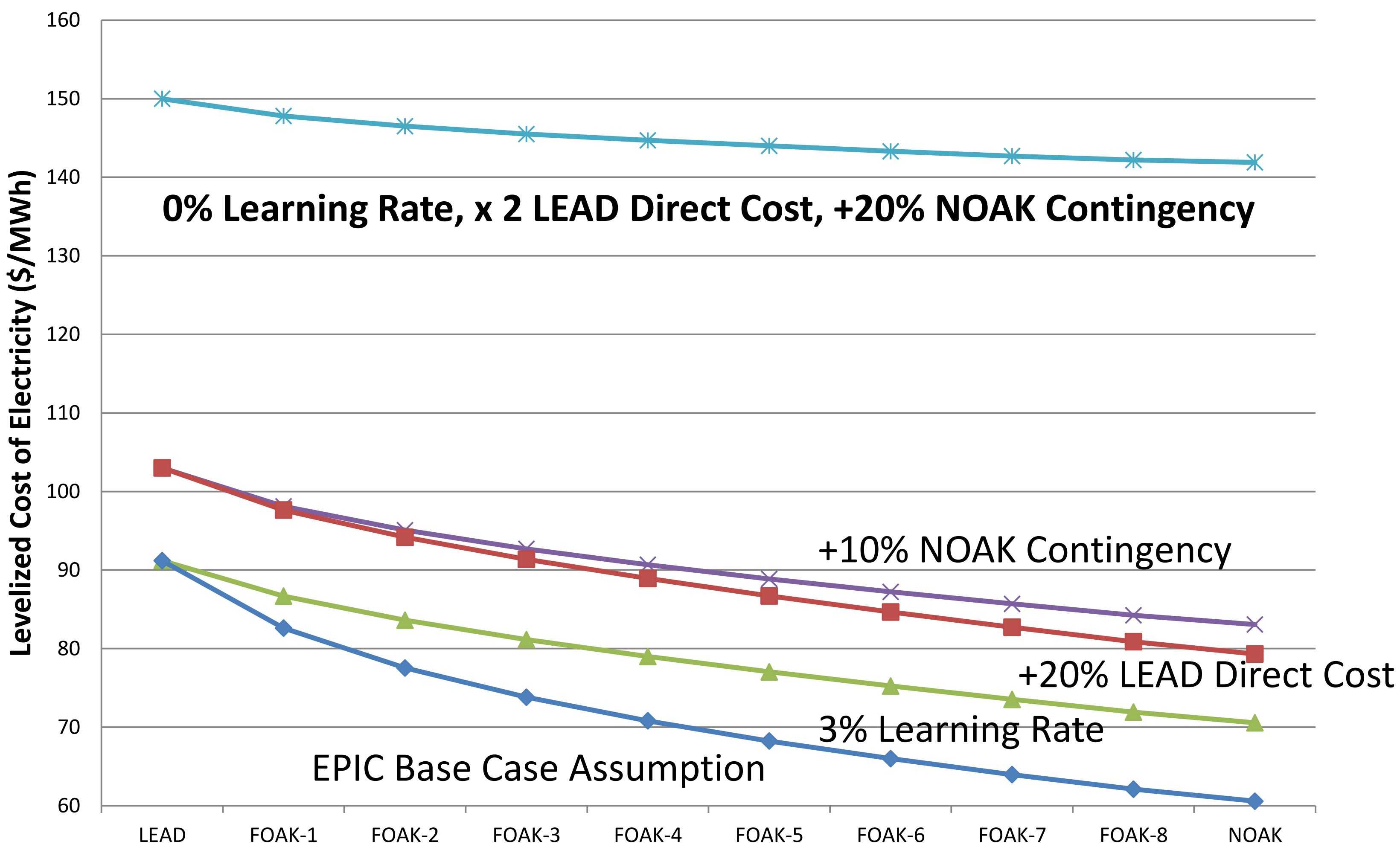
# Understanding the Potential Scale of Government Subsidies for the First 60 SMRs

## Small Modifications to Key U. of Chicago EPIC Model Assumptions

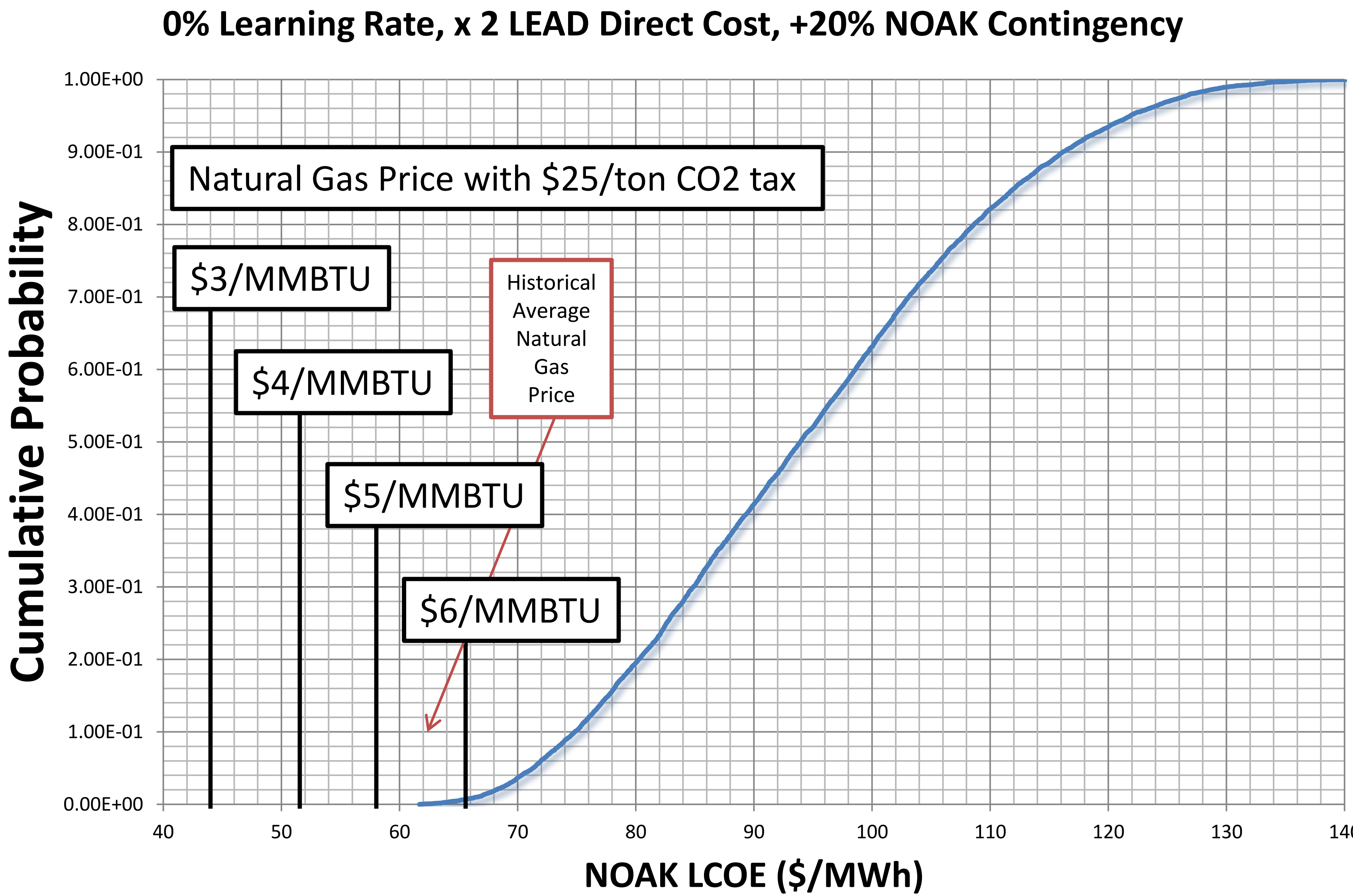



| Natural Gas Price | 3% Learning Rate, +20% LEAD Direct Cost and +10% NOAK Contingency | 3% Learning Rate and + 20% LEAD Direct Cost | 3% Learning Rate | EPIC Modeling Assumptions |
|---|---|---|---|---|
| $3/MMBTU | $91.03 | $76.03 | $61.83 | $47.64 |
| $4/MMBTU | $86.38 | $72.22 | $58.00 | $43.79 |
| $5/MMBTU | $67.26 | $53.04 | $38.85 | $24.63 |
| $6/MMBTU | $53.67 | $39.46 | $25.27 | $11.06 |

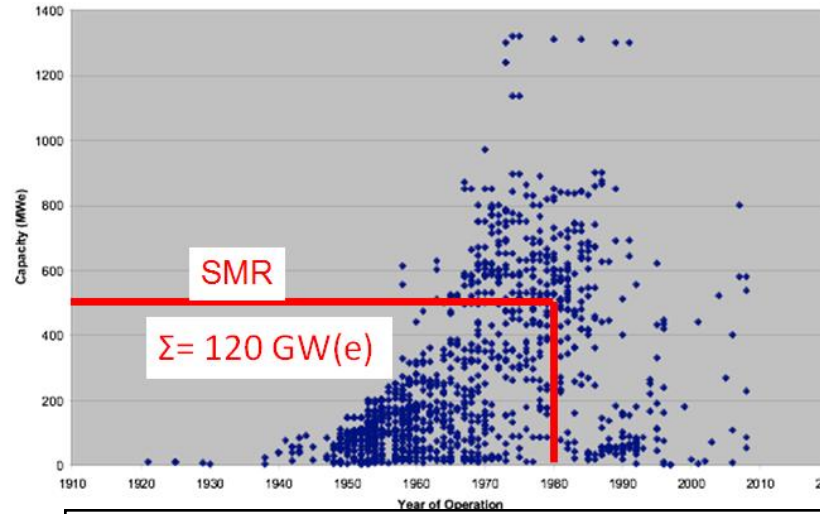
# Larger Modification to Key Assumptions within the U. of Chicago EPIC SMR Economy Model:



# Cumulative Probability Density for NOAK Levelized Cost of Electricity ($/MWh)



# Coal Replacement Has Been Suggested as a Domestic Market for SMRs




Pete Lyons, Presentation for SEAB SMR Subcommittee, March 9, 2012

## Statistical Plots of Coal Replacement Potential Ignore Key Issues:

Some Coal Generators:
- Are Associated with Business and Universities;
- Are Already Designed to Use Natural Gas as a Secondary Fuel;
- Can Incorporate Carbon Capture Technology;
- Are Already Being Replaced by Natural Gas Generators (Barry, AL);
- Are on Sites Unsuitable for Nuclear Power Due to Nearby Population Density.

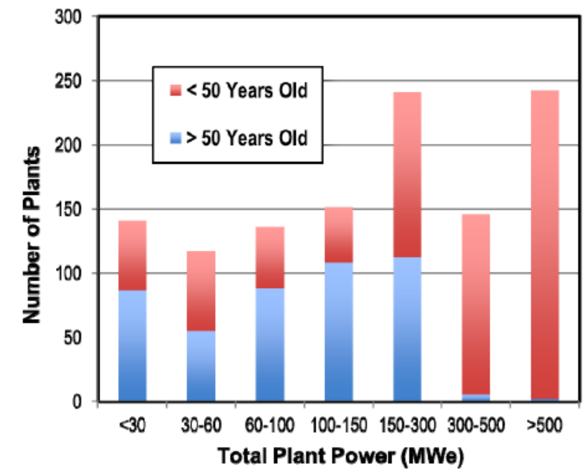



FIGURE 5 Distribution of Coal Power Plants by Generation Size and Age (2030)[51]

Rosner and Goldberg, November 2011

# What do the Direct Costs Estimates from the Vendors Assume with Regard to Resolving Regulatory Uncertainties?

- Emergency Planning Zone Radius
- Underground Siting
- Staffing and Security Requirements
- Refueling

# BROAD CONCLUSIONS AND QUESTIONS ON SMRs

In formulating conclusions and recommendations, there must be a full account of the wide range of unknowns and uncertainties, and difficult questions posed that require further analysis and resolution before large public sums are committed to an SMR industrialization strategy.

**The history of DOE is littered with DD&E programs or reactors that never found a home in the commercial marketplace, and thus there was never a return on the investment for US taxpayers or humanity at large.**

Our presentation has focused on the sensitivity of the U. of Chicago EPIC model's projected SMR economic viability in the US context to modest variations in assumptions for industrial learning rates, LEAD unit direct costs, required contingency funds,  and the future levelized cost of natural gas combined cycle generation.

But the range of SMR uncertainties extends well beyond variations in this narrow set of modeled parameters, and includes the following 12 issues:

# CONCLUSIONS AND QUESTIONS ON SMRs

1. Not all learning curve cost reductions derive from the same source, or occur uniformly over time. They are both time dependent and technology specific, and thus difficult to forecast accurately unless the details of the technology and production processes involved are already well understood. Early in the production cycle, sharp cost reductions can be expected going from the early LEAD units comprising the first plant to the next 6-12 FOAK plants built on an assembly line. But after these reductions, the rate of cost improvements could well decelerate or even disappear altogether, not only because of the law of diminishing returns to further capital investment at a given level of production, but also because "learning" works both ways, sometimes uncovering design or production defects that require increased costs to remedy.
2. The "negative learning" evident in the highly centralized and relatively standardized French nuclear program, is most likely the result of increased knowledge of, and required attention to, nuclear safety and quality control issues with each succeeding large LWR variant.
3. Another source of uncertainty is the reliability of component supplier and system vendor cost projections – the well known problem in noncompetitive markets of companies offering "buy-in" prices to the government and any commercial customers to get them "hooked," in the belief that either prices can be raised later, or costs recovered through the sale of larger numbers of components and systems than are actually represented in the forecast market demand.

# CONCLUSIONS AND QUESTIONS ON SMRs

4. Will international competition at the system vendor level help or inhibit the kind of dramatic cost reductions that are needed to make SMR's a viable factor in mitigating global climate change? If several significantly different SMR designs, each with their own customized supply chains, are dividing-up limited domestic and international markets, how does any one vendor reach the stage of "commoditizing" production of the various constituent components in its plant, thereby significantly reducing its cost.
5. This process of wringing out cost in the production of components in turn requires reductions in *the cost of the capital equipment* needed to mass produce these commodity components, which reduction (in required capital cost per unit output) has been the real source of final product cost reductions in the electronics and solar PV and many other industries. What evidence is there that SMR reactor vessels, for instance, will cost less to produce per kilowatt of capacity than those produced for large LWR's?
6. Is significant price competition among suppliers of key components, each susceptible of incorporation in multiple SMR designs – in place of a unique supply chain for each design -- also needed to achieve long term economies in the manufacture of SMR components.

# CONCLUSIONS AND QUESTIONS ON SMRs

7. What is the evidence for the proposition that nuclear-safety-grade steel forgings, concrete, pumps, piping, welds, wiring, and instrumentation will be appreciably cheaper in the future than they are now, and if not, what does the alleged cost-reducing "learning" actually consist of? The argument appears to be that the direct labor costs of integrating these components will be less, and achieved more rapidly, in a factory environment than at a construction site. But even if this is assumed to be true *to some extent*, given that the direct materials costs-per-kilowatt *must increase* when you build five or six reactors to achieve the same output as one large one, what evidence is there that the required labor-hours-per-kilowatt-of-capacity will go in the opposite direction, and *far enough to more than offset* the increased materials costs per kilowatt?
8. What is the evidence that staffing and O&M will be cheaper to operate and to maintain six 200 MW units rather than one 1200 MW unit, and if it is not cheaper, where will the necessary offsetting cost reductions be found, such that the levelized SMR electricity cost is in an acceptable price range for future low carbon resources.
9. Are current SMR vendor cost projections predicated on implicit assumptions linking prospective SMR "passive safety" improvements to streamlining and relaxation of current commercial LWR safety requirements that dictate costly requirements for emergency planning , operator staffing, and maintenance and inspection of safety related systems and components .

# CONCLUSIONS AND QUESTIONS ON SMRs

10. Could the longer proposed refueling interval (e.g. five years), intended to reduce O&M costs, create new safety issues in certain accident scenarios and actually add to costs by reducing the total energy output of the reactors?
11. A key question to consider is whether, in light of the above concerns, whether a nationally-focused SMR DD&E and deployment effort even makes sense. Is it plausible to believe that working on its own, DOE and a few U.S. vendors can development the SMR hardware, identify the a sufficiently large customer base, finance the sale, and economically construct a large fleet of SMRs. As we have noted, at least in the near to medium term, the "coal replacement" market for SMR's seems implausible in the light of competition from natural gas, although this could change over a longer time period, and the capital costs of constructing reactors in the U.S..
12. Are there national policies, such as carbon taxation and stricter environmental regulation of natural gas, that are REQUIRED accompaniments of an SMR deployment strategy, the absence of which makes the whole enterprise, at least on a national basis, seem hopeless?

**To avoid yet another failed DOE reactor development program that spends a billion or more of the taxpayers money and then grinds to a halt for want of any economically rational deployment strategy, the panel and DOE must seriously consider these questions before committing additional resources in pursuit of SMR development.**

# Bottom Lines

- If the government  intends to invest $452 million to certify designs and resolve NRC licensing issues, complete this program before offering further government subsidies for SMR development.
- In the US, the capital cost/kW of SMRs are high and the cost of natural gas is low. The market for SMRs would be far more attractive in countries where capital costs are lower and gas prices are higher.

# Extra Slides


James M. Barry Electric Generating Plant (AL): five coal-fired units, which came online in 1954–1971, with respective generating capacities of 138 MW, 137 MW, 249 MW, 362 MW, and 750 MW. Five natural gas-fired units, including three combined cycle combustion turbines (173 MWe each of winter capacity) and two combined cycle steam turbines (193 MWe each of winter capacity), were installed in 2000.

# Assumptions within EPIC SMR Economy Model: