THE ECONOMIC FAILURE OF NUCLEAR POWER AND THE DEVELOPMENT OF A LOW CARBON ELECTRICITY FUTURE:

WHY SMALL MODULAR REACTORS ARE PART OF THE PROBLEM, NOT THE SOLUTION

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EXECUTIVE SUMMARY

The ongoing collapse of nuclear power in the U.S. is readily apparent in the failure to launch 90 percent of "nuclear renaissance" reactors, delays and cost overruns for those that got started, the cancellation of projects to increase the capacity of existing reactors, and the early retirement of aging reactors. To reverse its fate, the U.S. nuclear industry has

- gone in search of a new technology to champion (small modular reactor [SMR]),
- launched an aggressive campaign to sell nuclear power as the primary solution to climate change, and
- sought to slow the growth of alternatives with vigorous attacks on the policies that have enabled renewable resources to grow at record levels.

Thus the collapse has lent greater intensity and significance to the 50-year debate over the economic viability and safety of commercial nuclear power:

- It is not only the fate of nuclear power at stake, but also the fundamental direction of the policy response to climate change.

This paper examines the fundamental choice policymakers are being asked to make. It reviews the prospects for nuclear technology in light of the past and present performance of nuclear power (Section I), assesses the economic and safety challenges that SMR technology faces (Section II) when confronting the alternatives that are available today (Section III), and the trends that are transforming the electricity sector (Section IV).

- The paper shows that nuclear power is among the least attractive climate change policy options (too costly, too slow, and too uncertain) and is likely to remain so for the foreseeable.
- The paper demonstrates that, worse still, pursuing nuclear power as a focal point of climate policy diverts economic resources and policy development from critically important efforts to accelerate the deployment of solutions that are much more attractive – less costly, less risky, more environmentally benign.

LEARNING PROCESSES AND NUCLEAR REACTOR COST TRENDS

The troubling track record: The experience of construction cost escalation in the U.S. and France, two nations that account for the majority of reactors built in advanced industrial market economies, shows that there is little in the track record of nuclear power to suggest that learning and innovation will solve the nuclear cost problem any time soon. Even after the purported learning processes within a technology have taken place, each subsequent technology results in higher cost. The larger the technological change, the larger the ultimate cost increase.

Small Modular Reactors are likely to suffer similar problems: SMR technology represents a particularly challenging leap in nuclear technology that is likely to suffer greatly form the historic problems of nuclear power. SMR technology will suffer disproportionately from material cost increases because they use more material per MW of capacity. The novel, even radically new design characteristics of SMRs pose even more of a challenge than the failed "nuclear renaissance" technology. The untested design and the aggressive deployment strategy for SMR technology raise important safety questions and concerns. Cost estimates that assume quick design approval and deployment are certain to prove to be wildly optimistic.

The technology is already failing the market test: Two of the leading U.S. developers have announced they are throttling back on the development of SMR technology because they cannot find customers (Westinghouse) or major investors (Babcock and Wilcox). The harsh judgment of the marketplace on SMR technology is well-founded.

THE DIM PROSPECTS FOR SMALL MODULAR REACTORS

Unachievable assumptions about cost: Even industry executives and regulators believe the SMR technology will have costs that are substantially higher than the failed "nuclear renaissance" technology on a per unit of output. The higher costs result from

- lost economies of scale in containment structures, dedicated systems for control, management and emergency response, and the cost of licensing and security,
- operating costs between one-fifth and one-quarter higher, and
- decommissioning costs between two and three times as high.

Irresponsible assumptions about a rush to market: To reduce the cost disadvantage and meet the urgent need for climate policy, advocates of SMR technology propose to deploy large numbers of reactors (50 or more), close to population centers, over a short period of time. This compressed RD&D schedule embodies a rush to market that does not make proper provision for early analysis, testing, and demonstration to provide an opportunity for experience-based design modifications. This is exactly the problem that arose in the 1970s, when utilities ordered 250 reactors and ended up cancelling more than half of them when the technology proved to be expensive and flawed.

Unrealistic assumptions about the scale of the sector: While each individual reactor would be smaller, the idea of creating an assembly line for SMR technology would require a massive financial commitment. If two designs and assembly lines are funded to ensure competition, by 2020 an optimistic cost scenario suggests a cost of more than $72 billion; a more realistic level would be over $90 billion. This massive commitment reinforces the traditional concern that nuclear power will crowd out the alternatives. Compared to U.S. Energy Information Administration (EIA) estimates of U.S. spending on generation over the same period, these huge sums are equal to

- three-quarters of the total projected investment in electricity generation and
- substantially more than the total projected investment in renewables.

Radial changes in licensing and safety regulation: SMR technologies raise unique safety challenges including inspection of manufacturing and foreign plants, access to below ground facilities, integrated systems, waste management, retrieval of materials with potentially higher levels of radiation, flooding for below-ground facilities, and common designs that create potential "epidemic" failure. Yet ,SMR advocates want pre-approval and limited review of widely dispersed reactors located in close proximity to population centers and reductions in safety margins, including shrinking containment structures, limitations of staff for safety and security, consolidation of control to reduce redundancy, and much smaller evacuation zones. In the wake of global post-Fukushima calls for more rigorous safety regulation, policymakers and safety regulators are likely to look askance at proposals to dramatically relax safety oversight.

Unfounded claims of unique supply and demand advantages: Despite their high costs, advocates argue that smaller reactors are more attractive than large reactors because they are more flexible, requiring smaller capital commitments and shorter construction times.

- By these same criteria, non-nuclear alternatives are far more attractive – smaller, less costly, quicker to market, and already scalable.
- The alternatives also do not possess the security and proliferation risks and environmental problems that attach to nuclear power.

BRIGHT PROSPECTS FOR ALTERNATIVE RESOURCES

Nuclear cost escalation provides half of the explanation for the economic failure of nuclear power. The other half is provided by the superior economics of alternatives. In the 1980s nuclear could not compete with coal and natural gas. Today it cannot compete with gas and a number of renewable resources.

Declining cost of alternatives: Wind and solar technologies are exhibiting dramatic declines in costs driven by innovation and economies of scale that have eluded nuclear for half a century. Improvements in design and operation efficiency, declining material and construction costs, and developments in storage technology have doubled renewable load factors in recent years. The trend is so strong that financial analysts have concluded that these renewable technologies are already cost competitive with natural gas, or soon will be, which makes them much less costly than current or projected nuclear reactors.

Downward pressure on peak prices: The increasing reliance on renewables and demand response reduces the sharp rise in peak load prices that have traditionally provided the scarcity rents that fund capital intensive facilities. The downward pressures will increase as reliance on decentralized resources increases.

THE RISE OF A 21ST CENTURY ELECTRICITY SYSTEM

The emergence of an integrated, two-way electricity system based on decentralized alternatives reduces the value and importance of baseload generation: The emerging electricity system relies on a dramatic increase in information, computational, and control technologies to intensively manage two-way flows in a system that integrates decentralized, diversified supply-side resources and actively manages demand. It causes a sharp reduction in demand and need for central station, baseload generation.

The inevitable conflict between nuclear power and the 21st century electricity system: The physical and institutional infrastructure to support an active 21st century electricity system is markedly different from and antithetical to the passive, one-way grid on which nuclear relies. In response, even though nuclear technologies have received 10 times as much subsidy on a life cycle basis, nuclear advocates attack the much smaller and more productive subsidies received by renewables. To save nuclear power they propose to jerry-rig markets with above-market prices to increase nuclear profits and remove the regulatory institutions that have allowed alternatives to enter the electricity resource mix.

Given this analysis, it is safe to say that nuclear power is part of the problem, not the solution: When it comes to making the case for SMRs as one of the cornerstones of the 21st century, low carbon electricity sector is remarkably weak.

First, the viability of SMRs is dependent on the very economic processes that have eluded the industry in the past. The ability of the small modular reactor technology to reverse the cost trajectory of the industry is subject to considerable doubt. The empirical analysis of learning processes in the "Great Bandwagon Market" discussed in Section I and the failure of regulatory streamlining, advanced design and standardization in the "nuclear renaissance" certainly question the ability of the new technology to produce such a dramatic turnaround. As a result, even under the best of circumstances, the SMR technology will need massive subsidies in the early stages to get off the ground and take a significant amount of time to achieve the modest economic goal set for it.

Second, even if these economic processes work as hoped, nuclear power will still be more costly than many alternatives. Over the past two decades wind and solar have been experiencing the cost reducing processes of innovation, learning and economies of scale that nuclear advocate hoped would benefit the "Renaissance" technology and claim will affect the small modular technology. Nuclear cost curves are so far behind the other technologies that they will never catch up, even if the small modular technology performs as hoped.

Third, the extreme relaxation of safety margins and other changes in safety oversight is likely to receive a very skeptical response from policymakers. This is just the latest skirmish in a 50 year battle over safety. The push to deploy large numbers of reactors quickly with a new safety regime recalls the mistake of the early "Great Bandwagon Market."

Fourth, the type of massive effort that would be necessary to drive nuclear costs down over the next couple of decades would be an extremely large bet on a highly risky technology that would foreclose alternatives that are much more attractive at present. Even if the technology could be deployed at scale at the currently projected costs, without undermining safety, it would be an unnecessarily expensive solution to the problem that would waste a great deal of time and resources, given past experience.

Finally, giving nuclear power a central role in climate change policy would not only drain away resources from the more promising alternatives, it would undermine the effort to create the physical and institutional infrastructure needed to support the emerging electricity systems based on renewables, distributed generation and intensive system and demand management.

The paper concludes that the prudent approach to resource acquisition is to build the institutional and physical infrastructure that achieves the maximum contribution from the more attractive resources available in the near and mid-term. With a clear path of more attractive resources, we do not have to engage in the hundred year debate today, although there is growing evidence that prospects for high penetration renewable scenarios for the long terms are quite good. The available and emerging alternatives can certainly carry the effort to meet the demand for electricity with low carbon resources a long way down the road, certainly long enough that the terrain of technologies available may be much broader before we have to settle for inferior options like nuclear power.

INTRODUCTION

THE IMPLOSION OF NUCLEAR POWER IN ADVANCED INDUSTRIAL MARKET ECONOMIES

A decade after advocates of nuclear power loudly declared a "nuclear renaissance," the U.S. nuclear industry appears to be on its death bed.

- About 90 percent of the new reactors that were put on the table in response to the passage of the Energy Policy Act of 2005, which offered nuclear reactor construction a number of regulatory and financial incentives, have been cancelled or mothballed.[1]
- While nuclear advocates envisioned hundreds of nuclear reactors being built over the next couple of decades,[2] only four new reactors are actively under construction and those have suffered from cost overruns and construction delays.[3]
- Even more alarming for advocates of nuclear power, five aging reactors have been retired early[4] – two of which were online at the time and three of which had serious repair challenges – and over two dozen more have been declared at risk of early closure for economic reasons. [5]

The story is similar in other advanced industrial market economies that were seen as the potential leaders in deploying a new generation of nuclear reactors, e.g., the United States, Japan, and Europe.[6] The only reactors that are being built in Europe, by the French, are way behind schedule and over budget, while several nations, most prominent among them Germany, have declared their intention to reduce or eliminate their reliance on nuclear power. The proposal to build a French reactor in the United Kingdom with Chinese backing is being opposed by the European Competition Authority, which claims that the guaranteed price of electricity of more than $150/MWh (twice the current average price of electricity in the UK) is an illegal subsidy that will "freeze out competitors, including developers of renewable resources such as offshore wind power."[7]

With the collapse of the "nuclear renaissance," nuclear advocates have shifted their focus from the failed "renaissance" technology to the hope for the development of yet another "new" technology – SMRs. Yet this new technology has already suffered setbacks in the marketplace.

- Westinghouse, one of the leading U.S. developers of small modular technology and the vendor supplying the design for the large nuclear projects under construction in the U.S., announced it was stepping back from development of small modular nuclear technology. The retreat came even though its utility partner, Ameren had convinced the state of Missouri to spend $40 million supporting the technology.[8] The reason for the decision: Westinghouse could find no customers. Instead of pushing ahead to build SMRs, Westinghouse said it would focus on decommissioning of existing reactors.
- Babcock & Wilcox, one of the firms that had received a federal subsidy, also has stepped back from the development of SMR technology[9] because of the failure "to secure significant additional investors or customer engineering, procurement, and construction contracts to provide the financial support necessary to develop

> and deploy mPower reactors."[10] Slashing spending by three-quarters, the company declared it "still expects to license mPower reactor by the mid-2020s."[11]

In a market economy, a technology that can find neither customers nor investors has very little prospect of succeeding. In the current context of climate change, a technology that cannot be deployed for well over a decade is a laggard, to say the least, in the race to respond to climate change.

THE BROADER IMPLICATIONS OF THE COLLAPSE OF NUCLEAR ECONOMICS

The collapse of nuclear economics has two immediate and important implications for public policy.

- First, the industry has launched vigorous attacks on the market mechanisms that are setting the price of electricity in the Upper Midwest and the Northeast, where the operating aging reactors were closed,[12] and launched a broad campaign to undermine the policies that promote alternative approaches to meeting the need for electricity.[13]
- Second, they try to tie the fate of nuclear power directly to the policy response to climate change,[14] and some policymakers insist that the nuclear power be supported as a condition for moving climate policy forward.

While four prominent climate scientists have called on environmentalists to embrace nuclear power, arguing that "in the real world there is no credible path to climate stabilization that does not include a substantial role for nuclear power"[15] environmentalists overwhelmingly still oppose nuclear power as a climate change solution.[16] They do so not only because they object to its environmental and public health risks,[17] but also because it is seen as an uncertain technology that is, at best, an unnecessary, extremely expensive and inadequately slow way to address climate change.[18] They argue a commitment to nuclear power would impose much greater harm than in the past by delaying or distorting the reforms needed to make the transition to a low carbon electricity sector built on decentralized alternatives.[19]

- Thus, the debate over commercial nuclear power that has raged for more than half a century has taken on greater importance because it is not only about the fate of nuclear power, it is about the fundamental direction of climate policy.

PURPOSE AND OUTLINE

In the current conditions in the electricity sector clear, empirically grounded knowledge about the costs and prospects for new nuclear technologies, compared to other alternatives, is more important than ever. A comparison between the dramatic cost escalation of nuclear construction and the declining cost of alternatives not only provides an important context for evaluating the likely prospects for the next generation of nuclear reactors, but also a critically important input into policy-making decisions on how to meet the challenge of climate change.

This paper places the effort to drive public policy to make a major commitment to the development and deployment of nuclear power, particularly small modular reactors, in context by examining the historical evidence on the past failure of nuclear power (Section I), the economic challenges that SMRs face (Section II), the comparative advantages of the alternatives available today (Section III), and the development of a 21st century sector to meet the need for electricity in a low carbon environment (Section IV).

Section I does not regurgitate the long history of cost escalation in the nuclear industry, which is well known. Rather, it examines the state of knowledge about nuclear cost escalation in the U.S. and France, focusing on the question of whether learning will lower costs as new technologies are introduced, which is the key to the claim that SMRs will be cost competitive.

Section II examines the challenge facing SMRs. It shows that this technology is unlikely to be cost competitive with other low carbon resources neither in the mid-term time frame that climate scientists believe is critical to a successful response to climate change, nor in the long-term. Careful examination of the arguments for SMRs shows they are dubious at best, providing clear insight into why SMR advocates are having difficulties selling the idea to customers, investors, and policymakers.

Section III describes the current economic predicament of nuclear power in advanced industrial market economies by comparing it to the alternatives available. It identifies key trends that are driving the electricity sector toward a decentralized structure based on renewables, e.g., the declining cost of renewables and other technologies, like storage, dramatic increases in efficiency reducing the growth of demand, and improvements in information and control technologies to manage supply and demand. These trends are heading in exactly the opposite direction SMR technology wants and needs it to go.

Section IV underscores the fundamental choice that confronts policymakers by locating the debate over SMR technology in the context of the emerging institutional transformation of the electricity sector. It notes that the subsidies lavished on nuclear power far exceed the totals spent on alternatives, but the alternatives have performed much better.

I. LEARNING PROCESSES AND NUCLEAR REACTOR COST TRENDS

After half a century of secrecy, the French have recently ordered and made public an audit of the cost of building and operating the French nuclear fleet. France, which embraced nuclear power more completely than any other advanced industrial nation, was frequently cited as an example that other nations could emulate, but the decision to review the French program and make the results of the audit public was driven by severe difficulties that the effort to build new reactors had encountered and vulnerabilities in existing reactors revealed by the Fukushima nuclear accident.

Taken together, France and the U.S. represent almost half of all reactors built in market economies and research on cost escalation in these two nations represents a substantial knowledge base about the evolution of nuclear reactor construction costs.[20] A close look at the long-term trends in both the U.S. and France offers clear and sobering lessons about the industrial process of nuclear reactor construction and operation. Two major reviews of the French data have recently been published, both of which attempt to draw lessons from the French experience for future efforts to develop nuclear power. This section reviews the key economic drivers of nuclear construction costs and examines the nature and magnitude of the "learning effect" that has applied to nuclear technology in the past.

Interestingly the analysis by Rangel and Leveque[21] explicitly tested and affirmed the findings in several of our earlier papers published on the causes of nuclear cost escalation[22] and their relationship to nuclear safety.[23] In analyzing the new French data, Rangel and Leveque seek to refine and extend the model of nuclear reactor construction cost by slicing the French reactors into very small subsets of specific types. They find a small and weak "learning" effect[24] and suggest that this supports the case "that standardization is a good direction to look, in order to overcome the cost escalation curse."[25] While we also found a hint of "learning" at a very micro level of analysis of reactor construction, when looking at individual U.S. reactor builders,[26] it is important to have a clear understanding of how far this finding can carry the industry, particularly in comparison to the rapid decline in costs being exhibited by other generation technologies.

The second paper by Boccard[27] concentrates most of its effort on estimating the past and projecting the future cost of nuclear power in France and offers some conclusions about how cost escalation can be contained. While the paper reinforces our earlier analysis, here, too, caution is needed in interpreting the historical pattern because it offers advice based on a very narrow range of observations even though it shows that large changes in technology have been associated with large increases in cost, which is the challenge that SMR technology faces.

Our analysis sought to advance the understanding of the nuclear cost-escalation problem in a number of ways. In the analyses referred to by Rangel and Leveque we conducted the first econometric analysis of U.S. nuclear construction costs in more than a quarter of a century:

- including more completed reactors than had been analyzed in the past,
- operationalizing a number of important variables that affect nuclear construction costs, such as safety regulation and economic conditions,
- tying cost escalation to the need to improve the safety of nuclear reactors,

- adding data on more than 100 cancelled or abandoned reactors so that the first econometric analysis of "build-cancel" decisions could be conducted, and
- demonstrating that the commitment to nuclear power development tends to crowd out alternatives.

In a more recent analysis, not reviewed in these studies of French costs, we have demonstrated that the nuclear cost problem is not confined to the early building phase of the nuclear reactor lifecycle, but also afflicts nuclear waste management and reactor decommissioning[28] and leads to the early retirement of aging reactors.[29] The marketplace pressures on aging reactors and the response of the industry provide important insights into the larger conflict between nuclear power and the alternatives that is playing out across the U.S.

This paper extends the analysis to the prospects for the future nuclear technology that is being touted by the industry as the solution to the "curse" of nuclear cost escalation and the challenge of climate change.[30] The size and potential impact of this learning effect are quite limited. The cost-reducing effects of learning are very likely to be overwhelmed by the other cost-increasing factors that affect nuclear technology, especially when a new technology is introduced. Given the distressed state of the "nuclear renaissance" and the history of hyping new nuclear technology in the U.S., this very modestly positive learning result is likely to be seized upon by nuclear advocates and blown way out of proportion in the SMR context .

CAUSES OF COST ESCALATION AND LEARNING IN NUCLEAR CONSTRUCTION

Rangel and Leveque confirm our basic finding that nuclear costs escalated, rather than declined as more capacity was added. This has been the finding of all previous econometric analyses of nuclear costs.

> This component represents what Cooper (2010) denominated as the Bupp-Derian-Komanoff-Taylor hypothesis. This hypothesis states that as nuclear power industry (vendors and utilities) gained experience, bigger reactors were made and this technological scaling-up induced greater complexity which resulted in longer lead times.
>
> This is a well-known phenomenon in nuclear power, since the construction of larger reactors is more complex, hence such a project implies greater risk of cost overruns (Cooper [2010]) overall experience and lead time represents the main driver to explain the cost escalation… [a]n increase in the installed capacity will induce higher construction cost per MW.[31]

After affirming our earlier findings, Rangel and Leveque parse through their data in search of cost trends within subsets of reactors and reach a conclusion that also supports our earlier findings.

> Regarding overall learning effects, we also found that cumulated experience had not induced a reduction in costs. This result is often seen as a consequence of the intrinsic characteristics of nuclear power, i.e., lumpy investments and site-specific design (Cooper, 2010; Grubler, 2010).
>
> As mentioned before, Cooper (2010) suggests that with the construction of a new reactor, the experience gained by vendors and operators translates in adjustments and improvements that complexify the reactors and make the new designs more expensive than their predecessors. In the French case, Grubler (2010) and Finon (2012) argue that the potential learning effects from the overall industry experience were not fully exploited, precisely because as they gained experience, it was decided to construct an entirely new French nuclear reactor. Nevertheless, when we take into account the experience within the same palier and type, we find a positive learning effect…. [W]e

> can see that the estimates for these variables are negative, however, their effect was less significant than the other variables. [32]

Boccard's analysis focuses on a very narrow subset of the reactors built in France to conclude that cost escalation can be contained.

> All in all, the 48 Westinghouse reactors built during the 1980s (and completed over just 13 years) display an overall great stability with a limited 1.4% yearly growth rate of unit cost. This feat has been ascribed to the standardization made possible by having public monopolies EDF and Framatome focused on dedicated tasks. [33]

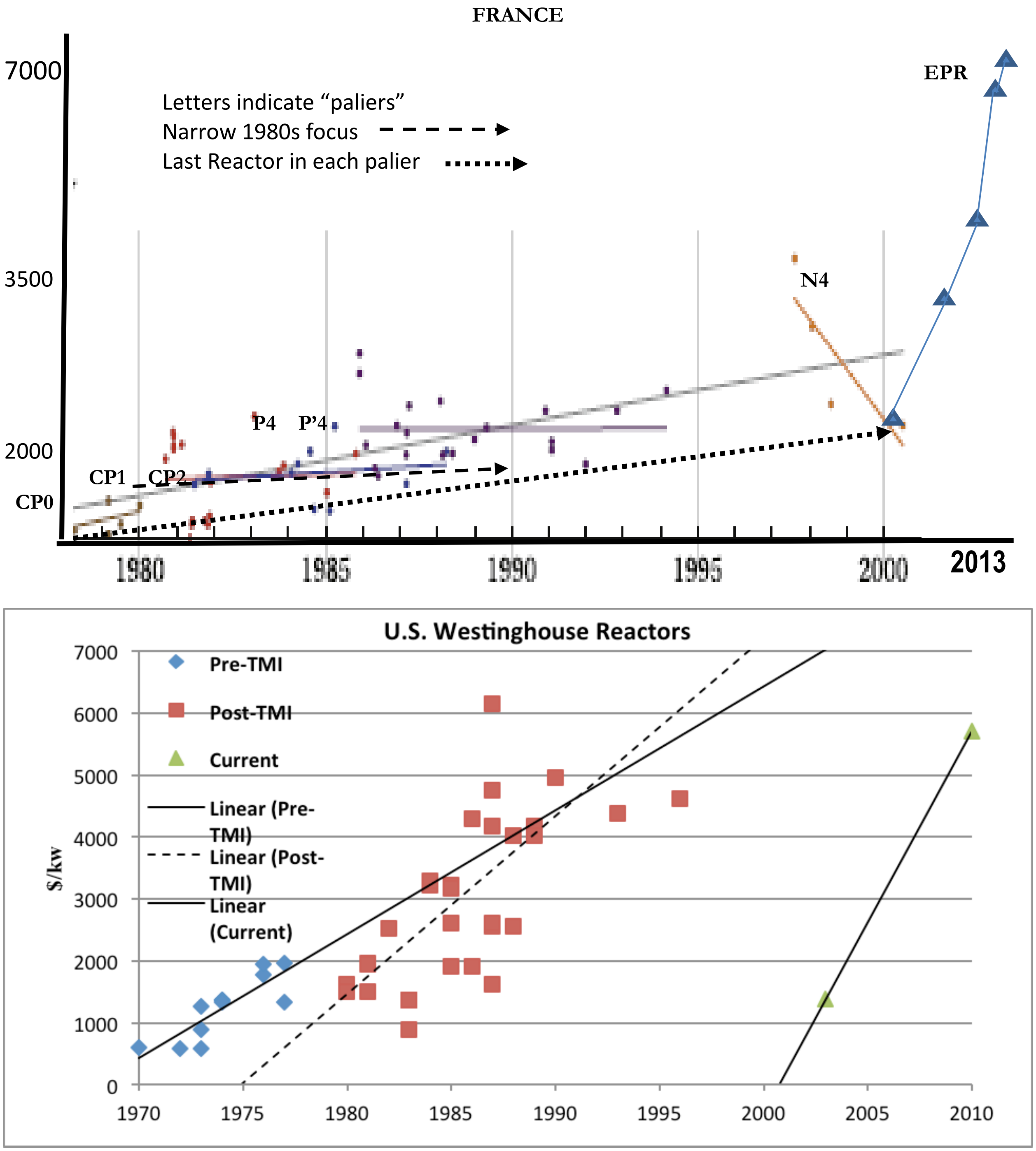
Exhibit I-1 shows the escalation of French and U.S. nuclear reactor construction across time. Time on the X-Axis serves as a proxy for industry experience and reactor size, as both scaled up over this period. The U.S. started its building program a little earlier than France with lower cost estimates. By the early 1980s, both nations were building reactors at about $2000/kw. As the U.S. pushed ahead with reactor construction in the late 1980s, the costs mounted and that trend has continued. Although the trend line for U.S. reactors was much higher, as the discussion below indicates, it is a better predictor of current cost projections than the French trend line, in part because the cost of developing and deploying new designs in France in the 1990s was hidden.

Focusing on the uniform technology in a short period, as Boccard does, can be misleading. This was the period in which the French were stamping out the imported U.S. technology. They were not implementing new designs, which yields a very low estimate of the cost escalation because it excludes the most difficult part of the process, developing, deploying and debugging new designs.

Exhibit I-1shows graphically how the analysis of the French data arrives at the conclusion that there is a learning effect. It shows that completed French reactors are divided into several technology categories, with some significant technological distinctions between them, even though they all share a basic technology (being pressurized water reactors). The figure shows that after the initial group of reactors, which exhibited rising costs through the construction of all reactors, four of the remaining five categories exhibit declining costs across the construction of the reactors in the category. Introducing new designs dramatically increases costs. Exhibit I-1 includes the "official" cost estimates for ongoing construction of the new French European Pressurized Reactor (EPR),[34] two of which are currently under construction in Europe (one in France – Flammanville – and one in Finland – Olkiluoto). The graph underscores the error of assuming that the end point of the last technology is a good indicator of the cost of the new technology.

Boccard offers four potential explanations for the dramatic increase in cost of the EPR – a post-Fukushima effect, the challenge of developing a new technology, the long delay in construction activity, and the possibility that earlier nuclear development costs were hidden in the French state budget.[35] Boccard estimates development costs at $10/MWh and notes that "This noteworthy cost item may partly explain why the novel EPR appears so expensive to build for there is nowadays less scope to bury such development cost into public accounts."[36]

Exhibit I-1: Overnight Costs within Technologies (PWR)



Sources: Boccard, Nicolas, 2014, “The cost of nuclear electricity: France after Fukushima,” *Energy Policy,* 66. Mark Cooper, *Policy Challenges of Nuclear Reactor Construction: Cost Escalation and Crowding Out Alternatives, Institute for Energy and the Environment*, Vermont Law School, September, 2010; *Nuclear Safety and Nuclear Economics, Fukushima Reignites the Never-ending Debate: Is nuclear power not worth the risk at any price?, Symposium on the Future of Nuclear Power,* University of Pittsburgh, March 27–28, 2012.

There are two additional potential explanations readily apparent in his historical analysis that are consistent with our earlier analysis and provide important context for extrapolating to the contemporary situation.

First, the technology was not only borrowed, but it was applied by a state monopoly that focused on building the same reactor repeatedly. "This feat has been ascribed to the standardization made possible by having public monopolies EDF and Framatome focused on dedicated tasks."[37] It is doubtful that one can extrapolate from the French case, with a single, largely state-owned builder, to the U. S. with multiple privately owned nuclear vendors. In our analysis of U.S. cost escalation, we examined the issue of cost escalation at the level of individual firms, which also generally controls for technology type, since most firms used a single technology and developed it over the years. While we found differences between the firms, all of them suffered from cost escalation. The largest builder produced a couple of dozen units and still suffered from cost escalation. In the statistical analysis, builder experience was a weak predictor of cost when controlling for technology type.

Second, the lower early French costs were achieved by adopting the U.S.-approved technology, and the farther the French got from that original design, the more the costs mounted. We should also not forget that the cost-escalation problem in the current design being deployed by the French started long before Fukushima, just as cost-escalation in the U.S. and France preceded Three Mile Island (TMI).

Boccard argues that the French program was an industrial success that was laid low by its own hubris combined with weak demand growth, more than its ineptitude.[38] However, he also notes that French nuclear power was fully utilized when French demand for electric heat was high in the winter, but could not find markets during slack periods of the summer because its power was too costly to export or unavailable.

> We thus come to the conclusion that the low capacity factor has a technical or organizational origin that EDF has not been able to solve for decades (and is therefore unlikely to improve upon in the future)… French nuclear power suffers from a rather hidden and indirect weakness as many of its assets are often unavailable to perform their basic duty, electricity generation.[39]

The bottom line that one can draw from this is similar to our conclusion about the American experience. If nuclear power had not suffered from high cost across reactor technologies, it would have been able to find markets.

THE DANGERS OF EXTRAPOLATION

The small learning effects observed in the French data set suggests that there are significant limitations on their importance that demand great care in using them to project the cost pattern for new technologies. Calculations within the analysis that demand caution in interpreting the results of the analysis include the following:

- The size of the learning effect is relatively small and statistically weak.
- The other negative, cost-increasing effects of adding a reactor reduce or

eliminate the positive, cost-reducing benefits of learning. That is, adding a reactor "at the mean" of the data set, which is a routine approach, increases costs.

- Introducing new technologies raises the cost significantly, to the point at which the reduction of cost within the technology as more units are added did not quite offset the increase in cost associated with introducing the technology.
- The final reactor in each subset tends to be as costly as, or more costly than, the final reactor in each previous subset. This is an important consideration when contemplating new technologies.
- The larger the technology leap, the bigger the increase in cost. The cost of the current technology – the EPR – is well above the cost of the last technology.

The weakness of the learning effect observed within a very narrow range of technological change is magnified when trying to extrapolate to a very different technology. The dangers of extrapolating beyond the analysis are substantial.

- Scaling up by 60 percent may be very different than scaling down 75 to 90 percent, which is what the SMR technology does.
- The magnitude of learning observed in the last two rounds of reactor construction involved a reduction of 25 percent in cost over a relatively small number (10) of reactors. Leaping to an assumption of a reduction that is twice as large over large numbers of units (54), exceeds the limits of reasonable extrapolation.
- Rates of learning in other technologies are much higher. Nuclear reactor construction is like a racer who starts behind the competitors and is accelerating at a slower pace. This is not a strategy that has much, if any chance of victory.

These observations tie directly into the debate over SMR technology because SMRs constitutes a relatively large change in the design. The expectation based on history is that the initial costs will be much higher and, while the process of learning may lower the cost somewhat, the final cost will still be higher than the previous technology. As discussed below, that is exactly what the direct analysis of SMR costs concludes. If we use the categories of technologies offered by Rangel and Leveque, history is set to repeat itself for the seventh time.

NUCLEAR SAFETY AND NUCLEAR COST

Rangel and Leveque confirm our basic finding that nuclear costs are driven by nuclear safety measures.

> According to Cooper (2012), safety variables (fines and the number of safety standards and rules adopted by the NRC) are the most consistent predictors to explain the cost escalation in the U.S. In previous studies (Komanoff, 1981; Zimmerman, 1982; Cantor and Hewlett, 1988; and McCabe 1996), safety improvements were related with the stringency of the regulatory agency which was represented with a time trend always found to be significant and positive.[40]
>
> In view of the results regarding the safety indicators, it appears likely that reducing the risk of a serious accident has also played its part in the French cost escalation, as it was found by Cooper (2010) for the U.S case. Our model shows that in the conception of new nuclear reactors, safety

> improvements are undertaken (reflected in better safety indicators). In consequence when safety concerns are partly internalized in the construction costs, safer reactors are inherently more expensive…
>
> For this reason, the economics of safety is perhaps the most challenging issue for the future of nuclear power… [T]he particular nature of serious nuclear accidents, huge damages but very low and uncertain probability of occurrence, makes it difficult to determine if the safety investments are cost-effective.[41]

Standing the U.S. and French safety/cost experiences side-by-side serves several important functions.

- Since there was no major accident in France, it helps to get past the claim that an overreaction to the Three Mile Island accident caused the problem. The nuclear safety problem is global, responding to the performance problems of reactors anywhere, a process affirmed in reaction to Fukushima.[42]
- Our econometric analysis measured safety by the number of rules and fines for violating rules. Rangel and Leveque measured it by the reduction in incidents at nuclear reactors and found that as costs increased, incidents declined. Qualitatively, our data shows the same relationship. From the mid-1970s to the late 1980s, incidents and outages were associated with increases in rules and fines. With the new safety regime in place, the number of incidents and outages declined – although they did not disappear.

Boccard emphasizes the break in the U.S. trend after TMI, which we noted. But as Exhibit I-1, shows when focusing in on the single design, the difference between the pre- and post-TMI trends is not that great. Boccard uses this to suggest that there may be a similar Fukushima effect, a "likely tightening of security regulation." Boccard puts operating cost increases to reflect post-Fukushima concerns at 4–5 percent of the total levelized total cost of new reactors. Although capital cost impacts are mentioned, they are not quantified.

These findings that nuclear safety drives nuclear costs highlights the inevitable question that nuclear safety confronts – is it worth the cost? It is extremely difficult to value accidents that do not happen. In fact, it is difficult to value accidents that do happen. While a great deal of attention has been focused on deaths and public health impacts from nuclear accidents and incidents, Chernobyl and Fukushima make it clear that economic disruption, social dislocation, and psychological despair are severe costs of major accidents. Tokyo Electric Power Company, at the time the fourth-largest electric utility in the world, did not go almost immediately into virtual bankruptcy because of the immediate public health impacts of the meltdown.

If safety measures are successful, nothing happens, which invites the claim that less could have been done at lower cost and nothing would have happened. Yet, nuclear operators have always insisted on socializing the risk of nuclear accidents with limitations on their liability (e.g., the regular Congressional renewal of the industry indemnifying Price Anderson Act).[43] They are unwilling to test the proposition that less safety regulation is better by accepting full private responsibility for safety. These results show that "blaming" nuclear safety regulation for nuclear cost escalation is a mistake. Poor performance made the safety regulation necessary, and those regulations had the intended effect of reducing, but not eliminating incidents.[44] Regulation also caused investment and innovation that improved performance.[45]

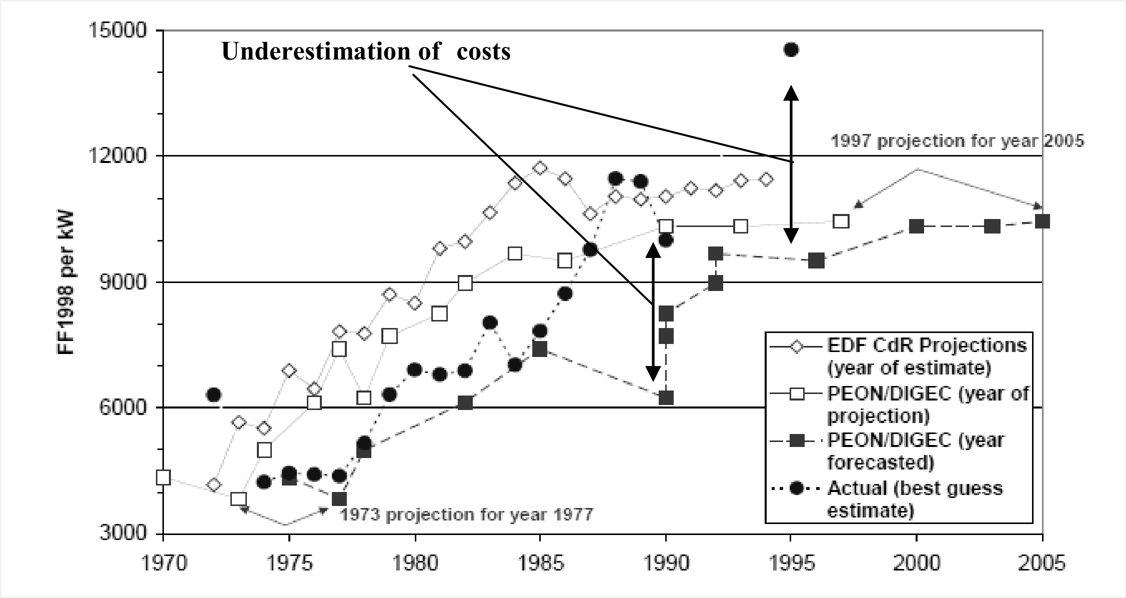
The 50-year debate over safety and the experience with improved safety in response to increased regulation is highlighted in the debate over SMR technology. SMR advocates are demanding a radical change in the approach to licensing and safety to move the technology ahead quickly. The rapid and dramatic reduction in oversight demanded by the advocates of SMR technology is necessary to prop up the economic prospects of the technology and to sell it as a response to climate change, but such a reduction raises concerns, given the effectiveness of safety regulation.

THE PERSISTENT UNDERESTIMATION COSTS

Over the course of almost three decades of building nuclear reactors, there is little evidence that learning or economies of scale lower costs in the nuclear sector. Yet the most obvious failure of learning in the nuclear industry is the failure of those estimating costs to learn from the nuclear track record. They failed to improve their cost projections. Referring to Exhibit I-2, Grubler describes the French problem as follows:

> Apparently, the projections no longer served their original purpose—to communicate the benefits of the nuclear program within France's technocratic elite—but were rather instrumentalized—so as not to add insult to injury—to communicate an economic success story whilst distracting from the difficulties encountered with the problem N4 reactors. Ever since, the cost projections have further lost their credibility and usefulness in public discourse and decision-making.[46]

EXHIBIT I-2: FRENCH COST UNDERESTIMATION



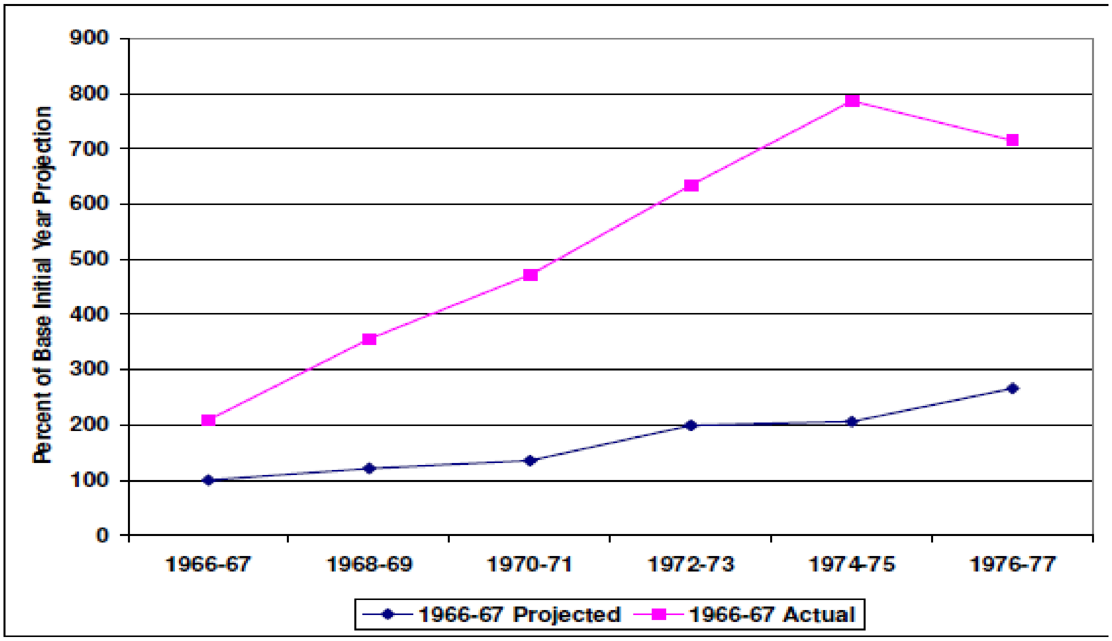
Source: Arnulf Grubler, 2010, "The costs of the French nuclear scale-up: A case of negative learning by doing," ***Energy Policy,*** **38. Figure 11.**

As bad as the projection of the N4 technology costs was in France, as show in Exhibit I-1 above, the dramatic difference between the initial estimates of the new French EPR reactor and the current estimates, would make it the worst underestimate in the French experience.

Bupp and Derien identified the same problem of persistent cost underestimation with respect to the U.S. data, as summarized in Exhibit I-3.

> Costs normally stabilize and often begin to decline fairly soon after a product's introduction… the reactor manufacturers repeatedly assured their customers that this kind of cost stabilization was bound to occur with nuclear power plants. But cost stabilization did not occur with light water reactors… The learning that usually lowers initial costs has not generally occurred in the nuclear power business. Contrary to the industry's own oft-repeated claim that reactor costs were "soon going to stabilize" and that "learning by doing" would produce cost decreases, just the opposite happened. Even more important, cost estimates did not become more accurate with time.[47]
>
> From the available cost records about changing light water reactor capital costs, it is possible to show that on average, plants that entered operation in 1975 were about three times more costly in constant dollars than the early commercial plants competed five years earlier. [48]

EXHIBIT I-3: U.S. COST UNDERESTIMATION

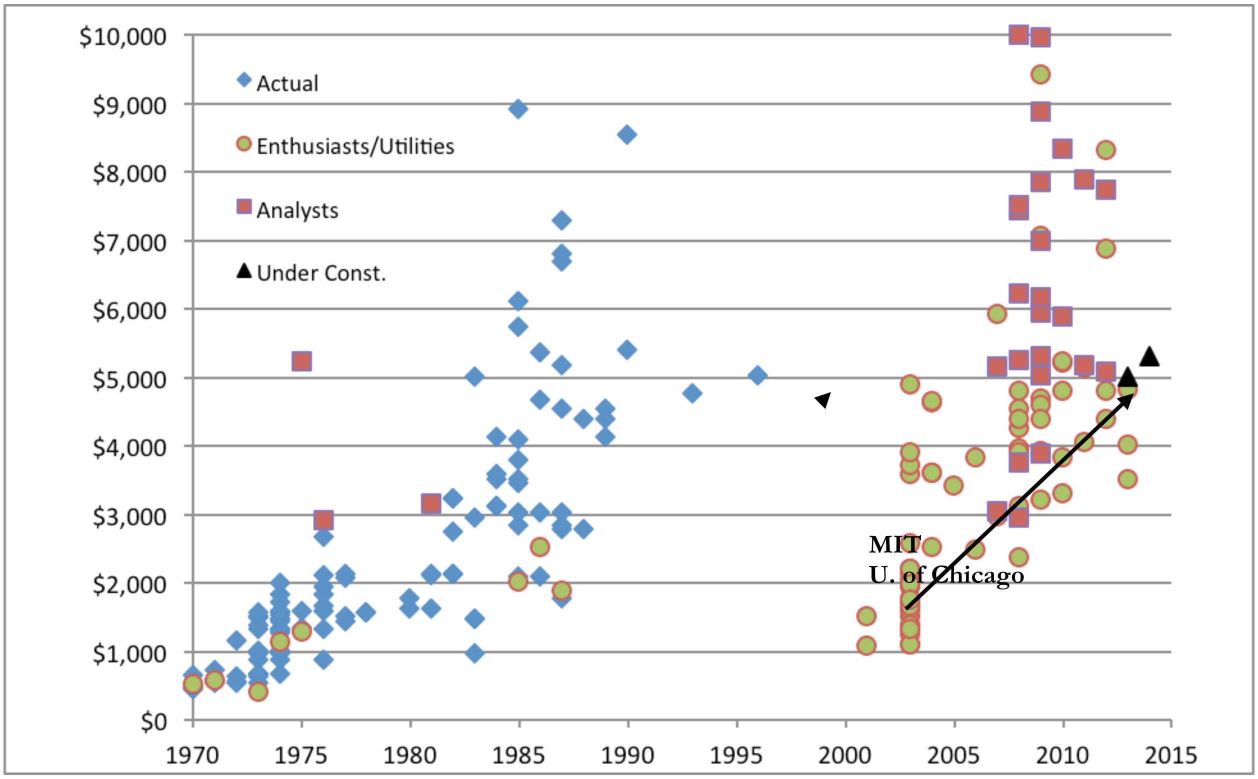


Source: Energy Information Administration, *An Analysis of Nuclear Power Plant Construction Costs*, January 1, 1986.

Much as in the French case, the projection of costs in the U.S. has gotten worse when the initial projections are compared to later projections and ongoing construction cost estimates. Exhibit I-4 shows the history of the cost of completed reactors and those under construction in the U.S. from a different perspective than in Exhibit I-1, above. In Exhibit I-4 we include the range of estimates for the "nuclear renaissance" reactors, with the sources of the estimates and the projections for those that are under construction.

Needless to say, this failure of cost projections should be a loud alarm for the SMR debate. As shown in the next section, the "hype cycle," with vendors offering unrealistically low-cost projections and others putting forward much higher projections, which prove to be closer to reality, is well under way for SMR technologies. Ironically, past low estimates were driven by assumptions about cost-reducing processes– economies of scale, learning by doing, and regulatory relaxation – that vendors said would kick in, but never did. This is the historical link and background to the current "hype cycle" surrounding SMRs where it is hoped that the cost-reducing processes that have failed to appear in the past will finally arrive.

EXHIBIT I-4: OVERNIGHT COSTS: ACTUAL AND PROJECTED COSTS: United States



Sources: Mark Cooper, *Policy Challenges of Nuclear Reactor Construction: Cost Escalation and Crowding Out Alternatives, Institute for Energy and the Environment*, Vermont Law School, September, 2010; Mark Cooper, *Nuclear Safety and Nuclear Economics, Fukushima Reignites the Never-ending Debate: Is nuclear power not worth the risk at any price?, Symposium on the Future of Nuclear Power, University of Pittsburgh, March 27–28, 2012.*

II. THE DIM PROSPECTS FOR SMALL MODULAR REACTORS

THE NUCLEAR HYPE CYCLE: DÉJÀ VU ALL OVER AGAIN[49]

At the start of the "nuclear renaissance" nuclear advocates argued that streamlining the regulatory process would allow advanced nuclear reactors with more passive safety design and standardized production processes in the third generation of commercial technology to be built quickly and deliver electricity at much lower cost. In less than a decade, the nuclear industry was force to admit that scaling up already huge gigawatt scale reactors in the "nuclear renaissance" had failed to make them cost competitive. The industry changed direction, hypothesizing that learning and standardization applied to the production of larger numbers of smaller units, rather than very small numbers of very large units, would do the trick. Under all circumstance, the key, constant demand they make is for a relaxation of licensing and safety requirements.

The vendors and academic institutions that were among the most avid enthusiasts in propagating the early, extremely optimistic cost estimates of the "nuclear renaissance" are the same entities now producing extremely optimistic cost estimates for the next nuclear technology.[50] We are now in the midst of the SMR hype cycle.

- Vendors produce low-cost estimates.
- Advocates offer theoretical explanations as to why the new nuclear technology will be cost competitive.
- Government authorities then bless the estimates by funding studies from friendly academics.

It is a pattern we have seen repeatedly in the nuclear sector, as described in the following analysis from a 1978 critique of the industry by Bupp and Derien.

> At the beginning of 1970, none of the plants ordered during the Great Bandwagon Market was yet operating in the U.S.
>
> This meant that virtually all of the economic information about the status of light water reactors in the early 1970s was based upon expectation rather than actual experience…
>
> In the first half of this crucial 10-year period, the buyers of nuclear power plants had to accept, more or less on faith, the seller's claims about the economic performance of their product. Meanwhile, each additional buyer was cited by the reactor manufacturers as proof of the soundness of their product…The rush to nuclear power had become a self-sustaining process...
>
> The result was a circular flow of mutually reinforcing assertion that apparently intoxicated both parties and inhibited normal commercial skepticism about advertisements which purported to be analyses. As intoxication with promises about light water reactors grew during the late 1960s and crossed national and even ideological boundaries, the distinction between promotional prospectus and critical evaluation become progressively more obscure. [51]

The rush to market is a central issue and problem for nuclear technology and, as the analysis in the previous section makes clear, the problem existed long before the accidents at Three Mile Island or Fukushima. While SMR vendors have put forward cost estimates that are between two and four times as high as the early "nuclear renaissance" projections, a frequently cited University of Chicago study combined high initial cost estimate with a scenario of accelerated learning and economic processes that was projected to quickly lower the cost. To achieve the cost reductions, the Chicago study envisions a rapid scaling up of production over a short period of time – 54/100-MW modules by 2020 for each design and production assembly line – and then assumes a steady stream of production of 12 units per year.[52]

This compressed RD&D schedule replicates a major mistake that contributed to the crash of the Great Bandwagon Market, and plagued the "nuclear renaissance." It embodies a rush to market that does not make proper provision for early analysis, testing, and demonstration that allows for experience-based design modifications.

> For 15 years many of those most closely identified with reactor commercialization have stubbornly refused to face up to the sheer technical complexity of the job that remained *after* the first prototype nuclear plants had been built in the mid- and late 1950s. Both industry and government refused to recognize that construction and successful operation of these prototypes – though it represented a very considerable technical achievement –was *the beginning and not near the completion* of a demanding undertaking.[53]

With a technology as complex as nuclear reactors, prototypes and real-world experiences are crucially important before full scale deployment is contemplated. Komanoff emphasizes two aspects of the process of putting a safe product into the market. Review needs to not only be thorough, but also ongoing with real-world deployment allowed to continually improve the understanding of safety and therefore the need for design modifications.[54] In more than 30 years since these devastating critiques of the industry were written and the crash of the Great Bandwagon Market, the industry behavior has not changed.

Even when analyses that advocate deployment of SMR technology give a nod to the challenge of ensuring that the technology is safe and the time it would take to make it ready for deployment, they dramatically underestimate the nature of the task. Ingersoll, whose analysis of "Deliberately Small Reactors, and the Second Nuclear Era" is probably the most often cited explanation of the advantages of SMRs, expressed some concern about the unfolding of the process.

> But whether the plants are large or small, it is vital that the nuclear community hold fast to lessons learned and not repeat the many failings that precipitated the fall of the first nuclear era. The number of options creates confusion in the market and dilutes the limited financial and human resources available in the nuclear community. Again, we must learn from mistakes of the first nuclear era and focus our attention on the few most promising designs with an eye toward standardization.[55]

He concluded that it would take up to 10 years to perfect the design. Yet his framing, which did not even necessarily include building a prototype or going through a demonstration phase, epitomizes the mistake that Bupp, Derien, and Komanoff put their fingers on.

> Assuming that credible engineering is achieved, it is further necessary to confidently demonstrate the unique plant features that result from making the reactor deliberately small. As discussed in a previous section, the significant economy of scale factor for nuclear plants will challenge the economic viability of SMRs unless innovative designs features result in a substantial cost savings. These innovations, such as integral primary systems and passive safety systems, will require

> thorough testing and demonstration through separate effects tests, scaled simulators, or perhaps even prototype units.[56]

This view clearly skips over the important demonstration phase as a critically important step to widespread deployment. Others affirm that the technology needs a decade of research and development before it can move into a deployment phase.[57]

THE ECONOMIC CHALLENGE

The case for SMRs is forced to assume an irresponsibly rapid rush to market because its viability as a technology and its role as a response to climate change diminish dramatically if it takes too long to roll the technology out. Indeed, even within the time frame claimed by the advocates, the case for SMRs rests on a series of assumptions and policy demands that are questionable and hotly debated.

Exhibit II-1, identifies the characteristics that are claimed as the source of advantage for SMRs. The analysis below examines the claims of potential advantage in terms of the two types of advantages claimed, supply-side cost and demand-side value. It shows that they are more like dark clouds that hang over the future of small modular nuclear technology rather than advantages.

Exhibit II-1: Benefits Claimed for Small Modular Nuclear Technology

Characteristic	Impact	Source of Advantage	
		Supply-Side	Demand-side
Economic Competitiveness			
Technological Maturity	Reactors are familiar technology with potential for progress	x	
Small Size	Less Risk, Manageable Finance	x	x
Multi-Unit	Repetition Rapid Learning	x	
Modularity	Standardized Mass Production	x	
Factory Fabrication	Quality Control, Ease of Transport	x	
Flexible Deployment	Scalability Matches Supply & Demand		x
Swift Deployment	Less Risk, Lower Front End Cost	x	x
Cogeneration/Co-siting	Large Incremental Value		x
System Impact			
Grid Support	Smaller, Distributed	x	x
Grid Integration	Base load, Local	x	x
Reliability	Redundancy, Small Size	x	
Safety/Waste			
Safety, Simplicity	Regulatory Relief	x	
Non-proliferation	Smaller, Loaded in Factory		x
Waste Management	Less Material	x	

Sources: Alexey Lokhov, Ron Cameron, and Vladislav Sozonuik, *OECD/NEA Study on the Economic and Market of Small Modular Reactors,* OECD/Nuclear Energy Agency, 2013; Geoffrey Black, *Economic and Employment Impacts of Small Modular Nuclear Reactors,* Center for Advanced Energy Studies, June 29, 2012; James R. Moody & Associates, *The Economics of Small Modular Reactors (SMR),* August 2012; Keith Brazil, *Feasibility of Small Modular Reactors for Ireland,* Department of Engineering Waterford Institute of Technology, N.D.; Iaonnis N. Kessides, *The Future of the Nuclear Industry Reconsidered: Risks, Uncertainties and Continued Potential,* The World Bank Development Research Group Environment and Energy Team, June 2012; Carelli, M.C., et al., "Economic features of integral, modular, small-to-medium size reactors," *Progress in Nuclear Energy*, 52, p. 403–414, 2010; D.T. Ingersoll, "Deliberately small reactors and

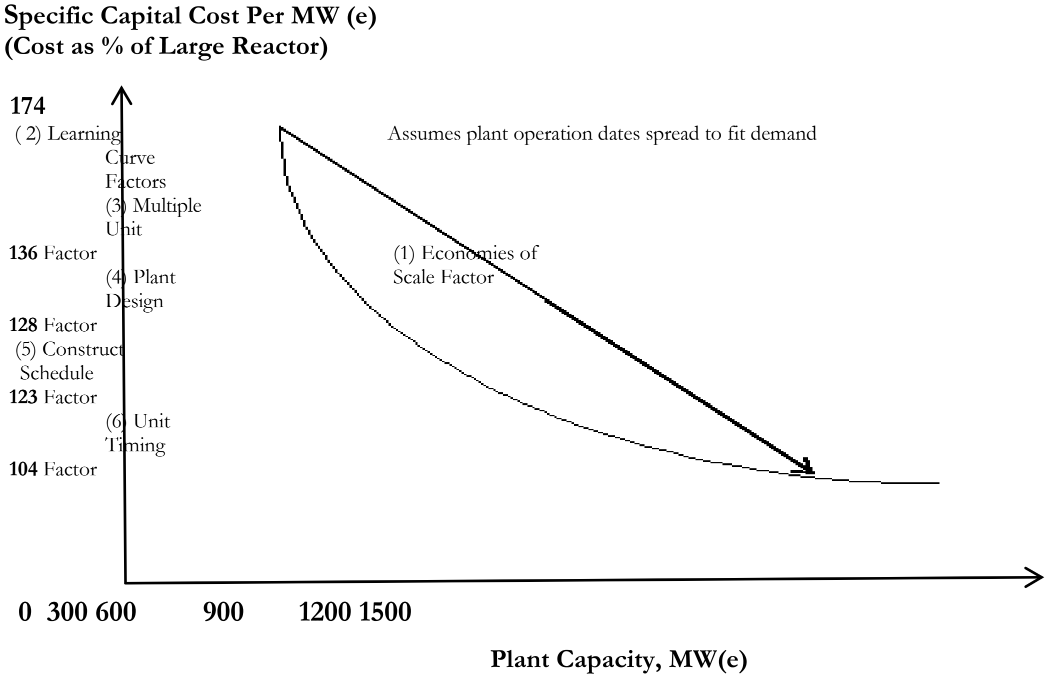
the second nuclear era,” *Progress in Nuclear Energy,* 51, 2009, Mycoff, C.W., et al., Paper for IAEA TECDOC Strategies to Demonstrate Competitiveness of SMRs in World Markets, Section IV.1. Methodologies and decision criteria for demonstrating competitiveness of SMRs, 2007.

High Cost on the Supply-Side: Overcoming Lost Economies of Scale

At the start of the SMR hype cycle, the assumption was that the “nuclear renaissance” technologies would succeed. The low-cost “renaissance” reactors would meet the demand for large, central station power. SMRs, exhibiting similar costs per kwh, would meet additional needs for smaller units.

The initial challenge was to explain how the diseconomies of scale of SMRs would be overcome (see Exhibit II-2). That is, there are certain large costs that have to be incurred regardless of the size of the reactor and these costs decline on a per MW of capacity basis as they are spread across larger units. Economists say they exhibit economies of scale.[58] Because SMRs are small, they forgo these benefits of economies of scale.

EXHIBIT II-2: POTENTIAL SMR CAPITAL COST ADVANTAGES MODEL



Source: The labeling and listing of the various factors that are assumed to lower SMR costs vary between articles. The figure shows the original language attributed to Westinghouse, in Vladimir Kusnetzov, “Options for SMRs to overcome loss of economics of scale and incorporate increased proliferation resistance and energy security,” *Progress in Nuclear Energy,* 50, 2008. The values for reduction in costs are from V. Kusnetzov and N. Barkatullah, *Approaches to Assess Competitiveness of Small and Medium Sized Reactors,* International Atomic Energy Agency, N.D. Table 2. The assumptions underlying the analysis include a 5percent discount rate.

SMR advocates argued that the economies of scale lost by building smaller reactors would be offset by economies of mass production. Offered at the height of the “nuclear renaissance” hype, this analysis acknowledged that on a per unit basis, small reactors have a substantial cost disadvantage. Westinghouse estimated that the diseconomy of small size would make the cost per

MW about 75 percent higher than the cost of a large reactor.[59] Westinghouse argued that the diseconomies of small size would be offset by economies of mass production of standardized units, as assembly lines of standardized modular units would achieve learning benefits faster to lower costs. The mass production and savings were hypothesized based on the experience in other industries, not rooted in the nuclear sector.[60]

Repeating the historic pattern for nuclear power, the SMR hype cycle appears to have begun with a vendor authored analysis of how SMRs would overcome their inherent cost disadvantage. The original vendor's promotional claims were regurgitated repeatedly, but the origin as a vendor promotion is obscured in the literature and the hypothetical economic process becomes gospel among the advocates of SMRs.[61]

Some critics of the analysis offered a number of challenges.[62]

- The diseconomies of small unit construction go well beyond the basic problems identified (the surface area of the reactors and containment structures) to include lost economies in dedicated systems for control, management, and emergency response and the cost of licensing and security.
- The economies of mass manufacturing were too optimistic because mass manufacturing has problems when applied to production of a relatively small numbers of very costly pieces of equipment.
- While the project size for individual utility deployments would be smaller, the challenge of creating a massive assembly line requires huge amounts of capital, suffers from a startup problem (chicken and egg), and will not sustain competition to drive innovation or cost reduction.
- The SMR design raises problems of reactor repair, waste retrieval, and decommissioning.

Ironically, the initial estimates of SMR costs were tied to the extremely low estimates of large reactor costs, which have doubled since the initial SMR cost analysis was presented. One can argue that the SMR costs should reflect the dramatic escalation in the large reactor costs for two reasons.

- SMR technology will suffer disproportionately from material cost increases because the underlying diseconomies of scale of SMRs suggests that they embody more material per MW of capacity.
- The design of the first "renaissance" reactor took 16 revisions to pass muster. Overly optimistic assumptions about how quickly new designs can be approved by regulators will greatly affect SMR technology because of the novel, even radically new characteristics of the design.

In fact, a debate has arisen over whether the goal adopted by the advocates of SMR technology of cost parity with large nuclear reactors is achievable.[63] The opinions on the bottom line for the cost of SMR are divided between two schools of thought. The experts directly involved in the industry (regulators and senior management employees) believe SMR will cost somewhat more that the current generation of reactors. Regulators project the highest cost (30% above current large reactors). The advocates claim cost parity between large and small reactors. The vendors and academics believe they will cost only a little bit more than the current reactors (5%). This repeats the pattern observed with the "nuclear renaissance" in which vendors and academic enthusiasts project the lowest costs by far, utilities had higher cost projections, and independent analysts had the highest projections.

While there is a debate about how much higher the construction costs of SMRs will be, there appears to be no debate that other costs associated with SMRs will be higher because the lost economies of scale cannot be made up with economies of mass production. Operating costs are projected to be between one-fifth and one-quarter higher than for large reactors.[64] Decommissioning costs are projected to be three times as high.[65]

Interestingly, direct comparisons of the SMR technology to "nuclear renaissance" technologies using a number of characteristics leads to the conclusion that SMRs do not enjoy a great deal of advantage on the supply-side. Exhibit II-3 evaluates six nuclear technologies with the star (*) representing advantages enjoyed by the technology.

EXHIBIT II-3: SUMMARY OF LIGHT WATER REACTOR FEATURES

Features	US EPR	US APWR	AP1000	ABWR	ESBWR	SMR
Economy of Scale	**	**		*	**	
Economy of Mass Production						**
Use of Proven Technology	**	**	*	**	*	*
Plant Simplification			**		**	**
Modular Construction		*			*	**
High Thermal Efficiency	*	*				
Passive Safety			*		*	*

Source: Jacob DeWitte, *Small Modular Reactors 101,* MIT Energy 101 Club, November 30, 2012.

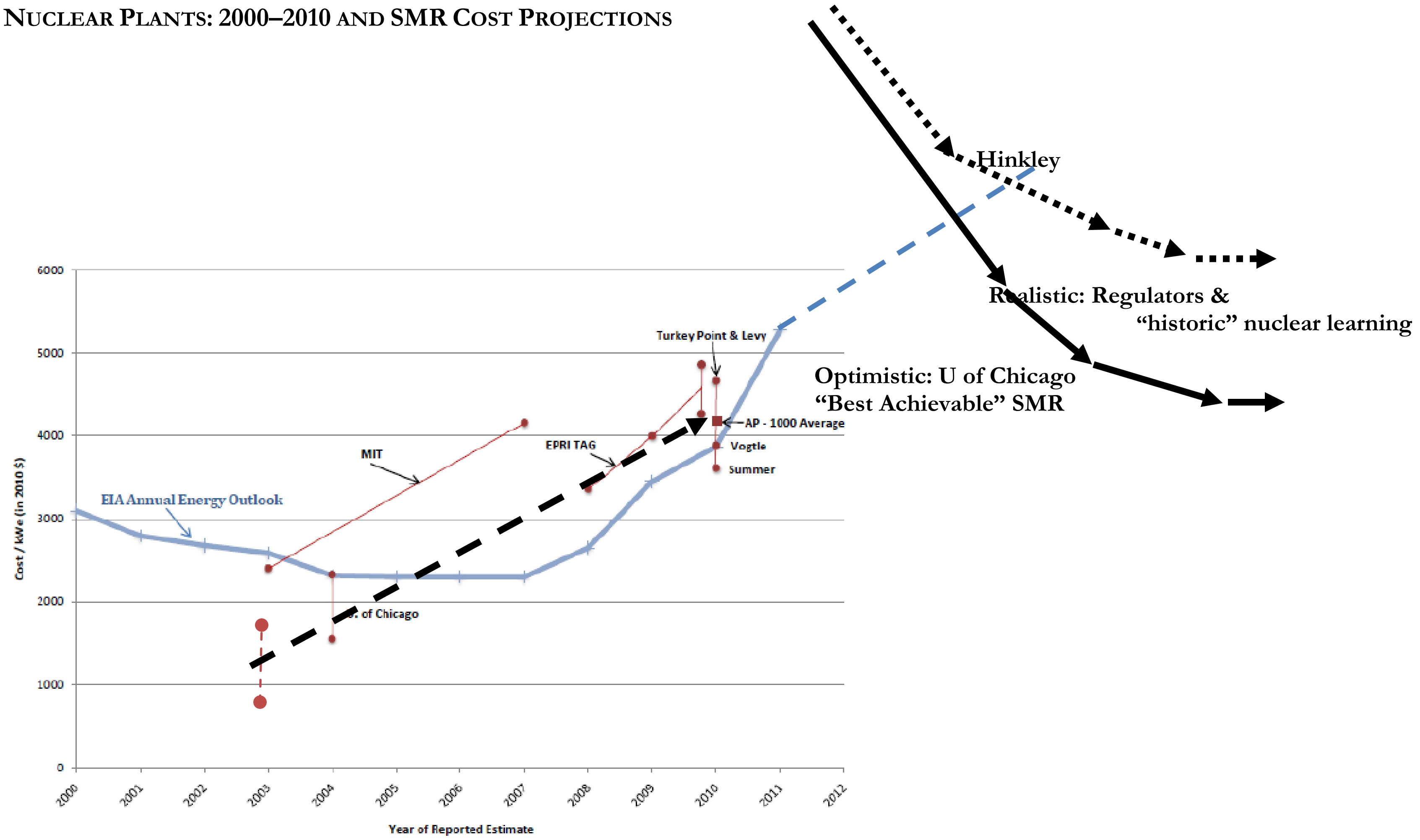
The top two rows in the table reflect the economic analysis discussed above. It is at best a wash. The next five characteristics differentiate the technologies at least somewhat.[66] SMR technology can claim, at best, a slight advantage over other light water reactors, but not a large enough advantage to suggest that the dramatic failure of the "nuclear renaissance" technologies will be reversed. This analysis shows that there is no reason to believe that the cost of production of electricity from SMRs is likely to be lower than "renaissance" technologies and is likely to be higher.

Exhibits II-4 shows the cost challenge faced by SMRs in the context of the "nuclear renaissance" experience, while Exhibit II-5 show the cost challenge in broader historical context. Whether the costs follow the optimistic projection of the University of Chicago study or the more pessimistic path of the industry regulators, the challenge is large. In essence, the claim is for a total reversal of past trends, although there has never been anything like it in the 50-year history of commercial nuclear power. Even with this unlikely reversal, the cost of power from SMRs is likely to be above the cost of the last nuclear technology, which repeats the historic pattern observed in Section I.

The Size of the Undertaking

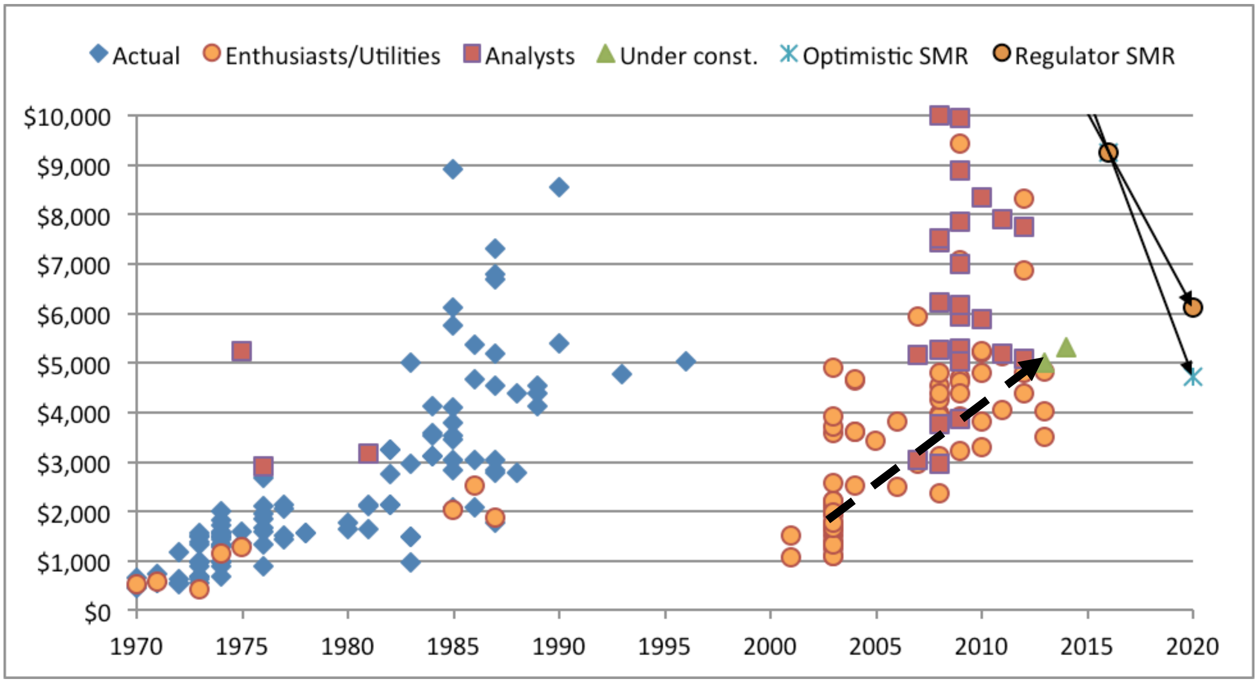
Although each individual SMR is smaller, the commitment necessary to drive the costs down is huge. With an average overnight cost of more than $6,500/kw, the University of Chicago study

EXHIBIT II-4: UNIVERSITY OF CHICAGO RECAP OF ENTHUSIAST/UTILITY ESTIMATES OF OVERNIGHT COST FOR NEW GW-SCALE NUCLEAR PLANTS: 2000–2010 AND SMR COST PROJECTIONS



Sources: Robert Posner, et al., *Analysis of GW-Scale Overnight Capital Costs*, Energy Policy Institute at University of Chicago, November 2011, p. 21. Low estimate is derived from Massachusetts Institute of Technology, *The Future of Nuclear Power: An Interdisciplinary MIT Study,* 2003; Robert Rosner and Stephen Goldberg, *Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S.,* Energy Policy Institute at Chicago, University of Chicago, November 2011, p. 19

EXHIBIT II-5: ACTUAL & PROJECTED OVERNIGHT CONSTRUCTION COSTS OF NUCLEAR REACTORS WITH SMR PROJECTED COSTS



"Great Bandwagon Market" **"Nuclear Renaissance"** **"SMR Hype"**

Sources: Mark Cooper, *Nuclear Safety and Nuclear Economics*, Institute for Energy and the Environment, Vermont Law School, 2011; Robert Rosner and Stephen Goldberg, *Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S.,* Energy Policy Institute at Chicago, University of Chicago, November 2011, p. 19.

calling for 54 100 MW units, the total for each design and production assembly line would be almost $36 billion. When Westinghouse stepped back from SMR development, it declared it needed a book of orders for 30 to 50 reactors.[67] Given the relatively large size of the reactors (225 MW), the size of the book would be well above $36 billion. Two lines would cost $72 billion. At the less optimistic estimates of regulators the total cost would be in the range of $90 billion

To appreciate the enormity of this undertaking, we can compare it to the total additions to capacity that are projected for the U.S. electricity sector until 2020. Exhibit II-6 presents estimates of the size of the SMR program compared to all electricity and all renewable capacity additions through 2020. While advocates of SMR hope that there will be a large global market, it is highly unlikely that these extremely expensive reactors could compete in a global market.

Since natural gas is the least cost alternative by far at present (less than one-six the overnight cost per kw of SMR capacity in the next decade), it is reasonable to assume that the commitment to SMRs would put greatest pressure on renewables. The capital needed to implement the University of Chicago SMR scenario with two designs, even with the optimistic projections of SMR cost, would exceed the total capital projected to be invested in renewables. Those who fear that the historic pattern of nuclear crowding out renewables will be repeated have good cause for concern.

EXHIBIT II-6: SMR CAPITAL NEEDS COMPARED TO RENEWABLE DEPLOYMENT THRU 2020

Source of Estimate	Capacity Added (GWe)	Overnight Cost ($/kw)	Total Cost (billions)
EIA			
Fossil Fuels	41	$1150	$47
Renewables	23	$2600	$60
Total	64	1670	$107
Small Modular Reactors			
2 Designs-Production Lines			
U. of Chicago Optimistic	11	$6500	$72
Realistic	11	$8645	$95

Sources: Energy Information Administration, Capacity, *Annual Energy Outlook,* Table A9; Capital Cost: *Updated Capital Cost Estimates for Utility Scale Generating Plants,* April 2013; Robert Rosner and Stephen Goldberg, *Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S.,* Energy Policy Institute at Chicago, University of Chicago, November 2011.

RELAXATION OF LICENSING AND SAFETY REGULATION

Given the very difficult SMR economics, advocates emphasize the need for relief in regulatory requirements in licensing and safety. The aspiration is for large numbers of small reactors widely distributed at sites with multiple units close to population centers. This is the way the best economics can be achieved for SMRs. The hope is for preapproval of design, centralization of inspection (at the fabrication facility), the virtual elimination of evacuation zones, and reduction in on-site personnel and back-up systems due to passive safety designs. Each of the assumptions about the justification for less stringent safety regulation has been challenged.

Exhibit II-7 summarizes the concerns raised about safety that have been expressed in response to the industry demands for relaxed standards. The debate over safety involves both fundamental process issues and specific substantive concerns. Concerns exist about changes in the approach to safety oversight. Envisioning a large number of "new" nuclear nations and locations increases the concern. The widespread dispersal and close proximity to population centers dramatically increases concerns. This was one of the key factors that triggered increased oversight of safety during the Great Bandwagon Market.[68] Close proximity to population centers required higher safety margins to reduce the probability and mitigate the impact of accidents.

Given the large set of difficult safety issues that small modular technologies raise, the call for reduced margins raises major concerns. Extremely thin margins are the primary way the cost of safety will be reduced, to the extent that the proposals call for almost no safety zones and very few safety and security staff on site, with little, if any redundancy. Every novel aspect of the new design poses new challenges for the oversight of safety. The below ground siting of the facility raises a number of questions about how inspection would be carried out. The challenge of repair and retrofit would be substantial. Throughout the history of the industry, this has been a bone of contention. Utilities resist retrofitting because of the expense and that expense would be much greater with a below ground facility. It is also likely to be greater with an integrated facility where the failure of a part could require the replacement of the whole.

EXHIBIT II-7: SMALL MODULAR REACTOR SAFETY CONCERNS

Shifts in General Approach
- Preapproval and limited review
- Static approach v. evolving standards
- Wide Dispersal
  - Proliferation concerns
  - Close proximity to population centers requires increased margins
- Reduction of Safety Margins
  - Shrinking containment
  - Limitations of staff for safety and security
  - Consolidation of control reduces redundancy
  - Evacuation zones

Unique Challenges for Safety Oversight
- Inspection
  - Manufacturing facilities problems and costs
  - Foreign sources
  - Access to below ground facilities
    - Repair/Retrofit/Recall
    - Integrated systems
- Waste Management and Retrieval
  - Potentially higher levels of radiation
- Flooding for below ground facilities
- Common design creates potential "epidemic" failure

Sources: Arjun Makhijani, *Light Water Designs of Small Modular Reactors: Facts and Analysis,* Institute for Energy and Environmental Research, June 2013; Edwin Lyman, *Small Isn't Always Beautiful: Safety, Security and Cost Concerns about Small Modular Reactors,* Union of Concerned Scientists, September 2013; Arjun Makhijani and Michele Boyd, *Small Modular Reactors: No Solution for the Cost, Safety and Waste Problems of Nuclear Power,* IEER, PSR, 2010; Sharon Squassoni, Small Modular Reactors: Contours of Proliferation/Security Risks, Proliferation Prevention Program Center for Strategic & International Studies, *Platts 4th Annual Small Modular Reactors Conference ,* Washington, D.C., May 29–30, 2013; Alexander Glaser, Laura Bezak Hopkins, and M.V. Ramana, "Resource requirements and proliferation risks associated with small modular reactors, *Nuclear Technology,* 2013.

The push to accept the theoretical claims of increased safety and deploy large numbers of these facilities quickly to drive the costs of mass production down is alarming to those concerned about safety. The rush to radically alter the safety regime is an approach that actually commits the worst mistake of the failure of the "Great Bandwagon Market" discussed above.[69] To make an economic case, SMR advocates want to leap from the early design phase to full-fledge deployment, without a proper demonstration phase. Ultimately, it was the failure to demonstrate that reactors that moved from the design to reality could be operated safely that undid the "Great Bandwagon Market." When the technology proved to be more difficult than anticipated, the industry had committed to and begun deploying too many reactors. They were stuck with a fleet of "defective products."[70] Retrofitting was expensive, so the battle with the safety regulator was engaged. It took the global nuclear industry 30 years to significantly improve its safety.

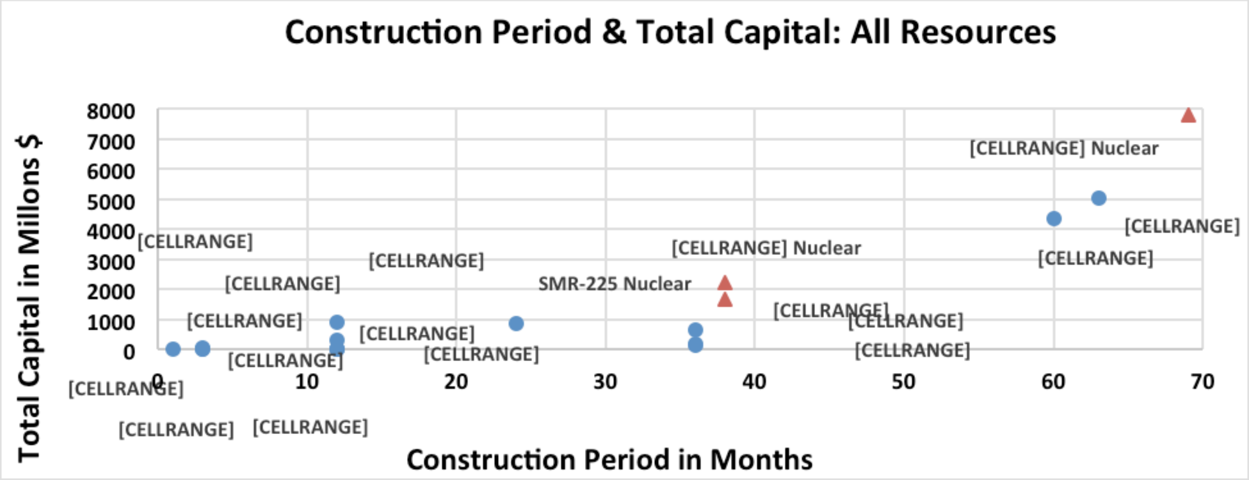
This push to relax regulatory oversight comes at a time when there is a broad consensus that the Fukushima accident highlights significant failings of nuclear regulation leading to vigorous calls for strengthening oversight.[71] The strategy of short circuiting oversight based on claims that a new approach to design "solves" many of the long standing safety issues without a significant period of testing and demonstrations is not likely to gain much traction, certainly not on the time scale that is envisioned by SMR advocates.

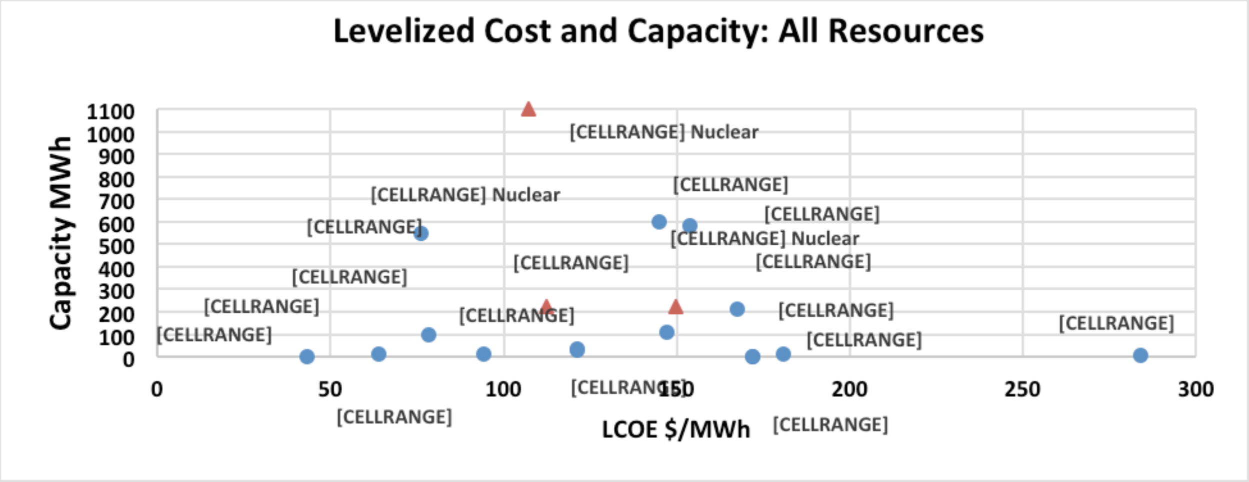
"OTHER" CHARACTERISTICS DO NOT MAKE SMR TECHNOLOGY MORE ATTRACTIVE THAN THE NON-NUCLEAR ALTERNATIVES

Without much in the way of cost advantages on the supply-side and regulatory relief in doubt, the market prospects for SMR technology hinge on the hope that unique characteristics of the technology will attract demand. The importance of climate change and niche applications is magnified. The slowing of growth in demand, caused in the short term by the severe global recession and reinforced in the long term by improvements in energy efficiency magnify the importance of small size and flexibility.

Many SMR advocates claim that it has demand-side characteristics that make it attractive. Focusing only on a comparison between large and small reactors, SMR advocates argue that SMRs have smaller total capital commitments, shorter construction times, and smaller unit size. Therefore, they are more flexible and better able to meet small load increases more quickly and would be easier to finance compared to large reactors. Typically, the characteristics of the alternative resources are never considered. Once they are factored in, there is no reason to believe that SMRs possess a unique set of characteristics that will drive demand, even in unique circumstances (see Exhibit II-8).

EXHIBIT II-8: PUTTING THE SMR SIZE FLEXIBILITY ADVANTAGES IN PERSPECTIVE





Sources and Notes: This analysis combines the most recent estimates of Lazard, 2011, 2013 with the most recent expert analysis of SMRs. I have included 225-MW SMRs at 105 percent of large nuclear, which is the consensus, and 45-MW SMRs at 140 percent of large nuclear. I use 38 months for construction of SMRs, which

is extremely optimistic, as is Lazard's estimate of 69 months for large reactors. Because the SMR costs are assumed to be at full production in 2030 (not early units), I include the long-term trends for solar.

Thus, SMRs gain little if any advantage compared to the decentralized alternatives by focusing on the economic impact of the size and flexibility of the investment. Although there may be some non-electric applications in which they gain some advantage,[72] there are other non-electric applications, like desalinization, that may favor the alternatives and alternatives with storage have attractive possibilities for grid independence.[73]

Once one moves into the broader realm of non-economic goals of the electricity system, nuclear power fares very poorly. Nuclear power has significant disadvantages in terms of security, [74] and proliferation risks[75] and continues to suffer from unique environmental problems.[76] Based on a non-commodity, local source of power, renewables have a large advantage in macroeconomic impacts.[77] As a result, in multi-attribute rankings and evaluations, the main renewables (wind, solar, hydro) and efficiency are much more highly rated[78] and have consistently been so for decades.[79]

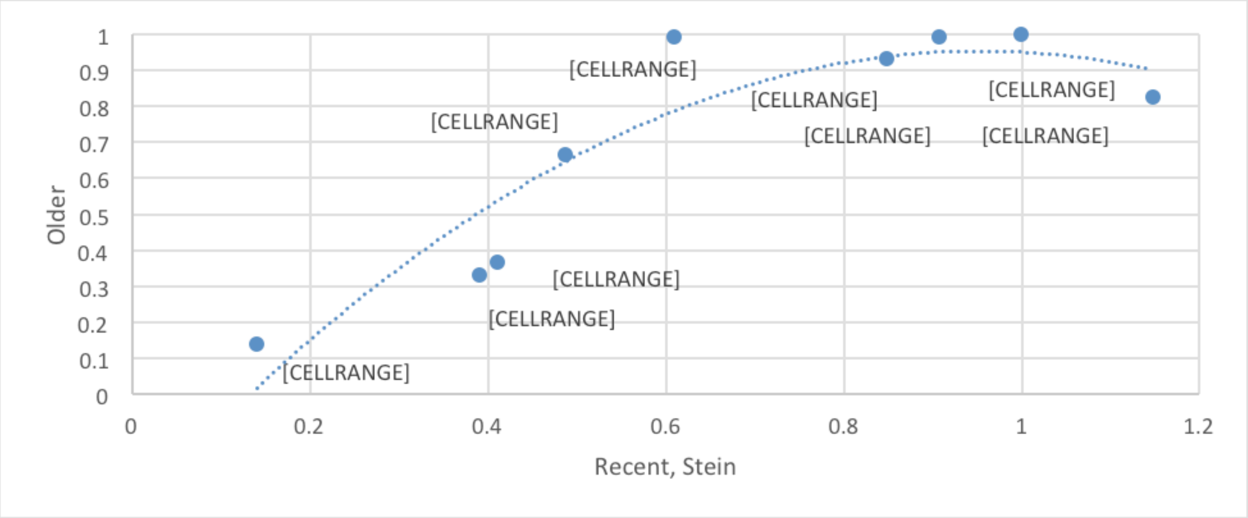
> Evaluation criteria: evaluation of each technology was based on the application of four primary criteria:
>
> - Financial (FC): financial value of the technology and return on investment.
> - Technical (TC): characteristics of the technology as a power source and its production capabilities.
> - Environmental (EN): impact of power plant on local and regional environment, as well as human health.
> - Social/Economic/Political (SEP): impact on local economy and communities, as well as congruence with over all national policies.
>
> The results indicate that wind, solar, hydropower, and geothermal provide significantly more overall benefits than the rest even when the weights of the primary criteria clusters are adjusted during sensitivity analysis. The only non-renewable sources that appear in three of the 20 top rank positions are gas and oil, while the rest are populated with renewable energy technologies. These results have implications for policy development and for decision makers in the public and private sectors. One conclusion is that financial incentives for solar, wind, hydropower, and geothermal are sound and should be expanded. Conversely, subsidies for non-renewable sources could be diminished. [80]

Exhibit II-9 shows the results of several evaluations of energy resources. The graph plots earlier evaluations against a recent ranking. It sets coal as the base (equal to 1) and then calculates the ratio of the other resources compared to coal, with lower scores meaning more preferable rankings. We have also included efficiency at the ranking from the earlier studies. The sharp break between efficiency and renewables as attractive resources and the conventional (fossil fuels and nuclear) is readily apparent in both sets of rankings.

CONCLUSION

This section has examined the problems that affected the two major efforts to deploy commercial scale nuclear reactors and has evaluated the prospect for the next technology that the industry wants to deploy at commercial scale. There are other technologies that the industry has touted that never reached commercial deployment. Some of these never got off the drawing board; others failed at the prototype phase. In fact, many of the concepts that have been incorporated into the design of SMRs are retreads of ideas that have been put forward over more than half a century, but failed to advance due to safety and economics problems. The failure of these technologies should also be recognized as part of the background for assessing the future prospects of nuclear power and how much weight to put on it in the response to climate change, particularly where these technologies exhibit characteristics or challenges that are similar to those of SMR technology, including fast breeder, [81] pebble bed,[82] and Thorium[83] reactors.[84]

EXHIBIT II-9: QUALITATIVE RANK ORDERING OF ENVIRONMENTAL IMPACTS (Coal =1; Lower scores indicate more attractive resources)



Source: Wilson B. Goddard, *A Comparative Study of the Total Environmental Costs Associated with Electrical Generation Systems*, G&GE Applied Research, 1997; U.S Congressional Office of Technology Assessment, *Studies of the Environmental Costs of Electricity*, Washington, D.C., September 1994; Richard Ottinger, et al., Pace University Center for Environmental Legal Studies; *Environmental Costs of Electricity*, Oceana, New York, 1990; Paul Chernik and Emily Caverhill, "The Valuation of Externalities from Energy Production, Delivery and Use, A Report by PLC, Inc. to the Boston Gas Co., Fall 1989; Olave Hohmeyer, *Social Costs of Energy Consumption: External Effects of Electricity Generation in the Federal Republic of Germany*, Springer-Verlag, Berlin, 1988; Michael Shuman and Ralph Cavanagh, *A Model of Conservation and Electric Power Plan for the Pacific Northwest: Appendix 2: Environmental Costs*, Northwest Conservation Act Coalition, Seattle, WA, November 1982. Bottom graph, recent is Stein, Eric W., 2013, "A comprehensive multi-criteria model to rank electric energy production technologies," *Renewable and Sustainable Energy Reviews*, 22.

The economic challenges, licensing and safety concerns make SMR technology, a very uncertain and risky economic and public safety proposition. As described in Exhibit II-10, the technology bold claims about the prospects for the technology were vastly overstated. Combined with the available alternatives, the prospects for SMR technology were vastly overstated in the hype phase.

EXHIBIT II-10: ADVANTAGES AND CHALLENGES OF SMR

Advantages	**Challenges**
Technological Issues	**Technological Issues**
Shorter construction period (modularization)	Licensability (delays due to design innovation)
Enhanced reliability	Technical challenge for non LWR technologies
Possibly enhanced safety	Infrastructure requirements
Reduced complexity in design and human factor and fuel cycle to proliferation resistance	Impact of innovative design
Suitability for non-electricity application	Operability
Tolerance to grid instabilities (i.e. process heat and desalination	Spent fuel management and waste handling policies
Non-Technological Issues	**Non-Technological Issues**
Fitness for smaller electricity grids	Economic competitiveness (economy of scale)
Options to match demand growth by incremental capacity	Reduced emergency planning zone
Site Flexibility	Regulation for fuel or NPP leasing
Lower capital cost	Limited market opportunities
Easier financing scheme	First of a kind cost estimate
Availability of design for newcomers	Limited technical benefit for newcomers

Source: Dr. M. Hadid Subki, 2011, Common Issues and Challenges in Development and Deployment of Small and Medium-sized Reactors (SMR), 22nd TWG Meeting on GCR, 28 – 30 March, IAEA.

III. THE ECONOMIC FAILURE OF NUCLEAR POWER

Nuclear cost escalation provides half of the explanation for the economic failure of nuclear power. The other half is provided by the superior economics of alternatives. Nuclear power has never been able to compete economically. Bold claims about low cost and projections for large numbers of reactors are quickly replaced by cost overruns and orders cancelled by buyers who have much less costly alternatives available. In the 1970s and 1980s the challenge came from coal and gas. Today the challenge comes from gas and a number of renewables, as well as energy efficiency.

CURRENT COSTS

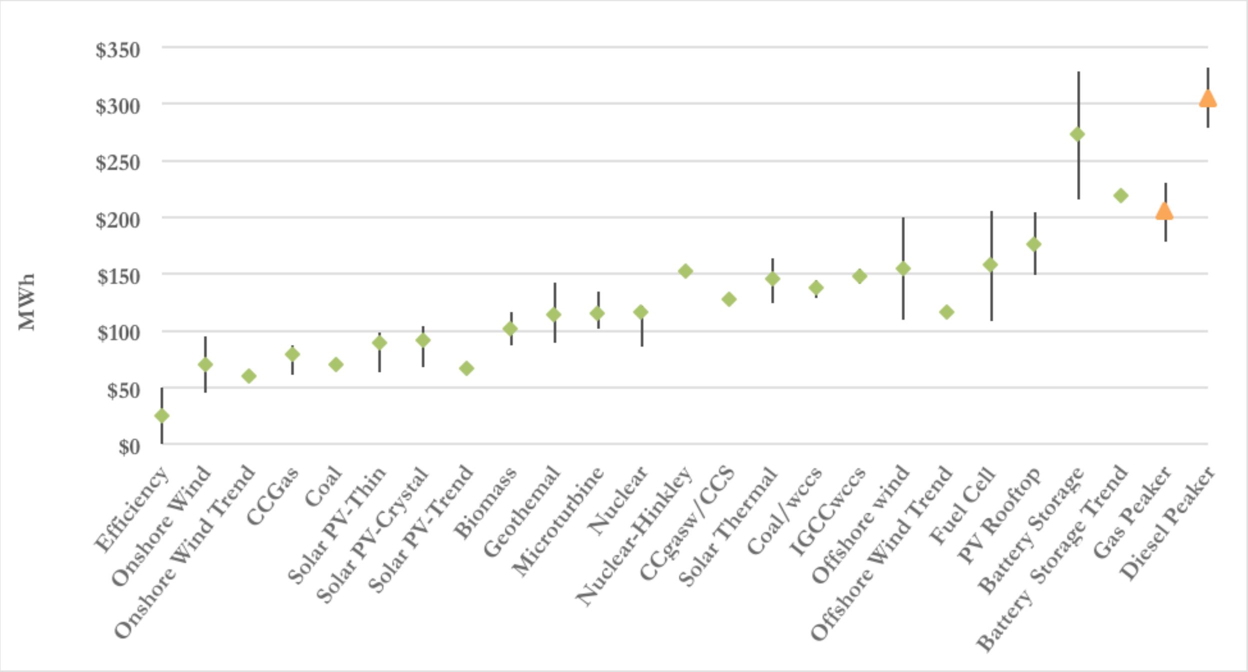
As suggested by Exhibit I-6 above, there have been almost 100 estimates of the cost of building new reactors since the start of the "nuclear renaissance." We have analyzed these in great detail several times to explain the factors that account for the wide range of estimates and identify the causes of escalating cost projections.[85] We have also examined the costs of alternatives in detail in those studies. Here we take a simpler approach to understanding the economic predicament that nuclear reactor construction faces, keeping in mind that the cost of SMRs are projected to be at least as high as large "nuclear renaissance" reactors.

Over the past 7 years Lazard has published an annual analysis of electricity resource costs, *Lazard's Levelized Cost of Energy Analysis* – that has become increasingly complex and nuanced as the electricity market has developed. Although the Lazard analysis continues to use relatively low costs for nuclear power – for example sticking to a construction period of a little less than 6 years, when no one has come close to that in market economies – the Lazard analysis is superior to most others and provides the basis for important and useful observations.

- From the outset, the analysis included efficiency, which is the least cost resource by far. None of the other major studies of electricity resources do so.
- The analysis was among the first to note the strong downward trend in the cost of solar and to begin arguing that solar was cost competitive in some major markets and for peak power, projecting that solar would be broadly cost competitive with natural gas by the middle of the second decade of the 21st century.
- The analysis always included estimates for coal with carbon capture and storage and has recently added an estimate for the cost of natural gas with carbon capture and storage.
- The most recent analysis adds important storage technologies, utility scale solar with storage, and utility scale battery storage.
- The current analysis presents "unsubsidized" costs strictly for generation (no transmission, system integration, or waste disposal and decommissioning).
- The analysis included peaking capacity costs and, in the current version, added a cross national comparison of technologies that might displace gas as the peaker resource.

In the peaker analysis Lazard included natural gas and diesel peakers for comparison with utility scale thin film and crystalline solar, arguing that these resources are already competitive with peak power. Folding peaking costs into the overall analysis is an important nuance that should be added because of developments in the electricity market (see Exhibit III-1).

EXHIBIT III-1: LEVELIZED COST: FULL SLATE OF OPTIONS WITH TRENDS



Source: *Lazard's Levelized Cost of Energy Analysis – Version 7.0, plus trends for wind and battery storage.*

Peaking costs were extremely important in the 20th century electricity system, since the inability to store electricity created a dramatic pattern of sharp price increases at times of peak demand. As our recent analysis of the early retirement of several reactors makes clear, in electricity markets, high peak prices provide the margins necessary to cover not only operating costs, but also make investment in capacity profitable.[86] Downward pressures on peak prices caused by increasing reliance on renewables have become a focal point of debate in electricity policy, since shrinking peak margins make it difficult for generation resources that have high capital costs and moderate operating costs to cover their costs. This is the predicament in which aging U.S. reactors find themselves.

Beyond solar, on which Lazard focuses, several resources that have very low operating costs are expanding could a substantial impact on the market clearing price at the peak. The lengthy discussion of the impact of wind on declining market clearing prices in the Midwest and Northeast is an indication of this effect.[87] Solar thermal with storage has also come on line and is effectively dispatchable. Rooftop solar has gotten the attention of utilities as a disruptive resource in the net metering debate, since it is likely to reduce grid demand at peak periods and reduce the need for both generation and transmission. Although battery storage costs are above natural gas peak costs, they are also advancing rapidly as a potential to meeting needle peaks, which would have an impact on the margins available to support non-peak generation, especially as they reduce needle peaks, where margins are the highest.

Exhibit III-1 presents the full array of resources Lazard analyzes. We have added the official cost of the Hinkley nuclear reactor, which has recently been commissioned in the UK, to provide perspective on nuclear costs. The guaranteed price of Hinkley – $150/MWh – is exactly the cost that we used in the our first review of new nuclear construction costs.[88] This nuclear cost estimate does not include waste management and decommissioning, which we believe adds as much as another $20/MWh to the cost.[89] We have also included cost trends for wind and renewables based on the literature reviewed below.

This analysis reaffirms what we already knew. The map of the options available in the U.S. to meet the need for electricity in the next decade includes a rich set of alternatives that are less costly than nuclear. It underscores the economic problems of nuclear power. Energy efficiency has long been recognized as the least cost resource to meet the need for electricity. Natural gas has been the fuel of choice for two decades. Wind and solar are cost competitive. Even the cost of carbon capture and storage is projected to have costs that are competitive with nuclear (natural gas slightly lower, coal slightly higher). While much of this is old news, there are three powerful trends that are driving change in the electricity sector. The first two of these trends – declining costs for alternatives and increases in efficiency – are discussed in the remainder of this section. The third trend, emergence of an efficient, decentralized, two-way electricity system, is discussed in the next section.

TRENDS OF DECLINING COST FOR ALTERNATIVES

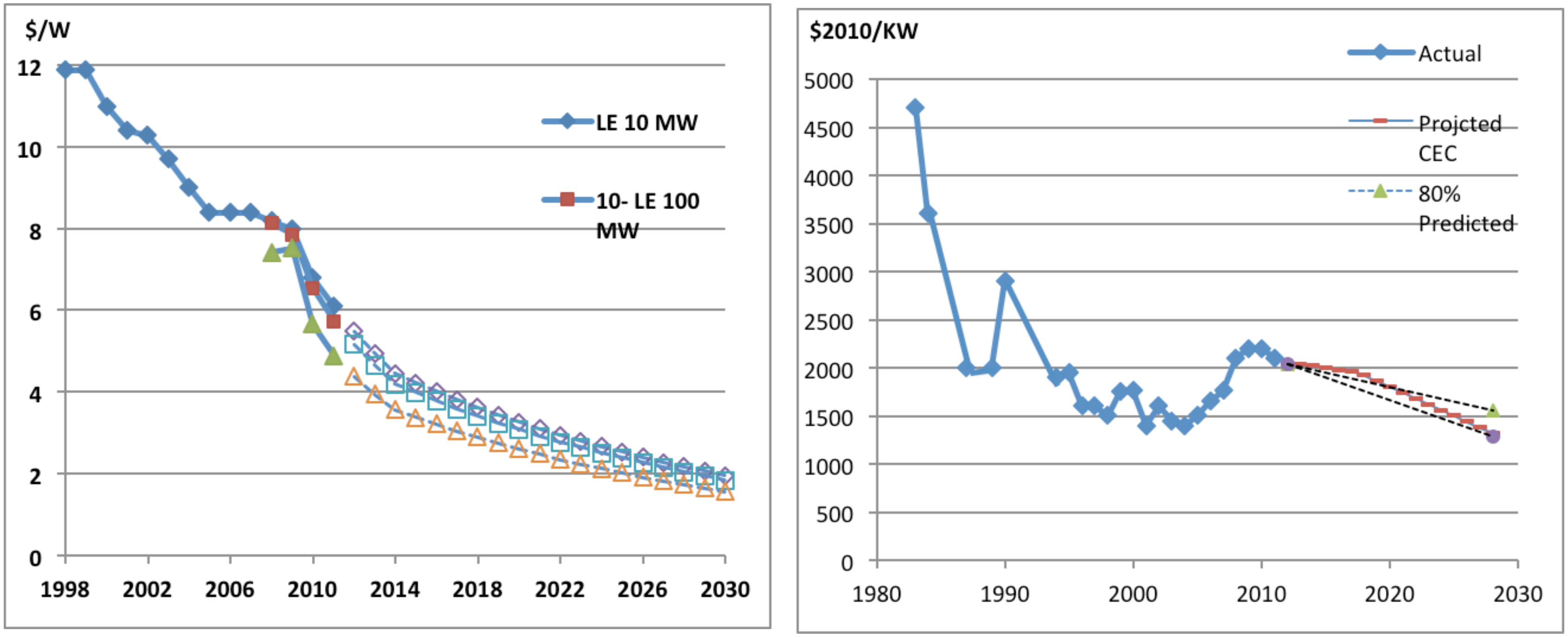
Cost trends are the most obvious and important factor affecting the electricity sector. Like the Great Bandwagon Market and the "nuclear renaissance," the economic viability of SMRs will be determined by the intersection of two cost trends – the future cost of other alternatives and the ability of SMRs to reverse 50 years of nuclear history and achieve a dramatically declining cost trajectory.

Exhibits III-2 and III-3 present several estimates of the cost trend for wind and solar. In contrast to nuclear power, which has yet to overcome its problem of cost escalation, the cost trends for alternatives, primarily wind and solar, but also storage are delivering much lower costs. Lazard's analysis is not the only analysis to make the case for solar. A late 2012 analysis from Citi Research concluded that "[o]n the residential-scale, solar is already competitive with electricity off the grid…Utility-scale solar will be competitive with gas-fired power in the medium term… Utility-scale wind is already competitive with gas-fired power."[90]

Citi research presents the global view, but Credit Suisse takes an even more aggressive view of the development of renewables in the U.S. Credit Suisse, picks up the theme of the supply-side transformation being driven by renewable energy that Lazard and Citi discussed. Credit Suisse argues that over the next decade, five-sixths of the need for generation could be met with the major renewables, with the result of reducing the pressure on gas supply.

> We see an opportunity for renewable energy to take an increasing share of total US power generation, coming in response to state Renewable Portfolio Standards (RPS) and propelled by more competitive costs against conventional generation. We can see the growth in renewables being transformative against conventional expectations with renewables meeting the vast majority of future power demand growth, weighing on market clearing power prices in competitive power markets, appreciably slowing the rate of demand growth for natural gas from. [91]

EXHIBIT III-2: RECENT AND PROJECTED COST OF U.S. SOLAR AND WIND



SOLAR POWER

ONSHORE WIND

Sources: Lazard, *Levelized Cost of Energy Analysis* – Version 5.0, June 2011; Galen Barbose, et al., *Photovoltaic (PV) Pricing Trends: Historical, Recent, and Near-Term Projections,* LBL and NREL, November 2012.

EXHIBIT III-3: RECENT AND PROJECTED COST OF GLOBAL SOLAR AND WIND

Figure 69. Historical average module prices against cumulative installed capacity

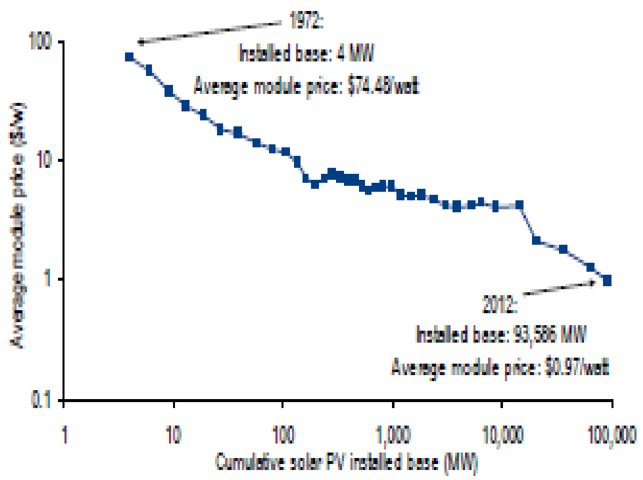


Figure 71. The 'single-speed' scenario, with price forecasts achieved by applying the historical experience curve factor to the 2012 price

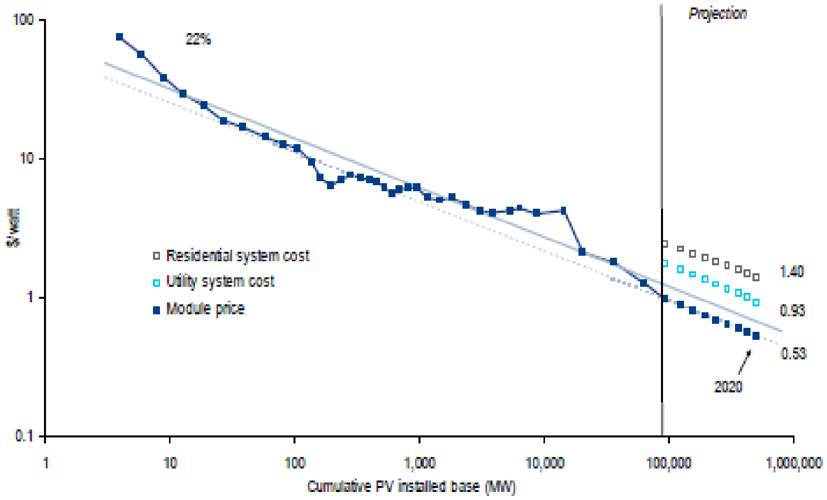


Figure 75. Historical average turbine costs against cumulative installed capacity

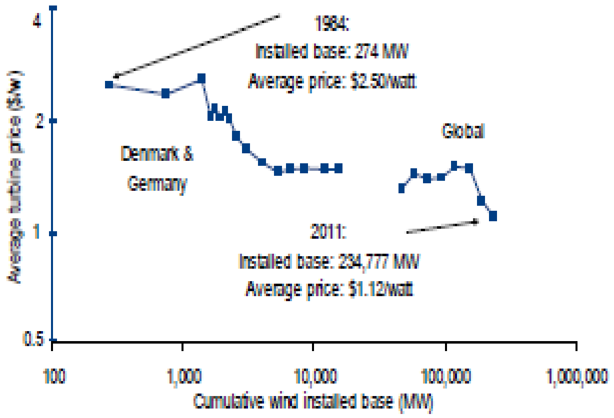
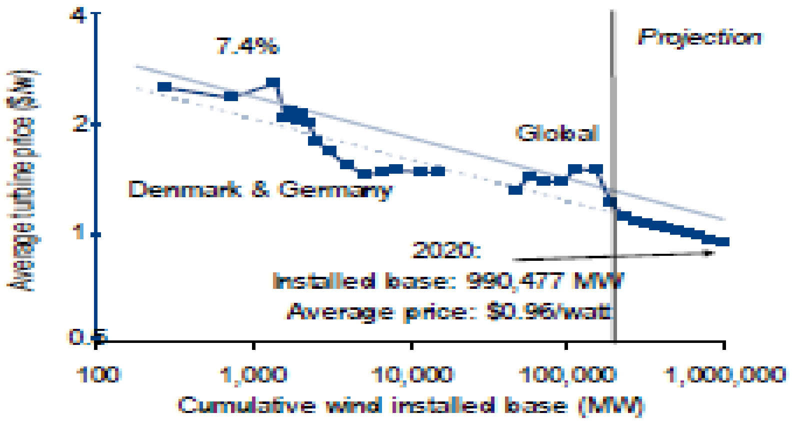


Figure 76. Forecast for average wind turbine costs



Source: CITI Research, *Shale & Renewables: A Symbiotic Relationship*, September 12, 2012.

While Credit Suisse cites policies that are promoting renewables as the context for the transformational impact on supply, it also argues that the renewables have become cost competitive with conventional baseload generation.

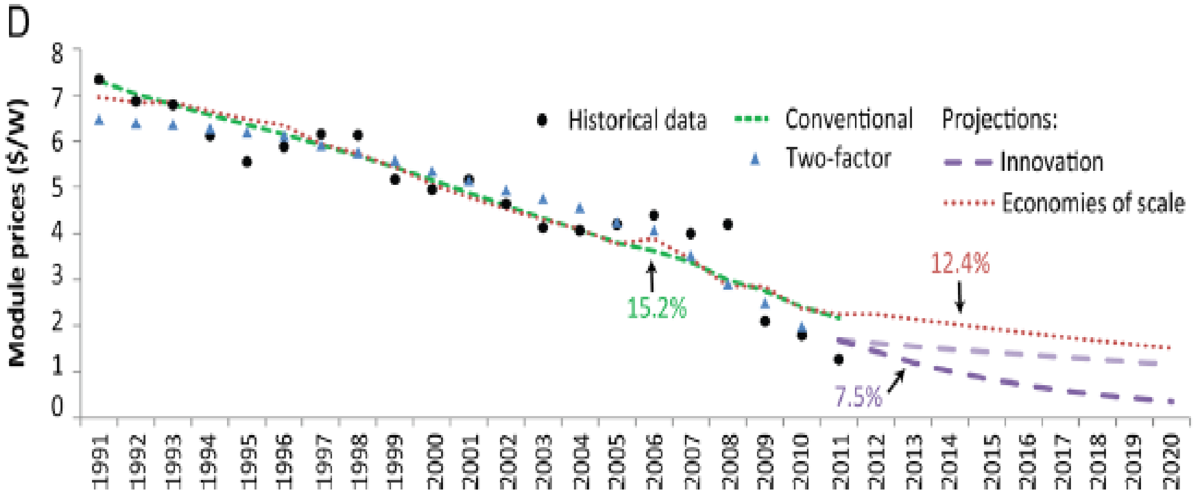
> Renewables are cost competitive to even cheap against conventional generation. The clearing price for new wind and solar continues to fall with improvements in utilization and falling capital costs. For wind we are seeing utilization rates 15–20 percentage points higher than 2007 vintage turbines, regularly supporting PPA pricing at or below $30/MWh that effectively 'creates' long-term equivalent natural gas at <$3/MMBtu. Lower capital costs for solar have dropped PPA pricing to $65–80/MWh from well over $100/MWh, making solar competitive with newbuild gas peaking generation.[92]

These observations not only correct the mistaken belief that the overwhelming cause of the woes of the "nuclear renaissance" is cheap gas, they also counter the fear campaign that nuclear advocates rely on to discredit natural gas because of price volatility. Not only is the long term pattern for natural gas not volatile,[93] but reducing supply pressures with renewables would dampen any volatility.[94]

The economic competitiveness of these generation resources reflects technological and economic progress. For wind, utilization has increased dramatically – achieving capacity factors above 50 percent with costs per kilowatt hour plummeting as the result of increasing tower height, longer and larger blades, better gearbox reliability, material optimization and more efficient computer programming.[95] Solar costs have been falling because of economies of scale in production and reduced utilization of key component materials, increasing cell efficiency, other system cost savings and streamlining of siting, all of which have lowered the cost of capital.[96]

Exhibit III-4 decomposes the long-term declining cost trend for solar into two key components, economies of scale and innovation. Each of these two factors has made a substantial contribution to declining cost and both are likely to continue to do so.[97]

EXHIBIT III-4: THE EFFECT OF ECONOMIES OF SCALE AND INNOVATION IN THE C-SI PV LEARNING CURVE



Zheng, Chengn and Daniel M. Kammen, 2014, "An innovation-focused roadmap for a sustainable global photovoltaic industry," ***Energy Policy*****, 67, p. 163.**

THE ROLE OF DEMAND

A second important trend driving change in the electricity sector is a reduction in demand growth. In Section II we showed that the specific demand-side characteristics of SMR technology do not afford it the advantage that its advocates claim. Here we focus on the broader trends in demand growth.

Credit Suisse notes the important role that declining demand growth plays in driving the transition of the electricity sector.

> The impact of energy efficiency has become more of a focal point after another year of lackluster power demand growth in 2013 and disappointing usage trends across customer classes.[98]
>
> Our take: Energy efficiency remains an under-appreciated but very important trend in power markets that will lead to structural drags on power demand growth impacting the outlook for competitive power market recovery and where utility capex will need to be allocated. We model efficiency lowering annual demand growth by ~70 bp (.7%) a year from a 'normal' baseline, putting core growth at +0.5-1.0% with downside risk barring better economic recovery…
>
> Our outlook for slower demand growth relative to a 'normal' +1.5% pushes out reserve margin equilibrium by 1–3 years, creating another unwanted headwind for competitive power.[99]

Credit Suisse notes that the slowing of demand growth places a great deal of pressure on the economics of utilities not only where it adds to the downward pressure on prices set in markets, but also in regulated states, where rate structures have relied on growing demand to ensure recovery of fixed costs.

> Regulated Utilities. Slower demand growth will hurt revenue growth between rate cases for most utilities, putting pressure on their ability to offset cost inflation and rate base growth leading to lower earned ROEs. We think utilities will need (a) to work with regulators to develop mechanisms that help to offset efficiency drag through decoupling, energy efficiency trackers, etc. and (b) focus on O&M cost management to reduce inflationary pressures[100]

A McKinsey and Company report ties together the supply and demand-side effects of technological progress. McKinsey reaches the same conclusion as Citi and Credit Suisse in projecting cost parity for solar with conventional generation within the next decade, but it goes on to argue that this can have a dramatic impact on the marginal demand for conventional resources. The report argued that the growth of solar has an "outsized" effect on the demand for baseload generation.

> These cost reductions will put solar within striking distance, in economic terms, of new construction for traditional power-generation technologies, such as coal, natural gas, and nuclear energy. That's true not just for residential and commercial segments, where it is already cost competitive in many (though not all) geographies, but also, eventually, for industrial and wholesale markets…
>
> Solar could seriously threaten the latter because its growth undermines the utilities' ability to count on capturing all new demand, which historically has fueled a large share of annual revenue growth. (Price increases have accounted for the rest.)
>
> Depending on the market, new solar installations could now account for up to half of new consumption (in the first ten months of 2013, more than 20 percent of new US installed capacity was solar). By altering the demand side of the equation, solar directly affects the amount of new capital that utilities can deploy at their predetermined return on equity. In effect, though solar will

> continue to generate a small share of the overall US energy supply, it could well have an outsize effect on the economics of utilities—and therefore on the industry's structure and future.[101]

The importance of the impact of renewables at the margin was also emphasized by analysts at Sanford Bernstein, who noted that at

> a conference… discussing the implications of distributed solar on U.S. utilities… the issue of *whether* solar is going to ramp up in the U.S. was not raised. Instead, …utilities themselves went directly to the issue of *how* to reach an accommodation with this rapidly expanding and disruptive technology…. Two things stand out. First, this is a live issue in one of the largest power markets in the world, with solar at .17% of global demand. Second, trends that start in California tend to travel well.[102]

PRESSURES FOR THE TRANSFORMATION OF THE ELECTRICITY SECTOR

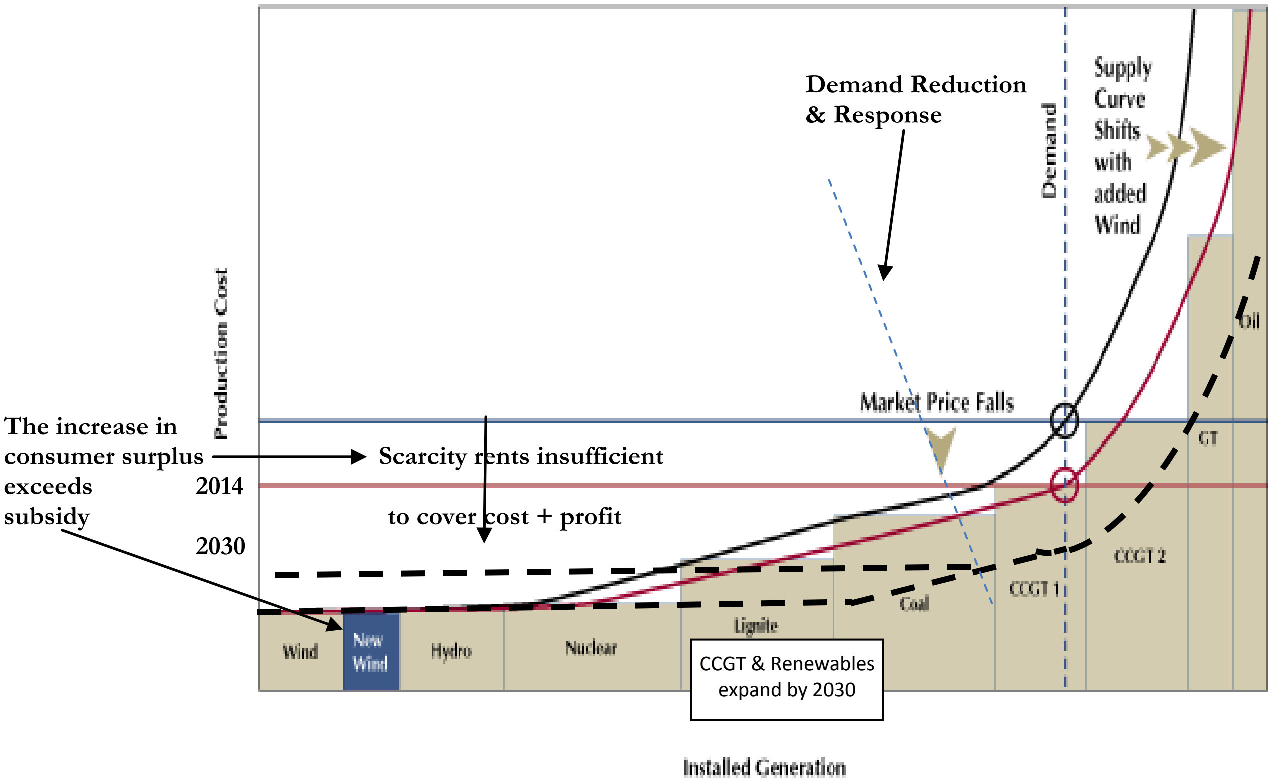
The 20th century electricity industry relied on baseload facilities that had to run constantly to meet off-peak demand and chose to meet higher levels of demand (shoulder and peak), not by storing electricity itself, but by storing potential electricity in the form of raw energy (primarily fossil fuels like natural gas and diesel, but also a small amount of water pumped above a generator). The scarcity rents necessary to pay the high capital cost of baseload facilities were created by allowing peak prices to skyrocket or setting of prices far above marginal cost.[103]

Over the past two decades it has become much more costly to meet peak demand in the old way. First, diesel became expensive. Second, the social costs of fossil fuels have been recognized. Third, carbon emissions have become a major concern. The search for low carbon alternatives to replace coal has unleashed a wave of innovation that is not only dramatically lowering the cost of alternatives but also leads to the use of resources that are likely to be dispatched on-peak because they have low operating costs. As these resources come on line, they shift the supply-curve, putting downward pressure on the market clearing price and the rents available for capital recovery. The technical term is the "merit order effect" because resources with lower variable costs are deemed to deserve (merit) to be dispatched first in a regime of economic dispatch.[104]

The supply-curve in Exhibit III-5 is taken from a group that is advocating on behalf of nuclear utilities and it captures the two most important effects of the expanding role of renewables on the market. As resources like renewables with very low operating costs enter the market, they shift the supply curve, backing out the least efficient peaking resources. This lowers the market clearing prices and squeezes with high capital costs. The figure suggests that the decrease in price is larger than the subsidies the resources is receiving, which is the case in studies of the merit order effect in virtually every advanced industrial economy with significant wind generation.

A utility sector that moves toward a more diversified, distributed resource base and directly addresses the storage issue will put further pressure on high capital cost resources (as shown by the dotted line in Exhibit III-5). The process of innovation for some alternatives is midstream, while for others, like storage it is just beginning. The pressure will continue to mount. Supply shifts to renewables and gas. Efficiency lowers demand and demand response shaves the peak. This economic transformation makes it clear that base load should not be characterized as a myth; rather it is an antiquated concept that has outlived its economic usefulness and is rapidly becoming obsolete. The electricity system is well into the transition from a "fuel based" traditional centralized electrical grid to an active and smart "renewables-based" electrical distribution system.[105]

Exhibit III-5: Effect of Adding New Wind Capacity



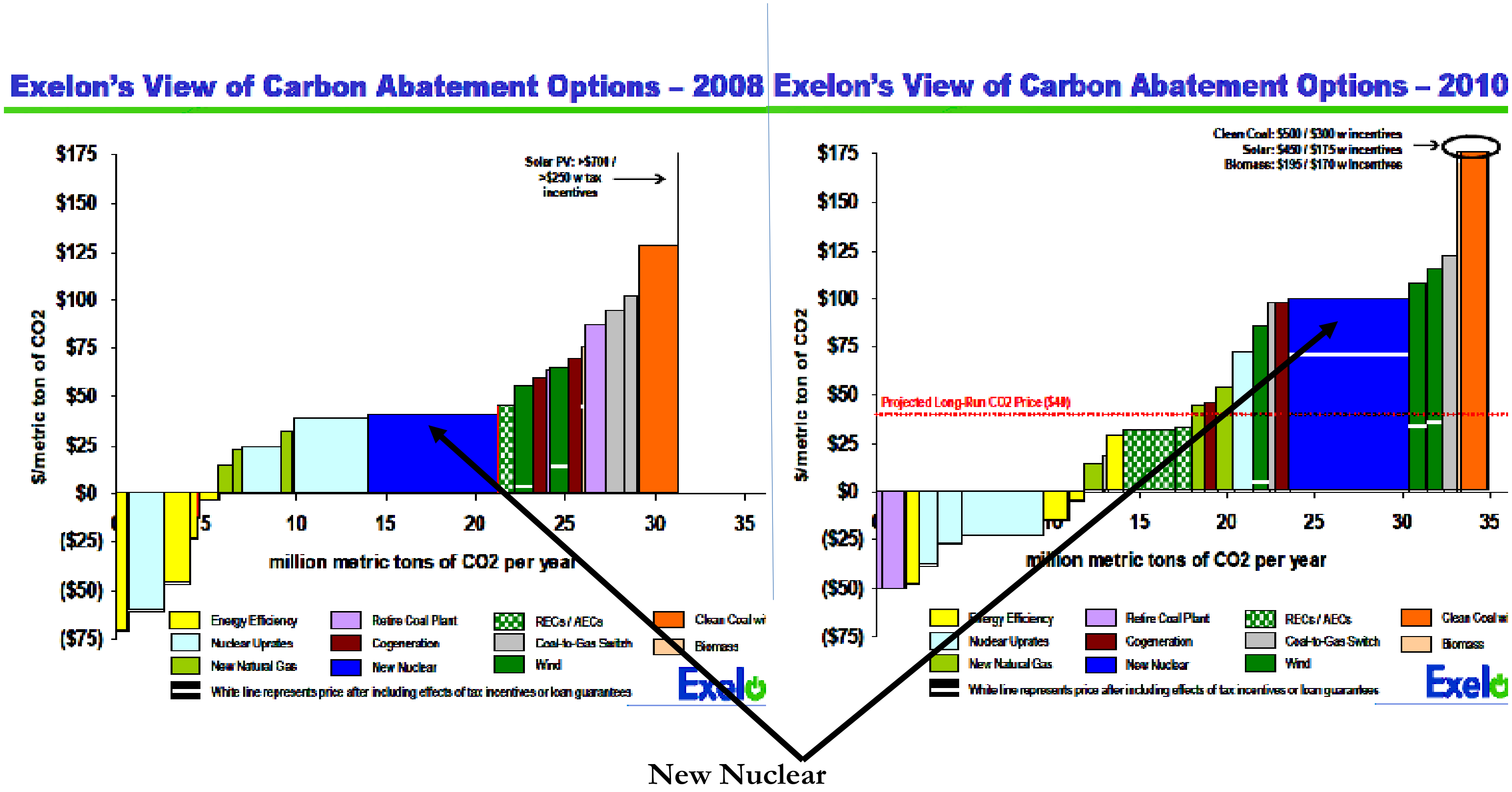
Source: Doug Vine and Timothy Juliant, 2014, *Climate Solutions: The Role of Nuclear Power,* Center for Climate and Energy Solutions, April, p. 6.

Conclusion: The Cost of Carbon Abatement

The cost of the resources that are needed to ensure that the lights and the computers stay on is the primary focus of policymakers and regulatory authorities. This cost of resources can be easily translated into the cost of carbon abatement, to provide a measure of the attractiveness of resources with respect to the challenge of climate change. Since coal is by far the largest source of carbon in the U.S. and global electricity sector,[106] with well-known emission rates, assuming that a resource replaces a coal-fired plant yields a clear measure of cost per ton of carbon emissions abated.

The most telling evidence against the economics of new nuclear reactor construction as an electricity resource **and** a carbon abatement strategy comes from within the utility industry itself. Most notable is the analysis that has been widely circulated by John Rowe, as the CEO of Exelon, the largest nuclear utility in the United States. The dim economic prospects from Exelon's point of view are summarized in Exhibit III-6, which Rowe presented at speeches at Resources for the Future and the American Enterprise Institute, two prominent market-oriented institutions. Exhibit III-6 shows side-by-side cost estimates for Exelon offered by Rowe for 11 technologies. He expresses the cost of resources as the cost per ton of carbon emission reduction, which is a common

EXHIBIT III-6: EXELON'S INCREASINGLY DIM VIEW OF NUCLEAR ECONOMICS AND IMPROVING VIEW OF ALTERNATIVES



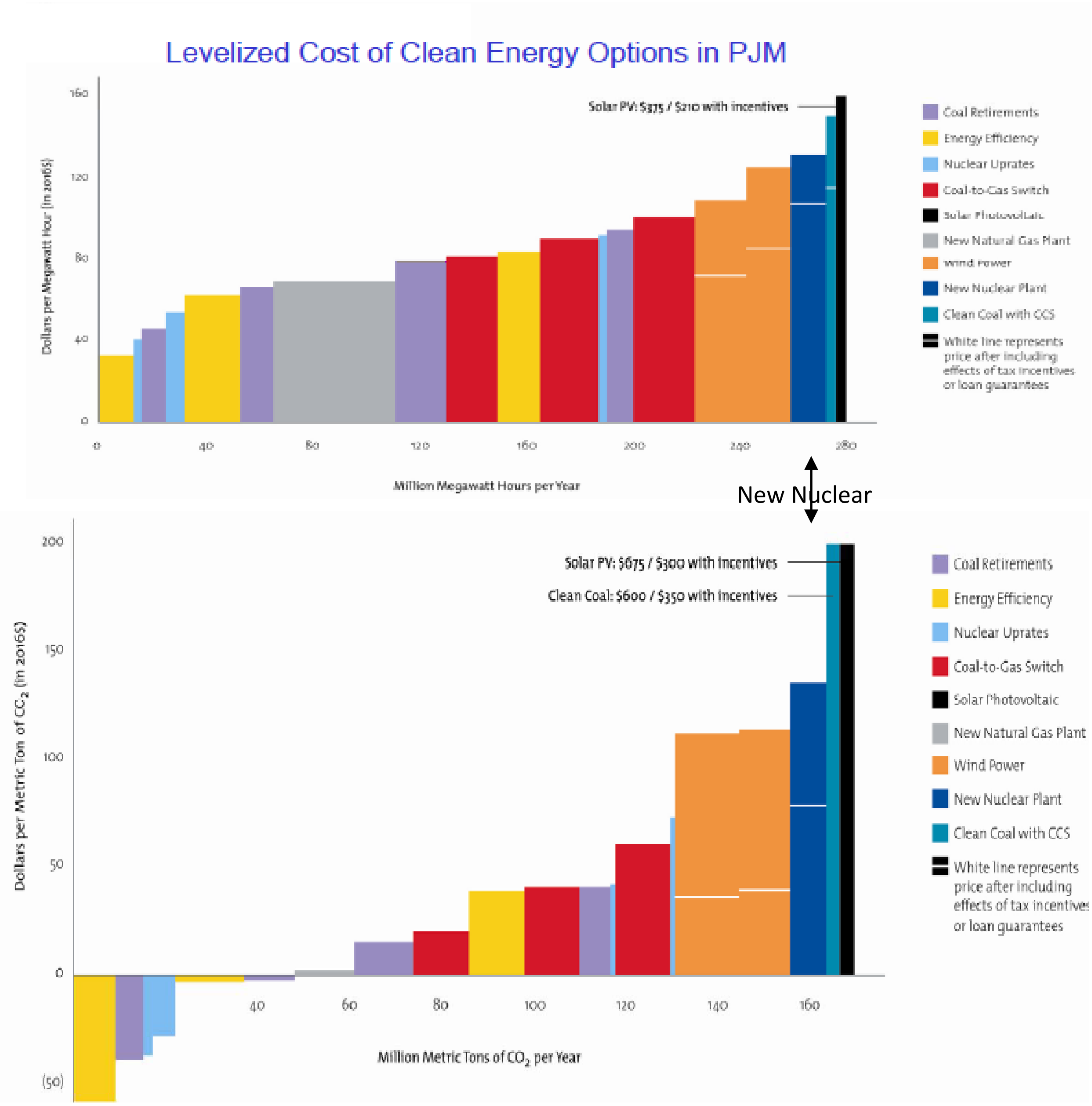
Sources: John Rowe, *Energy Policy: Above All, Do No Harm,* American Enterprise Institute, March 8, 2011;
Fixing the Carbon Problem Without Breaking the Economy, Resources for the Future Policy Leadership Forum Lunch, May 12, 2010.

way to frame the choice of resources in an environment where carbon emissions are believed to be an important consideration. He includes efficiency, which is an important resource. Exhibit III-7 shows cost curves from the East Coast Independent System Operator, PJM. It shows both the traditional measure of levelized cost per MWh and the cost per ton of carbon emissions reduced. It is similar to the Exelon analysis.

EXHIBIT III-7: PJM RESOURCE SUPPLY CURVES

There are Cheap Ways and Costly Ways to Clean the Generation Fleet

5



Source: John Rowe, *Energy Policy: Above All, Do No Harm,* American Enterprise Institute, March 8, 2011.

In 2008, new gas was less costly than nuclear, as were a number of other alternatives. By 2010, the less costly alternatives had increased in number and quantity of supply available, while the estimated cost of nuclear increased dramatically. The Exelon analysis captures several of the key dynamics that have unfolded since the early hyping of the "nuclear renaissance."

- The 2010 cost of nuclear is estimated to be about two times as high as it was in 2008. If the projected cost of nuclear had not risen so dramatically, it would have been more competitive with many more of the low carbon options available. In fact, with the dramatic increase in projected nuclear costs, carbon capture and storage technology costs are close to nuclear costs in Rowe's analysis, as seen earlier in the Lazard analysis.
- A striking feature of the cost of carbon abatement supply curve is the fact that there are a number of options with substantial potential that have "negative" costs. This simply means that the cost of the resource is lower than the current cost of generation. Therefore, carbon emissions can be reduced and the average cost of generation will be reduced. This is the key role of efficiency.
- The cost estimates reflect a 40 percent reduction in the cost of solar photovoltaics. This is the key trend for solar

The cost trends for carbon abatement are equally, if not more striking and important.

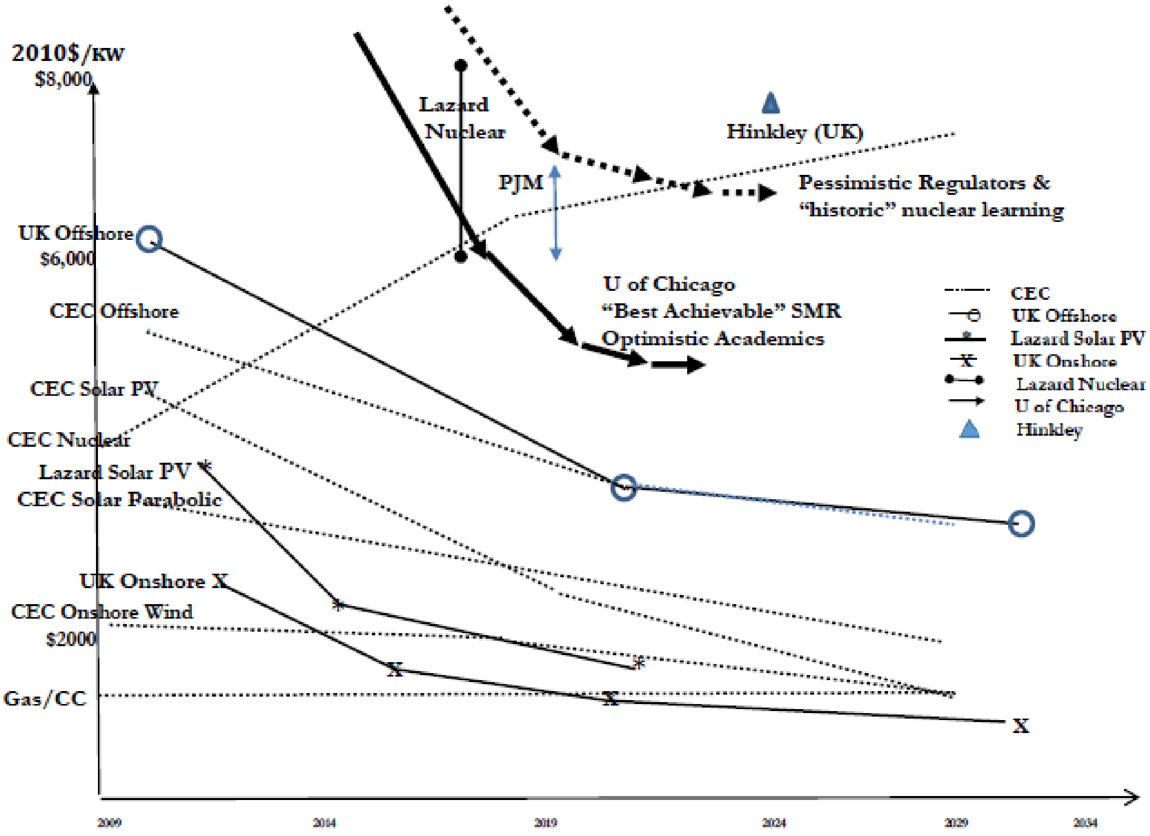
- In 2008, excluding nuclear reactors, we see about 20 million tons of potential CO_2 abatement primarily from efficiency and gas at a cost of $100 per ton at the margin. By 2010, the analysis shows 20 million tons of potential CO_2 abatement at $50 per ton, cutting the cost in half.
- The cost of nuclear carbon abatement more than doubled between 2008 and 2010, rising to about $100 per ton. In 2010, new nuclear delivers half the carbon abatement at twice the cost of the alternatives.

In both of these analyses, by 2010 nuclear was close to the last resource a prudent decision maker would select based on levelized cost either to meet the need for electricity or to reduce carbon emissions. These results are even more eye popping when we note that the cost estimates offered by Rowe do not reflect the continuing escalation of nuclear reactor construction costs, the even higher projected cost of power from SMRs, and the continuing decline in the cost of power from the alternatives.

The alternative technologies listed in Exhibit III-8 have lower capital cost and/or operating costs that are substantially below the operating costs of nuclear. Therefore, in the time frame when SMRs are projected to be available commercially at scale, the renewables will have a substantial cost advantage. Taking all of the alternatives into account, the challenge for nuclear power is substantial. Given that power from new nuclear reactors costs between 45 percent and 90 percent more than conventional combined cycle natural gas and that it would take a decade to bring new large or small nuclear reactors on line, power from new nuclear reactors is not a very attractive economic alternatives. It is at

- a severe economic disadvantage compared to all four of the main alternatives – efficiency, gas, wind and solar;
- a significant disadvantage with a respect to a number of other resources geothermal, biomass, microturbines, etc.; and
- at best competitive with carbon capture technologies.

EXHIBIT III-8: OVERNIGHT COST TRENDS: AVAILABLE TECHNOLOGIES COMPARED TO SMALL MODULAR REACTOR



Sources: California Energy Commission, *Cost of Central Station Generation,* January 2010; Mott MacDonald, *Cost of Low-Carbon Generation Technologies,* 2011; Lazard, *Levelized Cost of Energy Analysis* – Version 5.0, June 2011, 6.0, June 2012; Sensitivity to Cost of Capital; Robert Rosner and Stephen Goldberg, *Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S.,* Energy Policy Institute at Chicago, University of Chicago, November 2011, p. 19.

IV: THE PIVOTAL POLICY CHOICE

The third trend driving change in the electricity sector is the emergence of a 21st century high-technology approach to the electricity system. There is, indeed, a fundamental choice to be made between a 21st century electricity sector that is based on an active, smart and two-way, electricity system or a passive, dumb, and one-way grid. Given the economic plight of nuclear power, the push to adopt policies that will force it into the low carbon resource portfolio is essentially an effort to resist the underlying economics and jerry-rig the outcome in favor of nuclear by negating or slowing the evolution toward more decentralized resources. It is no longer a question of just subsidizing nuclear, although huge subsidies would be necessary. Nuclear advocates have launched a frontal attack on the alternatives.

THE CHALLENGE OF INSTITUTION BUILDING

In this paper and our earlier analyses we have seen that some financial analysts have been at the forefront of raising important issues when it comes to nuclear power including

- questioning the unrealistically optimistic cost projections offered by advocates in the early days of the "nuclear renaissance" and warning that new reactor construction would place severe burdens on utility finance, [107]
- identifying the implications of the dramatically declining cost of alternatives – wind, solar and storage, [108] and
- recognizing the economic problems of aging reactors in wholesale markets where renewables and efficiency are putting downward pressure on prices.[109]

Therefore, we should not be surprised to find financial analysts who have signaled the dramatic impact that the emergence of the 21st century electricity market could have on the 20th century utility business model.

> Investors beware: Distributed generation (DG) could kill utilities as we know them today. It could take a decade or more in the United States, but some European utilities already are facing change-or-die challenges due to DG. Technologies such as rooftop solar reduce the value of utilities' century-old centralized networks, and erode their efficient-scale competitive advantage. As more customers adopt DG, utilities' costs to maintain and operate the grid must be spread across a smaller customer base, raising customer rates and increasing the economic incentive to cut the cord. The death spiral ends when investors—equity and credit—are left holding an empty purse of dormant power plants and copper wires.
>
> We think the sector's imminent demise is premature, but DG is already starting to shrink some utilities' economic moats. The electric utilities industry group Edison Electric Institute (EEI) recently identified DG as the largest disruptive threat to utilities' business models and financial health. We agree. Utilities' efficient-scale competitive advantages rely on their centralized network monopolies, but that breaks down when customers become self-sufficient competitors. The cost-of-service regulatory model that allows utilities to earn at least their cost of capital in the long run also breaks down when fewer and fewer customers are bearing the costs of maintaining the

> centralized network. Ultimately, utilities' earnings will shrink, cash flows will suffer, ROIC will fall, and utilities' interest and dividend payments will become less certain.[110]
>
> Change is sweeping across the planes of our energy landscape. The combination of solar leasing, advances in renewable energy storage, and the brave new world of the "Internet of Things" spell doom for utilities as we know them. Utility shares could be worth a lot less, and sooner than investors would care to recognize.
>
> The electric utility business model has remained stubbornly unchanged for much of the last 50 years. While telecoms, health care, and other industry structures have hurtled ahead -- for better or worse -- in response to our modern technological and regulatory framework, the system that powers our homes and businesses seems almost anachronistic at this point. Utilities invest in building large-scale generation plants and a transmission and distribution architecture to move power from source to end user, and then recoup costs through the rates they charge customers.[111]

It is not only high capital cost generation that is feeling the profit pressures. Ironically, many in the utility industry – the non-nuclear part, which is the majority – recognize the forces operating on the industry. "Disruptive" is the watchword for this analysis. The Edison Electric Institute document referred to in the first quote above recognized the potential disruption.

> Recent technological and economic changes are expected to challenge and transform the electric utility industry. These changes (or "disruptive challenges") arise due to a convergence of factors, including: falling costs of distributed generation and other distributed energy resources (DER); an enhanced focus on development of new DER technologies; increasing customer, regulatory, and political interest in demand side management technologies (DSM); government programs to incentivize selected technologies; the declining price of natural gas; slowing economic growth trends; and rising electricity prices in certain areas of the country… the industry and its stakeholders must proactively assess the impacts and alternatives available to address disruptive challenges in a timely manner.[112]

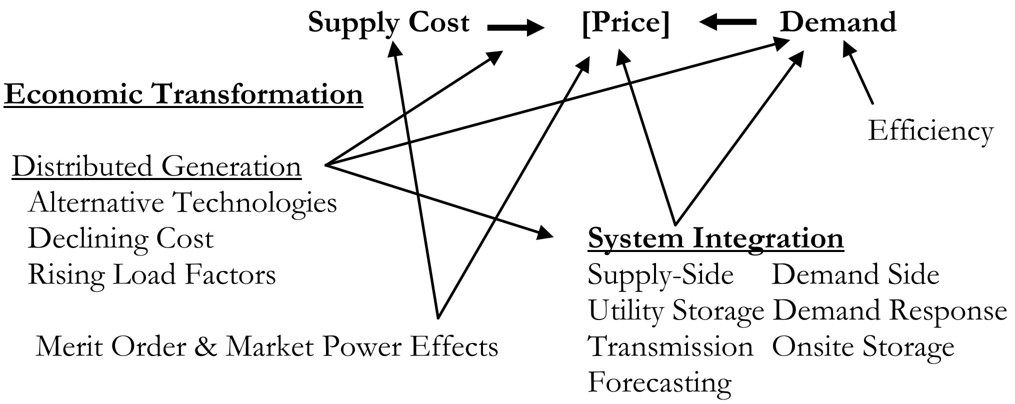
A year later, The Edison Electric Institute formed an alliance with a leading environmental group (NRDC) to call for changes in tariff and rates structures that recognize the emerging reality. Their joint statement recognizes the inability/inappropriateness of recovering capital costs in variable charges and the need to transform the grid and its operation into a two-way network that supports decentralized behaviors at the edge of the network to improve the efficiency of the sector, but requires a physical and institutional transformation.

> The future of America's vital electricity sector will continue to be a promising one as long as regulatory policies are fair and forward looking. As we move into a new age of innovation, the use of the grid is evolving, facilitating power flows in two directions, so that customers can engage in both purchases and sales of energy, and provide other services such as balancing, voltage support, and voluntary load management. Innovation is providing new incentives for customers to use the grid more effectively and efficiently, optimizing the use of existing infrastructure.[113]

Thus, the electricity sector has moved well beyond the point where environmentalists and renewable advocates argue for the possibility of a transformation. We now have Wall Street analysts and important segments of the utility industry not only observing the ongoing transformation, but also noting the need for institutional and infrastructural change to smooth it.

We do not mean to suggest that the transformation of the electricity sector is a simple task. As suggested by Exhibit IV-1, while falling costs and rising renewable load factors are the engines that are driving the change, it requires substantial new physical and institutional infrastructure that is centered on system integration and management.[114] Cost recovery to ensure the deployment of adequate facilities, a problem that plagues electricity markets in general,[115] can be compounded by the expanding role of decentralized resources with low operating costs. Incentives to innovate and compensation for intensive system management is a new challenge.

EXHIBIT IV-1: THE ECONOMIC, PHYSICAL AND INSTITUTIONAL TRANSFORMATION OF THE 21ST CENTURY ELECTRICITY SYSTEM



Infrastructure needs for the active, decentralized, intelligent two-way electricity system

Open resource acquisition	**True economic dispatch & net metering**	**Two-way intensive physical, informational infrastructure & smart grid management for integration & demand response**	**Cost Recovery Adequacy for Utilities Infrastructure and Management; Downsizing Benefits for Consumers**

However, the legitimate challenges of building these institutions can be exacerbated by the opposition of powerful incumbents. The institutional changes are direct challenges to the structure on which nuclear power and other incumbents depend. Open resources acquisition, economic dispatch and net metering dramatically reduce the rents available to fund nuclear construction and sustain its high capital costs. The two-way, information intensive system that allows integration and management of supply-side and demand side resources involve an entirely different set of skills and assets that are irrelevant to nuclear resources. Indeed they replace central station generation.

The baseload dominated electricity system was created by policy support and subsidies for physical and institutional infrastructure that favored a specific type of technology. The dominant incumbents will seek to slow or stop the spread of alternatives.

> Their diffusion can be slowed by effects of path dependence and lock-in of earlier technology systems…. high carbon technologies and supporting institutional rule systems have co-evolved, leading to the current state of 'carbon lock-in'. For example, reductions in cost and the spread of infra- structure supporting coal- and gas-fired electricity generation enabled the diffusion of electricity-using devices and the creation of institutions, such as cost-plus regulation, which

> encouraged further investment in high carbon generation and networks. This created systemic barriers to investment in low carbon energy technologies….
>
> the proposition that industries or technologies whose ascendancy is threatened by new competition tend to respond, carries some weight. It also suggests that actors, such as large energy companies, with substantial investments in the current system and its technologies, and relatively strong political influence, are likely to act to frustrate the implementation of institutional changes that would support the implementation of low carbon technologies.[116]

The conflict between nuclear technologies and the alternatives is inevitable and crucially important to determining the future path of the electricity sector. There are fundamental economic, technological, and institutional incompatibilities between the two approaches, which have given rise to the frontal assault by nuclear advocates on the alternative resources and institutions that will support them.

> "All of the above" scenarios are… undesirable for several reasons.
>
> First, central thermal plants are too inflexible to play well with variable renewables, and their market prices and profits drop as renewables gain market share. Second, if resources can compete fairly at all scales, some and perhaps much, of the transmission built for a centralized vision of the future grid could quickly become superfluous. Third, big, slow, lumpy costly investments can erode utilities' and other provider's financial stability, while small, fast granular investments can enhance it. Competition between those two kinds of investments can turn people trying to recover the former investments into foes of the latter – and threaten big-plant owners' financial stability. Fourth, renewable, and especially distributed renewable, futures require very different regulatory structures and business models. Finally, supply costs aren't independent of the scale of deployment, so PV systems installed in Germany in 2010 cost about 56–67% less than comparable U.S. systems, despite access to the same modules and other technologies at the same global prices.[117]

We certainly do not mean to suggest that the solutions for the challenges of building a 21st century electricity systems are all in hand. It is the case that much of the thinking about how to build and manage the physical and institutional infrastructure to operate the 21st century electricity system is in the early phase. However, this is equally, if not more true of the effort to conceive of a new SMR technology. Based on the history of the performance of the nuclear and the alternative industries, there are good reasons to expect the alternatives will overcome their challenges more quickly and efficiently.

First, in addition to the ongoing conceptual and design work, the nature of the renewable technologies involved affords the opportunity for a great deal of real world development and demonstration work before it is deployed on a wide scale. This is the antithesis of past nuclear development and the program that SMR advocates have proposed.

Second, the alternatives are moving rapidly along their learning curves. For example, half a dozen advanced industrial countries (Denmark, Ireland, Germany, Sweden, Spain, Portugal) have achieved three times the penetration of wind per capita as the U.S., even though the U.S. has a much greater wind potential.[118]

Third, the ability to move down the learning curves exhibited by renewables and alternative technologies can be explained by the fact that these technologies actually possess the characteristics that allow for the capture of economies of mass production and stimulate innovation. They involve the production of large numbers of units under conditions of competition. Nuclear power, even SMR technology, involves an extremely small number of units from a very small number of firms, with the monopoly model offered as the best approach.

In short, the underlying conditions and recent decades of experience suggest that the dramatic reversal of fortune the advocates of SMR technology are hoping for is not likely, to say the least, while the continued, dramatic decline in the cost of renewables, is quite likely and the prospects for the development of the building blocks of the 21st century electricity system are much better.

The broader literature on policy responses to the challenge of climate change reinforce these observations in a number of ways. The benefit of accelerating the transition to a new infrastructure are well grounded in the growing literature on the analysis of responses to climate change. This literature indicates that overcoming inertia to speed the transition yields substantial disproportionate benefits. The evidence suggests that the cost of inertia is quite large, and targeted approaches lower costs and speed the transition.[119]

- The general finding that the social return to R&D is twice as large as the private return appears to hold in the alternative energy technology space.[120]
- Because of the magnitude of the change required, the macroeconomic impacts of policy take on great significance, with analysis of the macroeconomic savings from a smoother, swifter transition yielding very substantial projected economic savings of at least 50 percent.[121]

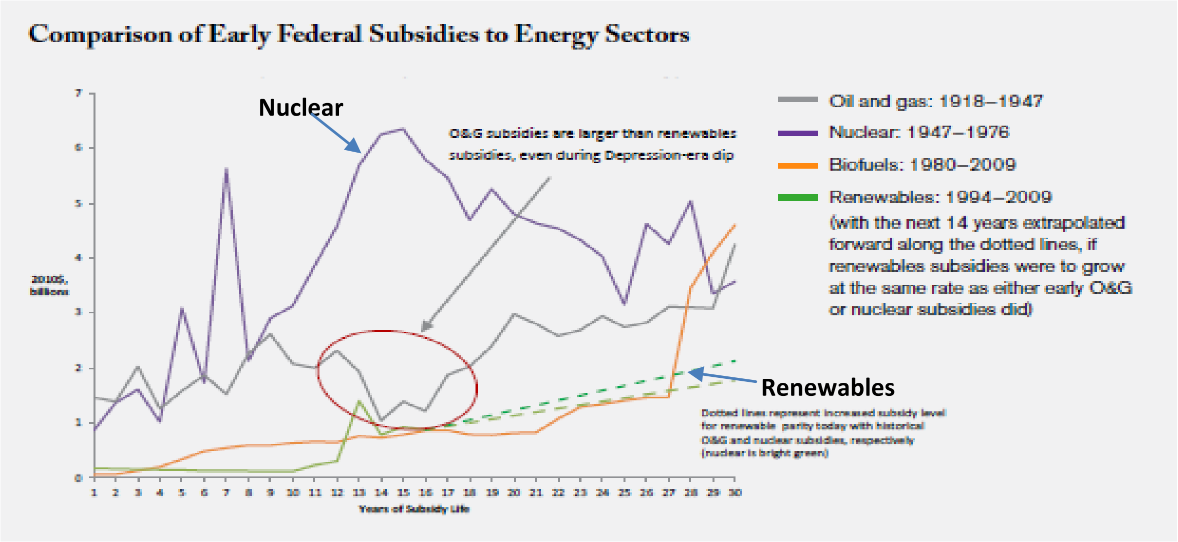
The analyses reach this conclusion because delaying the start of the transition results in a longer, more costly transition that result in higher costs and greater reductions in economic activity for a longer period. The nuclear history and analysis of the leading nuclear technology candidates shows they do not exhibit these benefits and policies to promote them would have the effect of delaying the benefits of the development of alternatives.

Whether the question is the delay in transitioning to alternatives that results from expanding the role of nuclear power, or the lost opportunity to speed the transition to alternatives, the inertia that supports the incumbent technology is a central factor.[122] Inertia is the result of several factors that exacerbate the problem of underinvestment in alternatives,[123] including the ability of dominant incumbents to implement practices and promote policies that magnify the barriers to entry,[124] like control of access to the grid or dispatch,[125] Other market structural problems not associated with market power are equally important,[126] including market size, the tendency to invest in incremental innovation focused on the dominant technology, innovative activity[127]and existing skill sets;[128] lack of substitutability between the alternatives, limited spillovers from innovation in the incumbent technology, and the undifferentiated nature of the product makes it hard for new entrants to secure a foothold (niche) from which to build scale and learn-by doing.[129]

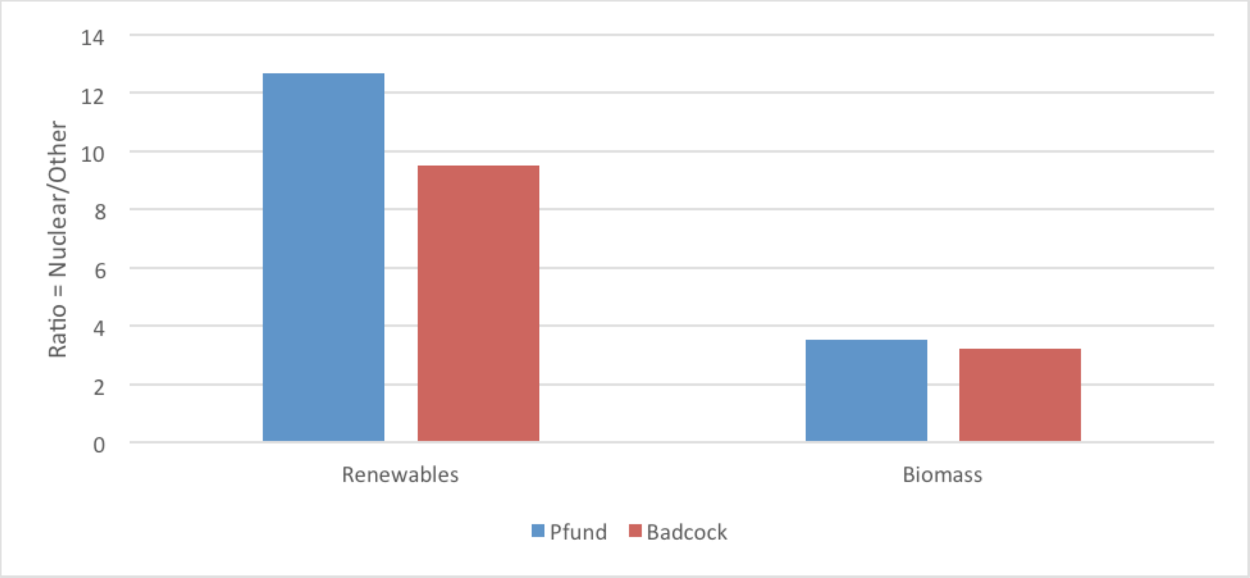
SUBSIDIES

Subsidies play a crucial and unavoidable role in the policy decision. Renewables are in the early stage of development and receiving subsidies (see Exhibit IV-2). The irony in the effort of the nuclear industry to secure additional subsidies to keep existing reactors online and advance the next generation of reactors, at the expense of alternatives, is that the incumbent baseload facilities, nuclear among them, were the winners in the past, in large part, because they were picked in the past and have been favored with policy advantages over a long period of time.[130] The fact that the incumbent technologies have been and continue to be the beneficiaries of subsidies reflects the fact that energy markets need these interventions to achieve important social goals, particularly when inertia must be overcome.[131]

EXHIBIT IV-2: FEDERAL SUBSIDIES FOR INFANT ENERGY INDUSTRIES AND BEYOND



Ratio of Total Subsidies: Nuclear Compared to Others



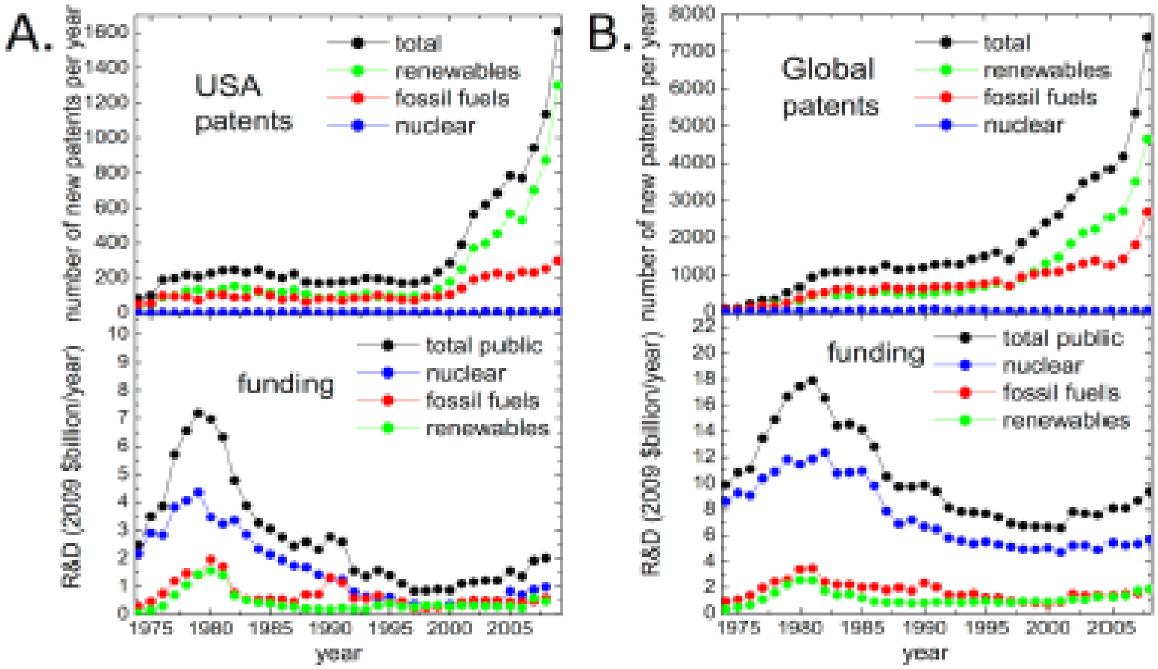
Sources: Nancy Pfund and Ben Healey, *What Would Jefferson Do? The Historical Role of Federal Subsidies in Shaping America's Energy Future*, Double Bottom Line Investors, September 2011, pp. 29–30; Badcock, Jeremy and Manfred Lenzen, 2010, "Subsidies for electricity-generating technologies: A review" *Energy Policy,* 38, Table 4.

While the nuclear industry complains about the subsidies that are bringing renewables into the market today and resist programs to promote energy efficiency, analysis of the historical pattern demonstrates that the cumulative value of federal subsidies for nuclear power dwarf the value of subsidies for renewables, as shown in the upper graphs of Exhibit IV-2.[132] Analyses of subsidies in globally reach similar conclusions.[133] These estimates of subsidies generally do not include estimates of the value of socialization of insurance and waste management.[134] The most critical point of the historical analysis is to recognize the timing of subsidies in the life cycle of technologies. Nuclear power required much larger subsidies earlier in the life cycle to get into the resource mix.

There can be debate about the current level of subsidies, particularly given the difficulty of valuing the insurance and waste subsidies which are existential rather than material (i.e., without the socialization of liability and waste disposal the industry would not exist), but there is no doubt that the long-term subsidization of nuclear power vastly exceeds the subsidization of renewables and efficiency by an order of magnitude of 10 to 1 (as shown in the lower graph of Exhibit Iv-2).[135] The ultimate irony is that with a much smaller level of subsidy to drive innovation and economies of scale, the renewables have achieved dramatically declining costs in a little over a decade, which is exactly the economic process that has eluded the nuclear industry for half a century.

Exhibit IV-3 captures the essence of the subsidy issue by juxtaposing the magnitude and timing of subsidies and the extent of innovation, as measured by patents issued. The large and early support for nuclear is clear in the U.S. and the global data, as is the meager output of patents. In contrast, public funding for R&D for renewables was much smaller, but patent activity is much higher. The dramatic increase in innovative activity with relatively low levels of R&D subsidy and much lower cumulative levels of total subsidies, reflects the decentralized nature of innovation in the renewable space and leads to the dramatic pay-off in terms of declining price. As we have seen, while wind had the earlier success, solar is now catching up.[136]

EXHIBIT IV-3: INNOVATION AND PUBLIC SUPPORT FOR R&D



Source: Bettencourt, Luı´s M.A., Jessika E. Trancik, and Jasleen Kaur, 2013, "Determinants of the pace of global innovation in energy technologies," *PLoS ONE*, October 8, p. 10.

The analysis of the potential transformation has progressed to modeling how to build a sector that captures the synergies of utilization of geographically diverse and widespread renewables, combined with key infrastructure components of – transmission, storage and demand response – to lower cost and meet demand.[137] In fact, some have argued that the benefits of stimulating innovation are so large that they can even offset the apparent "cost" of phasing out nuclear power altogether,[138]

> Our results show that phasing out nuclear power would stimulate investment in R&D and deployment of infant technologies with large learning potentials. This could bring about economic benefits, given the under provision of innovation due to market failures related to both intertemporal and international externalities.[139]
>
> The evolution of the renewables costs in the coming years will not be independent of the future of nuclear power, as well as of energy and climate policies. In this context of uncertainty, policymakers need to understand the economic consequences of nuclear power scenarios when accounting for its interplay with innovation and cost reduction in renewables.[140]

THE PRUDENT POLICY CHOICE

It is pure speculation whether the options available or the terrain of decision making and policy choice will be significantly different in a half century or a full century. The potential contribution of the non-nuclear low carbon alternatives, which are less costly, more environmentally benign, low carbon resources has only begun to be exploited and the prospects are quite good.[141] The prudent approach to resource acquisition is to build the institutional and physical infrastructure that achieves the maximum contribution from the more attractive resources available in the near and mid-term. With a clear path of more attractive resources, we do not have to engage in the hundred year debate today, although there is growing evidence that prospects for high penetration renewable scenarios for the long terms are quite good.[142] The available and emerging alternatives can certainly carry the effort to meet the demand for electricity with low carbon resources a long way down the road,[143] certainly long enough that the terrain of technologies available may be much broader before we have to settle for inferior options like nuclear power.

The most recent report of the Intergovernmental Panel on Climate Change suggests that the prudent economic choices are also the prudent climate change actions.

- Speed is essential.[144]
- Flexibility and innovation combine with speed to hold costs to modest levels.[145]
- Efficiency is the first pillar for a successful response.[146]
- The electricity sector is the second pillar.[147]
- Renewable technologies are the best hope for near term reductions.[148]
- Natural gas is an attractive option.[149]
- Nuclear power continues to be plagued by long-standing problems.[150]
- Carbon capture technologies are uncertain.[151]

CONCLUSION: NUCLEAR MYOPIA TAKES A TURN FOR THE WORSE WITH SMR TECHNOLOGIES

Over the past 5 years our analysis has consistently shown that "nuclear renaissance" technology is too big to properly meet demand, too expensive to compete with alternatives, takes so long to build it creates significant marketplace risk, and requires so much sunk capital that it cause severe financial risk. The arguments were ridiculed by nuclear advocates and dismissed as based on purely anti-nuclear bias, notwithstanding the empirical analysis presented. It is deeply ironic to now hear those same advocates make exactly the same arguments against large reactors in trying to build the case for SMRs.

Has the nuclear industry been cured of its myopia? Not at all. In fact, there is a sense that the disease is getting worse, not better, since the characteristics that are said to make small modular technologies attractive are precisely the characteristics that make other alternatives more attractive. In the past, the refusal to look at alternatives could be explained by the fact that the advocates were looking at different characteristics – claiming that huge baseload facilities are indispensable. They dismissed the alternatives because they are too small or too variable. Today, they emphasize small size and speed to market, characteristics on which the alternatives are vastly superior. At the same time they ignore the innovation that has sharply increased renewable load factors and the dramatic advances in information and control technologies that have improved the ability to forecast and integrate renewables. They simultaneously, they ignore the repeated failure of cost reduction and make bold claims for a new technology.

- Nuclear myopia has not only become worse, it has combined with nuclear amnesia to become nuclear blindness.

The failure to find customers and investors is the ultimate rejection in a capitalist economy. The market recognizes what the nuclear advocates continue to ignore. Nuclear blindness is epitomized in the Babcock & Wilcox explanation for its failure to find investors in its SMR technology, in spite of the fact that it had received a development subsidy.

> The issue, he insists, is that the market for small reactors is likely to be about three to five years further out than B&W anticipated when it started the program in 2009.
>
> That is because... the growth in demand for electricity remains weak, and may even flatten out over the next few years….Combine that fact with the low cost of natural gas plants in the current market, and he estimates the market for mPower has been pushed back three to five years. That makes it hard to justify significant investment now…
>
> Now the company is looking at slowing investment and waiting until the market catches up with the technology.[152]

Westinghouse used the same language, not only in blaming cheap gas, but also in declaring that it did not want "to ahead of the market."[153] In the case of Westinghouse, their caution was tied to the failure to find orders for its AP600, a design that had been licensed fifteen years earlier[154] and its claim that it needed a large book of orders, 30-50 reactors (7 to 10 GW given its design). The failure of SMR technology makes it impossible to ignore the huge scale that nuclear power demands to succeed. Shifting that need up back in the supply chain does not eliminate its importance. The problem that utilities have in swinging the financing and development of large reactors is replaced by the problem that vendors have, but it is essentially the same problem.

Blaming cheap gas and a temporary slump in demand ignores the fundamental changes in the electricity sector. A comprehensive view that includes **all** of the emerging alternatives **and** the history of nuclear technology and cost escalation explains why nuclear technology, large or small, cannot find either customers or investors today and suggests that the market will not "catch up" any time soon.

The extent of the pullback by B&W, which had a large federal subsidy, caught the nuclear advocates by surprise. From spending around $80 million per year, initial figures of less than $60 million were floated, but the actual figure was put at $15 million, with the departure of the head of the program.[155] The declarations of confidence in the technology could not hide the fact that in less than a decade its development was "grinding to a halt."[156]

The rapid and stunning collapse of the SMR hype is extremely important in the policy context.[157] Westinghouse and B&W are big names in the nuclear space, had thrown a create deal of weight and money into advancing SMRs as the next big thing and the savior of the nuclear industry. Westinghouse had spent close to a decade propounding a theory of economic competitiveness that had become gospel among nuclear advocates, yet, in stepping back it was clear that they "had no way to calculate the cost"[158] and much larger subsidies would be necessary to move the technology forward. This dose of reality came amid the failure of the "nuclear renaissance," the immense market pressures on aging reactors, and the rapidly declining cost that led to the dramatic expansion of alternatives, not to mention the increasingly urgent need for action to address climate change.

Over the course of the past five years, we have demonstrated that the prudent course from the point of view of the resource costs economics of large reactors[159] and in the context of a complex decision making framework[160] is to add alternative resources to the portfolio of assets to meet the need for electricity in a low carbon future. The above analysis shows that this is the prudent course of action in the context of climate policy and small modular reactors. The 50 year lessons of the 50-year history of nuclear power do not change with the size of the reactors:

- Nuclear power is an extremely complex technology based on a catastrophically dangerous resource that is vulnerable to natural events and human frailties, which suggests that nuclear safety and affordable reactors are currently incompatible and are likely to remain so for the foreseeable future.[161]
- Nuclear power is far too costly, risky, and slow to play a major role in the response to climate change today and for the foreseeable future, since there are many more promising low carbon alternative that are less costly and less risky.

END NOTES

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[1] Cooper, Mark, 2013c, Exhibit I-1 presents a comprehensive accounting of the collapse of the "nuclear renaissance."

[2] The figure of 100 reactors has received a great deal of political attention because Senator Lamar Alexander has been advocating for that number to be built over the next two decades (Lamar Alexander, 2009.)

[3] Cooper, 2012b and 2012c, provide accounts of the difficulties in the ongoing construction in Georgia and South Carolina.

[4] Cooper, 2013a.

[5] Daniels, 2014.

[6] Schneider, et al., 2013.

[7] Fairley, 2014.

[8] Litvak, 2014; Adams, 2014. The failure to secure a government subsidy had foreshadowed the decision (Barker, 2013). Although Westinghouse said it would focus on its AP-1000 projects, it also noted that "Westinghouse will focus its attentions on its decommissioning business, which is a $1 billion dollar per year business for the firm – which is equivalent to Westinghouse's new reactor construction business, and rededicate its staff to the AP1000 reactor design."

[9] Downey, 2014.

[10] Roanoke.com, 2014.

[11] Henderson, 2014.

[12] Turmelle, 2014, There was nothing wrong with these plants," Fertel said. "There is something wrong with the design and operation of the markets in which they are operating. They do not value the base load capacity that can be dispatched when needed, do not provide value for fuel end technology diversity;" Daniels, 2014, Exelon officials have met with Senate President John Cullerton. And CEO Chris Crane met in recent weeks with Illinois House Speaker Michael Madigan to brief him on the problems. "It's about market conditions and the impact on the nuclear fleet"… Exelon's plants are buffeted by low wholesale power prices tied to surging natural gas production and slack demand. In addition, the company has complained of **acute pricing pressures** at nukes near wind farms, which can profit from tax subsidies while depressing spot prices and forcing nukes to sell their output at a loss. Exelon lobbyists have floated the idea of creating a state "clean energy" standard or credit that would recognize the nukes for their clean-air and their dependability as a 24/7 power sources. That designation would entitle the plant to extra payments in some form – presumably from ratepayers.

[13] Conti, 2014; Kucro, 2014; Von Hoene, Jr., 2014.

[14] See Cooper, 2014, for a discussion.

[15] CNN, 2013.

[16] Upton, 2014.

[17] Bastasch, 2014;

[18] Northey, 2014a; Geman, 2014.

[19] Lovins, 2011, 2014.

[20] France and the U.S. account for 162 out of 346 reactors not in formerly Iron Curtain nations or China. An additional 32 reactors are in developing nations (e.g. Pakistan, India, Brazil, etc.) (European Nuclear Society, 2014). .

[21] Rangel and Leveque, 2012.

[22] Cooper, 2010.

[23] Cooper, 2012a.

[24] Rangel and Leveque, 2012, pp. 16.

[25] Rangel and Leveque, 2012.

[26] Cooper, 2010, pp. 26-29.

[27] Boccard, 2014.

[28] Cooper, 2013b.

[29] Cooper, 2013a

[30] Rangel and Lévêque, 2013.

[31] Rangel and Leveque, 2012: 12…14.

[32] Rangel and Leveque, 2012, pp. 14… 15.

[33] Boccard, p. 452.

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[34] Schnieder, et al., 2013, p. 50.

[35] Boccard, p. 452.

[36] Boccard, p. 456.

[37] Boccard, p. 452.

[38] Boccard, p. 452. In retrospect, the French nuclear program was an industrial success, but its economics were too ambitious and self-centered, having drawn on an expected demand growth that did not materialize due to the oil shocks. Clearly, the full economic benefit could have been achieved with the N4 class of reactors if the output market had been conceived to be the European one in the first place as the sheer size (and cost) of each reactor requires a very large market to achieve scale economies.

[39] Boccard, p. 453.

[40] Rangel and Leveque, 2012, p. 8.

[41] Rangel and Leveque, 2012, p. 16–17.

[42] Cooper, 2012b.

[43] Cooper, 2011a.

[44] A World Bank study advocating nuclear power applies a series of pejoratives to the regulatory response for new nuclear technology in the 1970s and 1980s including terms like "the public's demand for super-super safety (13), regulatory ratcheting (13), turbulence (14)" Kessides, 2012.

[45] Berthelemy, 2012. The econometric analysis in Cooper, 2010, shows increases in overnight cost post-TMI associated with increases in safety regulation, which is consistent with this observation.

[46] Grubler, p. 30.

[47] Bupp and Derian, 1978, pp. 72…79.

[48] Bupp and Derian, 1978, pp.71… 72…74…75…76…78…79.

[49] "Déjà vu all over again" is a phrase taken from a famous (attributed) quotation from Yogi Berra, http://en.wikipedia.org/wiki/Deja_Vu_All_Over_Again

[50] University of Chicago, 2004; Rosner and Goldberg, 2011a; Scully Capital Services, 2002, used Westinghouse's cost estimates for the AP1000 as the example. These estimates were reported in the University of Chicago, 2004, report and identified by Harding, 2007, as one of the early estimates. Westinghouse employees were in the forefront of the SMR estimates, see Carelli, et al., 2007.

[51] Bupp and Derian, 1978, pp. 71… 72…74…75…76…78…79.

[52] Litvak, 2014; Downy 2014a.

[53] Bupp and Derian, 1978: 154–155.

[54] Komanoff, 1981: p. 27

[55] Ingersoll, 2009, pp. 589–603 591…600.

[56] Ingersoll, 2009, p. 600, emphasis added.

[57] Zhitao and Fan, 2014, pp. 27–28,

[58] http://en.wikipedia.org/wiki/Economies_of_scale, In microeconomics **economies of scale** are the cost advantages that enterprises obtain due to size, output, or scale of operation, with cost per unit of output generally decreasing with increasing scale as fixed costs are spread out over more units of output.

[59] Kuznetsov, 2008, p. 50 cites a 2007 "Westinghouse Electricity Company Estimate" as the source – Carelli, 2007, a paper whose lead authors were Westinghouse employees offers the same graph, without attribution.

[60] Rosner and Goldberg, 2011a.

[61] Kuznetsov, 2008 (50) cites a 2007 "Westinghouse Electricity Company Estimate" as the source. A 2010 (M. D. Carelli, et al., 2010, piece jointly authored by vendor (Westinghouse) employees and academics presents the curve as a theoretical proposition and makes assumptions to estimate cost effects. Kessides, 2012, p. 48, cites a different 2010 source (Mycoff, et al.) which drops the original source and is contained in an article co-authored by employees of a vendor (Westinghouse) and an academic institution. Similarly, the University of Chicago 2011 (Rosner and Goldberg) cost estimates are repeated in Kurth, 2013.

[62] Makhijani, 2013; Lyman, 2013; Glaser, Bezak and Ramana, 2013.

[63] The difference cited are from Abdulla, Lima, and Morgan, 2013. Similarly broad ranges of opinion are reflected in Anadon, 2011; Anadon, Nemet and Verdolini, 2013.

[64] Carelli, et al., 2010, p. 412, According to the model it is possible to conclude that a site with four SMRs (335MWe) has an O&M cost 24% greater than a site with one 1340MWe LR, or likewise a site with three SMRs has an O&M cost 22% greater the a site with one 1005MWe LR.

[65] Locatelli and Mauro Mancini, 2010, p. 6366, "According to Locatelli and Mancini (2009) it is possible to compute the decommissioning cost of a small medium reactor by multiplying for: 3.09 (because of the economy of scale) and by

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0.81. This latter value is the quantification of the technical saving i.e. advantage of adopting the solutions embedded in the small medium reactors. Therefore, the decommissioning cost for a 335 LWR implemented in the model is 1251.45 $/kWe; Locatelli, and Mancini, 2009. Locatelli and Mancini, 2010, p. 2. The results show that when all of these factors are accounted for in a set of realistic and comparable configurations, and with the same power installed on the site, the decommissioning costs of a SMR with respect to a LR drop from three times higher to two times. If more than one large reactor is considered, the gap increases since the large reactor investment also reaps advantages from site sharing." Since most new build large reactors are at existing sites, the cost of decommissioning SMRs is likely to be closer to the higher estimate of three times as costly.

[66] Three characteristics were common to all the light water technologies, Coolant, Neutron Spectrum and Fuel.

[67] Litvak, 2014.

[68] Cooper, 2012a.

[69] Cooper, 2012a.

[70] Tomain, 1988, p. 9.

[71] Cooper, 2012a, reviews early reactions through late 2011. More recent summations and recommendations can be found in Wang, Qiang and Xi Chen, 2012; Wang, Qiang, Xi Chen, and Xu Yi-chong, 2013; Masahiko and Rothwell, 2013.

[72] Locatelli, Bingham and Mancini, 2014.

[73] Belouda, M., et al., 2013; Nogueira, Carlos Eduardo Camargo, et al., 2014; Akikur, R.K., et al., 2013.

[74] Johansonn, 2014.

[75] Katarzyna, et al., 2009, 187, the examined nuclear technologies, despite their enhanced safety, reduced costs and minimized waste, still have to face the major issues of weapons proliferation, safety, waste handling and high costs as well as public acceptance, which have been affected by the recent Fukushima accident.

[76] Stein, 2013; Rabl and Rabl, 2013, find the externalities of renewables and nuclear are similar because the load factor on gas is 70 percent. If the load factor is 50 percent, nuclear has much higher externalities.

[77] Llera, 2013; Santiago, et al., 2014. Islam, Mekhilef and Saidur, 2013; Pleßmann, Guido, et al., 2014, Branker and Pearce, 2010; Black, Geoffrey, et al., 2014, p. 141, The removal of this incentive in Idaho results in a net reduction in tax revenues as well as the loss of significant economic benefits in terms of employment, incomes, and total output for the State. (36) There are two main approaches to estimate the tax effects of alternative energy generation. First is the direct calculation of sales, and other taxes paid during the preconstruction, construction and operation phases of alternative electricity production? ..In addition to these direct fiscal calculations, this study estimates the increased tax revenues stemming from measurable increases in incomes, employment, total output of goods and services, and tax revenues. To do so, this study tracks the expenditures on goods and services purchased in the State during each phase of alternative energy development projects as well as the incomes of employees. The output that results from these expenditures by producers is known as the direct economic effects... The purchases on the part of suppliers of goods and services to alternative energy producers are known as the indirect effects and also increase incomes and tax revenues. Spending by households whose incomes have increased, and the corresponding fiscal impacts, are known as the induced effects in Input–Output analysis. It should be noted that the direct economic effects are by far the largest component of the total economic impact. It is also important to note that the indirect and induced effects constitute real and important increases in incomes and tax revenues, besides the opportunities for employment and income for Idaho residents.

[78] Stein, 213, Karakosta, et al., 2013, Verbruggen, Laes and Lemmens, 2014.

[79] U.S. Congressional Office of Technology Assessment, 1994, evaluating Ottinger, Richard ET. al., 1990, Chernik, Paul and Emily Caverhill, 1989, Hohmeyer, Olive, 1988 and Shuman, Michael and Ralph Cavanagh, 1982.

[80] Stein, 213, 646… 640.

[81] Cochran, et al., February 2010, pp. 5, 8, 9, 11.

[82] Makajani and Boyd, 2010.

[83] National Nuclear Laboratory, 2010.

[84] Fusion is another technology whose time seems never to come (see, e. g. Moyer, 2010, Tokimatsu, 2003).

[85] Cooper, 2009a.

[86] Cooper, 2013a.

[87] Cooper, 2013a.

[88] Cooper, 2013a.

[89] Cooper, 2013b; Cooper, 2014.

[90] Citi Research, 2012, pp. 54, 55, 56. The academic literature reflects this trend as well. See, for example, Sener, Can and Vasilis Fthenakis, 2014; Hernandez-Moro and Martınez-Duart, 2013; Reichelstein, Stefan and Michael Yorston,

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2013: projecting recent industry trends into the future, we estimate that utility-scale solar PV facilities are on track to become cost competitive by the end of this decade. Furthermore, commercial-scale installations could reach "grid parity" in about ten years, if the current federal tax incentives for solar power were to expire at that point. (117); Bazilian, Morgan, et al., 2013; Branker, K., M.J.M. Patha and, J.M. Pearce, 2011.

[91] Eggers, Cole and Davis, 2013b, p. 1.

[92] Eggers, Cole and Davis, 2013b, p. 1.

[93] Cooper, 2013c.

[94] Eggers, Cole and Davis, 2013b.

[95] Eggers, Cole and Davis, 2013b, p. 3.

[96] Eggers, Cole and Davis, 2013, p. 11.

[97] Zheng, Chengn and Daniel M. Kammen, 2014.

[98] Eggers, Cole and Davis, 2013a, p. 1.

[99] Eggers, Cole and Davis, 2013a, p. 1.

[100] Eggers, Cole and Davis, 2013a, p. 3.

[101] Frankel, Ostrowski, and Pinner, 2014.

[102] Parker, et al., 2014, p. 3.

[103] Amer and Amer, 1984, describe a situation of scarcity that applies well to the peak load problem, noting that "when the supply is exceptionally small – its price will be exceptionally high, and it will be said to have *scarcity value"* (p. 416) and links it to the definition of *quasi-rent,* defined as "a return on capital or labor whose supply is temporarily or permanently fixed, so called to distinguish it from a *real rent,* the return on land (whose supply is always fixed). Pearce, 1984, p. 395, applies the concept of absolute scarcity to fossil fuels.

[104] The impact of the Merit Order Effect has been documented in a number of nations in which renewables have shown strong growth in recent years, demonstrating not only that market clearing prices are lowered, but also that they are lowered by an amount that is larger than any subsidies the resources receive. The result is a net benefit to consumers. See for example, United States, Bob Fagan, et. al. 2012, Caperton, 2012, Charles River Associates, 2012; Canada, Ben Amora, 2014; Australia, McConnell, 2013, MacGill, 2013, Melbourne Institute, 2013; Ireland, Mahoney, and Denny, 2011; Denmark, Munksgaard, 2011; Germany, Sensfuss, Ragwitx and Genoese, 2008; Spain, de Miera, 2008; United Kingdom, Green, and Vasilakos, 2011. A separate effect that lowers the market clearing price is the fact that renewables tend to lower the level of concentration of supply, reducing the exercise of market power, Misir, 2012, Twomey, and 2010), Wirl, 2014, Mountain, 2012, p. 16, the exercise of market power is likely to result in a preference for investment in conventional fossil fuel based electricity generation, relative to investment in wind farms. It also concludes that while wind farms have taken market share from conventional generators, wind farms are not likely to have reduced spot prices in South Australia to the extent that seems apparent in electricity markets in other countries where wind farms are as prevalent but market power is less significant. The implication of these conclusions is that higher subsidies will be needed to ensure that the Australian Government's renewable electricity targets will be met, than would be the case if the exercise of market power did not have these distributional effects. (iii) We concluded that whereas the profitability of investment in conventional generators appears to be highly sensitive to the exercise of market power, the exercise of market power has made little difference to the profitability of wind farms.

[105] Steinke, Wolfrum, and Hoffmann, 2013, Ippolito, M.G., et al., 2014.

[106] Environmental Protection Agency, 2013, chapter IV, estimates that the electricity sector is the largest source of greenhouse gas emissions in the U.S., accounting for one-third of the total and coal is the single largest source of electricity sector emissions, accounting for four-fifths of the sector total.

[107] Cooper, 2009b, reviews several of these analyses including, Moody's, 2009; Moody's, 2008; Standard & Poor's, 2009; Standard & Poor's*,* 2008; Standard & Poor's*,* 2007; Maloney, Stephen, 2008; Maloney, Stephen, 2009; Edward Kee 2009.

[108] Lazard, 2011; Citi Research, 2012; Eggers, Cole and Davis, 2013.

[109] Credit Suisse, 2013; UBS Investment Research*,* 2013a, 2013b, 2013c; Platts, 2013, Moody's, 2012

[110] Bischof, 2014.

[111] Murphy 2014. Parker, et al., 2014, p. 3. For regulated distribution businesses, there is a stabilizer embedded in the business model: increase power prices to make up for the loss of volume. However, the power price increase simply increases incentives to install roof-top solar. The response of simply raising prices per KWh is therefore unsustainable. The options for distribution utilities become increasingly less attractive. First, refuse to accept power into the grid (or pay a reduced rate for that electricity) this merely crease economic incentives for homes and

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businesses to start thinking about domestic energy storage solutions. Second, charge a connection fee to reflect the true value of the service (the *ability* to buy electricity itself)…. Third, admit defeat and become a roof-top solar developer. The behavior from here seems clear: the solar industry will expand. Retaliatory steps from distribution utilities will increase the market for cost-effective storage. This becomes – initially – a secondary market for battery storage technologies being developed for the auto sector. A failed battery technology in the auto sector (too hot, too heavy, and too rigid in form factor) might well be perfect for the home energy storage market… with an addressable market of 2 billion backyards. All of the above eats away – at the margin. In off-grid areas in developing markets means less demand for kerosene and diesel… in the Middle East… less oil demand… in China and developed Asia… less natural gas demand.

[112] Kind, 2013, p. 1.

[113] EEI/NRDC, 2014.

[114] On system integration see, for example, Lu, Xi, 2013; Veena, P., et al., 2014; Phuangpornpitak, N. and S. Tia, 2013; Jamel, M.S. A. AbdRahman and A.H. Shamsuddin, 2013.. On demand management, see for example, Falsafi, Hananeh, Alireza Zakariazadeh and Shahram Jadid, 2014; Arif, Ahmer, Fahad Javed and Naveed Arshad, 2014; Biegela, Benjamin , et al., 2014; Bergaentzlé, Claire, Cédric Clastres, and Haikel Khalfallah, 2014. On resource diversity, see for example, Tascikaraoglu, A., and M. Uzunoglu, 2014., Grossmann, Wolf D., Iris Grossmann and Karl W. Steininger, 2014. On storage and its integration with renewables to achieve reliability see Katarzyna Sobotka, 2009; Bose, Tapan K., et al., N.D.; National Renewable Energy Laboratory, N.D**.** Boie, Inga, et al., 2014; Pleßmann, Guido, et al., 2014**;** Komiyamaa, Ryoichi and Yasumasa Fujiib, 2014; Elkind, 2010; Hasan, Nor Shahida, et al., 2013; Koohi-Kamali, et al., 2013; Díaz-González, et al., 2012; Ippolito, 2014; Lu, 2013; Steinke, 2013. Gao, Dan, et al., 2013, Kucseraa, Dénes and Margarethe Rammerstorfer, 2013.

[115] Pringles, Olsina and Garcés, 2014; Edenhofer, et al., 2013; Bushnell, J. 2010, The rapid expansion of renewables exacerbates the particular conditions and situations in which… market failures and imperfections arise in at least two ways. First, rising price volatility may discourage investors or require a significant risk premium for investments beyond the level prevailing in traditional markets. Second, decreasing average prices make investment in new plants less attractive and induce early closures of old plants. This creates an additional strain on the reserve margin and is bound to result in a higher frequency of scarcity events. Since spot prices during such events are likely to be suboptimal (see above), a market with a high proportion of renewables is more prone to experience a "missing money problem", resulting in decreased reliability. In addition, how the more atomistic market structure usually associated with renewables would affect the coordination failure is open to speculation.

[116] Pearson and Foxon, 2012, pp. 123–124.

[117] Lovins, 2011, p. 216.

[118] Sahu, Hiloidhari and Baruah, 2013, pp. 349–353.

[119] Acemoglu, et al., 2012, p. 132.

[120] Cooper, 2013c; Qui and. Anadon, 2012; Massetti and Nicita, 2010,

[121] Michael Grubb, Thierry Chapuis and Minh Ha Duong, 1995; Antoine Dechezleperte, et al., 2011.

[122] De Cian, 2012, p. 6, [t]here is no doubt at all that nuclear power can be considered a mature technology, having been deployed starting in the 50s and definitively consolidated during the 70s and 80s. As such, it is characterized by low learning rates and potentials, and specifically lower than the other technologies with which it would compete.

[123] Kalkuhl, Edenhofer and Lessmann, 2012, p.340.

[124] They have an advantage in the ability to lobby for policies that favor their interests, Friehe, 2013; Freeman, Anderson, 2013.

[125] Walz, 2007; Walz, Schleich and Ragwitz, 2011.

[126] Robert Gross, et al., 2012; Nicolli and Vona, 2012.

[127] Acemoglu, et al, 2012, pp. 137. [T]his structure implies that innovation builds on the existing level of quality of a machine and, thus, incorporates the "building on the shoulders of giants" feature. [T]his implies that here is a "state dependence" in the innovation possibilities frontier, in the sense that advances in one sector make future advances in that sector more profitable or more effective. This is a natural feature in the current context, since improvements in fossil fuel should not (and in practice do not) directly translate into innovation in alternative and renewable energy sources.

[128] Gross, et al., 2012, p.18.

[129] Kalkuhl, Edenhofer and Lessmann, 2012, p. 10, the energy sector is highly vulnerable to lock-in because electricity is an almost perfect substitute for consumers. In contrast, many innovations in the manufacturing or entertainment electronics sector provide a new product different from existing ones (e/g/ flat screens vs. CRT monitor). The

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low substitutability implies a high niched demand and, thus, provokes ongoing learning-by-doing although considerable spillovers exist and market prices are distorted.

[130] Gross, et al., 2012, p.18.

[131] Gross, et al., p.18, The phenomenon of "learning by doing", whereby costs for technologies reduces as experience is gained from deployment of the technology creates lock-in. It also creates better, cheaper technologies. The incumbent fossil and nuclear forms of generation have had many decades of technical refinement through experience which have driven their costs down to low levels relative to new, renewable technologies. In part, this was financed by considerable public subsidy… The very same effects that created lock-in to high carbon systems offer the potential to decrease the costs and improve the commercial/consumer attractiveness of new forms of low carbon energy.

[132] Goldberg, 2000; Slavin, 2009; Branker, K., Pearce, J.M., 2010; Badcock, Lenzen, 2010; Pfund and Healey, 2011.

[133] Badcock, Jeremy and Manfred Lenzen, 2010;

[134] Zelenika-Zovk and Pearce, 2011, p. 2626, The results clearly show that not only does the indirect insurance liability subsidy play a significant factor for nuclear industry, but also how the transfer of such an indirect subsidy from the nuclear to photovoltaic industry would result in more energy over the life cycle of the technologies.

[135] BWE, German Wind energy Association, 2012; Kitson, Wooders, and Moerenhout, 2011; Berwick. 2012; Energy Information Administration, 2011; Pfund and Healey, 2011; GAO, 2007; Goldberg, 2000.

[136] Badcock and Lenzen, 2010. Branker and Pearce, 2010.

[137] Rasmussen, et al., N.D.; Schaber, Steinke Hamacher, 2013; Rodriguez, 2013; Rasmussen, Andresen, and Greiner, 2012 ; Greiner, et al., 2013.

[138] Zelenika-Zovk, Pearce, 2011

[139] De Cian, 2012, p. 14.

[140] De Cian, 2014, p. 1-2.

[141] See for example, Hoffert, M.I.,2010; Bettencourt, L.M.A., Trancik, J.E., Kaur, J., 2013; Petkovi, Dalibor, 2014; Sueyoshi , Toshiyuki and Mika Goto, 2014; Chmutina, Ksenia and Chris I. Goodier, 2014; Maia, Trieu, et al., 2014; Santiago, de Souza and Bezerra, 2014; Sueyoshia, Toshiyuki, Mika Gotob, 2014; Johnson, Erik Paul, 2014; Zheng, Chengn and Daniel M. Kammen, 2014.

[142] There are a growing number of scenario analyses at the global (Jacobson and Delucchi, 2011; Jacobson, et al., 2013; Delucchi and Jacobson, 2011, Budischak, et al., 2013; Delucchi and Jacobson, 2013; Cochran, Mai and Bazilian, 2014), national (xx) and local levels (xx) that suggest a high renewable penetration approach (80% or more) is quite feasible. These analyses have moved well beyond merely counting the potential resource base, which is huge, but also to exploring and explaining how the system would be managed to deliver power that is at least as reliable as the base load approach of the 20th century. (xx)

[143] Jacobson and Delucchi, 2011; Jacobson, et al., 2013; Delucchi and Jacobson, 2011, Budischak, et al., 2013; Delucchi and Jacobson, 2013; Cochran, Mai and Bazilian, 2014.

[144] IPCC WGIII AR5; Delaying mitigation efforts beyond those in place today through 2030 is estimated to substantially increase the difficulty of the transition to low longer-term emissions levels and narrow the range of options consistent with maintaining temperature change below 2°C relative to pre-industrial levels (*high confidence*). (16)…Delaying additional mitigation further increases mitigation costs in the medium to long term. Many models could not achieve atmospheric concentration levels of about 450 ppm CO2eq by 2100 if additional mitigation is considerably delayed or under limited availability of key technologies, such as bioenergy, CCS, and their combination (BECCS). (17)

[145] These numbers correspond to an annualized reduction of consumption growth by 0.04 to 0.14 (median: 0.06) percentage points over the century relative to annualized consumption growth in the baseline that is between 1.6% and 3% per year. Estimates at the high end of these cost ranges are from models that are relatively inflexible to achieve the deep emissions reductions required in the long run to meet these goals and/or include assumptions about market imperfections that would raise costs. Under the absence or limited availability of technologies, mitigation costs can increase substantially depending on the technology considered. (17)

[146] Efficiency enhancements and behavioural changes, in order to reduce energy demand compared to baseline scenarios without compromising development, are a key mitigation strategy… Near-term reductions in energy demand are an important element of cost-effective mitigation strategies, provide more flexibility for reducing carbon intensity in the energy supply sector, hedge against related supply-side risks, avoid lock-in to carbon-intensive infrastructures, and are associated with important co-benefits. Both integrated and sectoral studies provide similar estimates for energy demand reductions in the transport, buildings and industry sectors for 2030 and 2050. (21)

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[147] Decarbonizing (i.e., reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies in achieving low-stabilization levels (430–530 ppm CO2eq); in most integrated modelling scenarios, decarbonization happens more rapidly in electricity generation than in the industry, buildings, and transport sectors (*medium evidence, high agreement*) (Figure SPM.7). In the majority of low-stabilization scenarios, the share of low-carbon electricity supply (comprising renewable energy (RE), nuclear and CCS) increases from the current share of approximately 30% to more than 80 % by 2050, and fossil fuel power generation without CCS is phased out almost entirely by 2100. (23)

[148] Since AR4, many RE technologies have demonstrated substantial performance improvements and cost reductions, and a growing number of RE technologies have achieved a level of maturity to enable deployment at significant scale (*robust evidence, high agreement*). Regarding electricity generation alone, RE accounted for just over half of the new electricity-generating capacity added globally in 2012, led by growth in wind, hydro and solar power. However, many RE technologies still need direct and/or indirect support, if their market shares are to be significantly increased; RE technology policies have been successful in driving recent growth of RE. Challenges for integrating RE into energy systems and the associated costs vary by RE technology, regional circumstances, and the characteristics of the existing background energy system (*medium evidence, medium agreement*). (23)

[149] GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined-cycle power plants or combined heat and power plants, provided that natural gas is available and the fugitive emissions associated with extraction and supply are low or mitigated (*robust evidence, high agreement*). (23)

[150] Nuclear energy is a mature low-GHG emission source of baseload power, but its share of global electricity generation has been declining (since 1993). Nuclear energy could make an increasing contribution to low-carbon energy supply, but a variety of barriers and risks exist (*robust evidence, high agreement*). Those include: operational risks, and the associated concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapon proliferation concerns, and adverse public opinion (*robust evidence, high agreement*). New fuel cycles and reactor technologies addressing some of these issues are being investigated and progress in research and development has been made concerning safety and waste disposal. (23)

[151] Carbon dioxide capture and storage (CCS) technologies could reduce the lifecycle GHG emissions of fossil fuel power plants (*medium evidence, medium agreement*). While all components of integrated CCS systems exist and are in use today by the fossil fuel extraction and refining industry, CCS has not yet been applied at scale to a large, operational commercial fossil fuel power plant. CCS power plants could be seen in the market if this is incentivized by regulation and/or if they become competitive with their unabated counterparts, if the additional investment and operational costs, caused in part by efficiency reductions, are compensated by sufficiently high carbon prices (or direct financial support). For the large-scale future deployment of CCS, well-defined regulations concerning short- and long-term responsibilities for storage are needed as well as economic incentives. (24)

[152] Downey, 2014.

[153] Litvak, 2014.

[154] Litvak, 2014

[155] Henderson, 2014.

[156] Martin, who had authored positive study of SMR at Navigant, admitted that even the low estimate of 4.6 GW by 2030 “seems optimistic now.”

[157] Lewis, 2013, notes that in February, 2013, “tow of the biggest innovators of SMRs right, now Babcock & Wilcox, an engineering behemoth… and Westinghouse, the electricity giants… Both are wildly optimistic about SMRs future,” a year later they had both slashed their investment.

[158] Adams, 2014a, a leading advocate of nuclear power used this phrase.

[159] Mark Cooper, 2009b, p. 1–5.

[160] Cooper, 2012a.

[161] Cooper, 2012a, p. 61.

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