Energy Research & Social Science 3 (2014) 161–177

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Review

# Small modular reactors and the future of nuclear power in the United States

Mark Cooper*

*Institute for Energy and the Environment, Vermont Law School, Yale University, United States*

ARTICLE INFO

*Article history:*
Received 30 May 2014
Received in revised form 28 July 2014
Accepted 31 July 2014

*Keywords:*
SMR technology
Nuclear cost escalation
Decentralized resources

ABSTRACT

Small modular reactors are the latest "new" technology that nuclear advocates tout as the game changer that will overcome previous economic failures of nuclear power. The debate over SMRs has been particularly intense because of the rapid failure of large "nuclear renaissance" reactors in market economies, the urgent need to address climate change, and the dramatic success of alternative, decentralized resources in lowering costs and increasing deployment. This paper assesses the prospects for SMR technology from three perspectives: the implications of the history of cost escalation in nuclear reactor construction for learning, economies of scale and other process that SMR advocates claim will lower cost; the challenges SMR technology faces in terms of high costs resulting from lost economies of scale, long lead time needed to develop a new design, the size of the task to create assembly lines for modular reactors and intense concern about safety; and the cost and other characteristics – e.g. scalability, speed to market, flexibility, etc. – of available alternatives compared SMR technology. The paper concludes that the decision of the major vendors (Westinghouse and B&W) to dramatically reduce SMR development efforts reflects the severe disadvantages that SMR technology faces in the next several decades.



**Contents**



* Tel.: +1 3013842204.
*E-mail address:* markcooper@aol.com

http://dx.doi.org/10.1016/j.erss.2014.07.014
2214-6296/

## 1. Introduction

### 1.1. Purpose

This paper presents an evaluation of the prospects for development and deployment of significant numbers of Small Modular Reactors (SMR) in the mid-term through the lens of nuclear power's fifty year struggle to be cost competitive with alternative technologies in the United States.

- In that 50 year period there was one round of deployment of a significant number of reactors in the 1970s and 1980s, which came to be known as the "Great Bandwagon Market." It ended up with the number of reactors canceled exceeding the number that were built [67,81]
- A second effort to start another round of major construction,[1] known as the "Nuclear Renaissance," never got off the ground.[2] Only 10 percent of the reactors that were put on the table in response to the regulatory streamlining and financial incentives in the Energy Policy Act of 2005 went into construction and those projects suffered substantial delays and cost overruns [34].
- The economic woes of nuclear power in the U.S. have now extended to aging reactors,[35,39] with five retired early, most major uprates canceled and over two dozen more declared at risk of early closure for economic reasons [41].

The primary reaction of nuclear advocates to these setbacks has been to blame policymakers in one way or another[3] and simultaneously put forward new technologies that they claim address the obvious problems of the old technology. Heralded as a new technology that will solve many of the problems that commercial nuclear power has encountered, SMR technologies fit neatly into this pattern.[4] Yet, even before SMR technology has gotten off the drawing board, it has begun to exhibit the same pattern that has afflicted prior efforts to kick start the industry, with two of the three leading U.S. SMR developers dramatically throttling back on their SMR efforts [11,47,48,63,91,123].

The ingredients for failure have been similar throughout the history of the commercial nuclear industry. The technology proves to be uneconomic for several reasons:

- Initial cost estimates prove to be wildly optimistic as design and construction realities set in.
- Cost escalation results from a combination of the difficulty of executing extremely complex projects and the demands of nuclear safety.
- As the design or construction process unfolds, it becomes clear that there are a number of alternatives available that are less costly and less risky than the construction of new reactors.

However, the current round of debate involves other, more important and ominous elements. The industry is pushing nuclear as an indispensable cornerstone of climate policy, [20,149,146,147,128,13,124,112] while launching a broad campaign to improve nuclear prospects by attacking competing technologies. The attacks include vigorous efforts to alter the market price mechanisms in the Upper Midwest and the Northeast, where the operating aging reactors were closed [38,143] and an attempt to undermine the policies that promote alternative approaches to meeting the need for electricity [30,83,150].

Thus, the 50-year debate over commercial nuclear power is not only being repeated with SMR technology, but it has taken on greater importance. It is not only about the fate of nuclear power, it is about the fundamental direction of electricity and climate policy. A thorough review of the prospects for SMR technology, as the potential savior of nuclear power and a major contributor to climate policy, is an ideal lens through which to view the unfolding debate.

### 1.2. Approach

This paper takes a broad social science perspective on the economic challenges facing SMRs by emphasizing and locating SMR technology within the patterns of analysis and debate that have recurred in the three rounds of proposed nuclear expansion in the United States. Throughout its history, the fate of nuclear power has been determined by its political economy, in the classic sense of "examining how political forces affect the choice of economic policies,"[5] as much as its basic economics. The resolution of the debate over nuclear power at the pivotal moment of initiation of policies to address climate change is very much a question of the political choices that society will make about how to meet the need for electricity in a low carbon future.

Sections 1–6 briefly describes what SMRs are and how they fit in five recurring themes in the history of commercial nuclear power in the U.S. – the nuclear hype cycle, the rush to market, the absence of learning effects, the inability to estimate costs and nuclear safety and nuclear economics. These traits that are endemic to nuclear technology contribute to its ultimate failure in market economies.

Sections 7–10 examine the economics of SMR technologies from four perspectives – the cost per unit of output, the magnitude of the effort to create an SMR assembly line, demand side characteristics like size, flexibility, time to market and non-economic factors, and the competition with alternatives in terms of cost and cost trends. It concludes by tying the historical and contemporary factors that cast considerable doubt on the economic viability of SMR technologies to the decision of the leading vendors to throttle back their investment in its development.

---

[1] A figure of 100 reactors was used by Senator Lamar [5].

[2] [34,36,37], 2012c, provide accounts of the difficulties in the ongoing construction in Georgia and South Carolina. The story is similar in other advanced industrial market economies (e.g. Japan, France, Germany, the United Kingdom) that were seen as the potential leaders in deploying a new generation of nuclear reactors [130,56]. Nuclear construction activity is now concentrated in former communist nations, half in China, a quarter in former members of the Soviet Bloc. http://www.world-nuclear.org/info/current-and-future-generation/plans-for-new-reactors-worldwide/.

[3] The perennial target is licensing and safety regulation (see e.g. [23,34]), while the plight of aging reactors is being blamed on electricity market design [37].

[4] An influential University of Chicago study was entitled—*Small Modular Reactors—Key to Future Nuclear Power in the U.S.* [126]; the Senior Director of Policy Development for the Nuclear Energy Institute characterized SMRs as an "elegant evolution relative to large light water reactor technology, one whose development over the next decade will kick start an entire industry [110]. Other operative phrases were—last best hope ([141,99], also [106]), path forward [40].

[5] A rapidly growing mainstream literature from the 1970s has expanded... toward examining how political forces affect the choice of economic policies, especially as to distributional conflicts and political institutions... *Political economy* most commonly refers to interdisciplinary studies drawing upon economics, sociology, and political science in explaining how political institutions, the political environment, and the economic system—capitalist, socialist, or mixed—influence each other [153]. The study and use of how economic theory and methods influences political ideology. Political economy is the interplay between economics, law and politics, and how institutions develop in different social and economic systems, such as capitalism, socialism and communism. Political economy analyzes how public policy is created and implemented. http://www.investopedia.com/terms/p/political-economy.asp. Political Economy. Until recent times the common name for the study of economic process. The term has connotations of the interrelationship between the practical aspects of political action and the pure theory of economics. It is sometimes argued that classical political economy was concerned more with this aspect of the economy and that modern economists have tended to be more restricted in the range of their studies ([123], p. 342).

## 2. The nuclear hype cycle

### 2.1. Small modular reactors

Simply defined as reactors with capacity below 300 Mwe, the description of small modular reactors focuses on the three broad types of advantages that these reactors are presumed to have:

- small size and modularity are said to allow major components to be standardized and fabricated in significant quantities on assembly lines, which gives the manufacturers greater ability to learn and control costs and results in a significant simplification of deployment,
- passive safety design, integration of major systems into a single unit and below ground deployment are said to dramatically lower safety concerns and costs, and
- small size is said to expand the potential market for SMRs by allowing them to meet much smaller increments of demand and alleviating the burden of financing huge megaprojects.

For example, the opening paragraph on the U.S. Department of Energy Small Modular Reactors page describes them as follows:

> Small modular reactors (SMRs) are nuclear power plants that [are] smaller in size (300 MWe or less) than current generation base load plants (1000 MWe or higher). These smaller, compact designs are factory-fabricated reactors that can be transported by truck or rail to a nuclear power site (http://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors).

The World Nuclear Association provides a similar but more detailed description on its small modular reactor page

> 'SMR' is used... as an acronym for 'small modular reactor', designed for serial construction and collectively to comprise a large nuclear power plant. (In this paper the use of diverse pre-fabricated modules to expedite the construction of a single large reactor is not relevant.) Generally, modern small reactors for power generation are expected to have greater simplicity of design, economy of mass production, and reduced siting costs. Most are also designed for a high level of passive or inherent safety in the event of malfunction. Also many are designed to be emplaced below ground level, giving a high resistance to terrorist threats. A 2010 report by a special committee convened by the American Nuclear Society showed that many safety provisions necessary, or at least prudent, in large reactors are not necessary in the small designs forthcoming. Since small reactors are envisaged as replacing fossil fuel plants in many situations, the emergency planning zone required is designed to be no more than about 300 m radius. (http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Small-Nuclear-Power-Reactors)

D.T. Ingersoll[6] provided a description of "Deliberately Small Reactors and the Second Nuclear Renaissance," published in 2009 (and circulated as slides in 2010) that is essentially a catalog of the advantages clamed for SMR technology (see Table 1). It is one of the most often cited articles in the early literature and exhibits a loud exuberance for a second round of nuclear construction and the role of deliberately small reactors (DSRs) in it:

> The United States is unquestionably in the early phase of the second nuclear era or nuclear renaissance. . .. enabled by a number of key factors, including: (1) a continually growing demand for electricity and a steadily dwindling margin of generating capacity, (2) the excellent safety and performance record of the existing fleet of LWRs, (3) a growing concern for the environmental impacts of large-scale burning of fossil fuels, especially as it impacts global climate change, and (4) the new awareness of the impact of energy supply on national and energy security. . .. DSRs have many substantial benefits that should position them well to be a key player in the second nuclear era and complement the larger plants that will be built for base load electricity ([69], p. 591).

Ingersoll's list of the "substantial benefits" summarized in Exhibit II-1 is a good example of a number of analyses put forward, first by vendors (Westinghouse) and then in co-authored pieces from academic institutions, funded by international agencies with an interest in promoting the technology, frequently with governmental support.[7] Over the course of almost a decade the list was repeated endlessly, with little real world experience or evidence to back it up [94,17,132,107,24,109,25].

While it is obvious that no technology lives up to the hype of its vendors, in the early period of touting nuclear power, the advocates rarely incorporate the challenges into their analysis. Early cost estimates for a new technology are invariably uncertain, but nuclear cost projections have been particularly problematic, exhibiting extraordinary cost overruns.[8] Under these circumstances, one might expect a great deal of caution on the part of both vendors and customers. That has not been the case for nuclear power. Bupp and Derian describe the early hype cycle in the case of the "Great Bandwagon Market" as follows:

> 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. The distinction between cost records and cost estimation may seem obvious, but apparently it eluded many in government and industry for years. . .
> 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. . . ([23], p.71)
> There were few, if any, credible challenges to this natural conclusion. Indeed, quite the contrary. Government officials regularly cited the nuclear industry's analyses of light water plants as proof of the success of their own research and development policies. The industry, in turn, cited those same government statements as official confirmation.
> 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. . . during the late 1960s. . .the

[6] At Oakridge national laboratory at the time of the article and later at NuScale (an SMR developer).

[7] A [84] (50) cites a 2007—Westinghouse Electricity Company Estimate as the source. A 2010 ([24], piece jointly authored by vendor (Westinghouse) employees and academics presents the benefits as a theoretical proposition and makes assumptions to estimate cost effects [79], 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. In addition to these Carelli articles, [68] cites personal communications with Carelli and Kuznetsov and a large number of reports on agency efforts to develop the technology.

[8] While one can argue that cost overruns afflict all megaprojects, the evidence is that nuclear cost problems are more severe than other megaprojects [134]. More importantly, the competition that nuclear faces are not generally megaprojects, which therefore do not have anywhere near the cost overrun problem.

**Table 1**
Benefits claimed and challenges for small modular nuclear technology.

| Characteristic | Source of advantage | Supply side | Demand side | Challenges |
|---|---|---|---|---|
| Economic competitiveness | | | | |
| Technological maturity | Reactors are familiar technology with potential for progress | × | | Limited technical benefit for newcomers, user and owner issues* Availability of design for newcomers, Proprietary design protection* |
| Small size | Less risk, manageable finance | × | × | Economic competitiveness (economy of scale), first of a kind cost estimate, Severe diseconomies[a] |
| Multi-unit | Repetition rapid learning | × | | Limited market opportunities, Relatively small number of units[a] |
| Modularity | Standardized mass production | × | | Licensability (delays due to design innovation), technical challenge for non LWR technologies |
| Factory fabrication | Quality control, ease of transport | × | | Standardization and licenses for manufacturing, Challenge of building an assembly line[a] |
| Flexible deployment | Scalability fits supply and demand | × | | Infrastructure requirements |
| Swift deployment | Less risk, lower front end cost | × | × | Reduced emergency planning zone |
| Cogeneration/Co-siting | Large incremental value | | × | Operability |
| System impact | | | | |
| Grid support | Smaller, distributed | × | | Viability of multiple-modules station*l room staff* |
| Grid integration | Base load, local | × | | Regulation for fuel or NPP leasing |
| Reliability | Redundancy, small size | × | | Technology challenge for non-LWR |
| Safety/waste | | | | Risk informed licensing,* Mechanistic Source Term,* Repair, retrieval and waste management[a] |
| Safety/simplicity | Regulatory relief | × | | Ergonomics and control room staff* |
| Non-proliferation | Smaller, loaded in factory | | × | Impact of innovative design, Proliferation resistance and Physical Security* |
| Waste management | Less material | × | | Spent fuel management and waste handling policies |

Sources: Benefits: [68,69]; Challenges: [137] for a tabular display and p. 14 for additional issues identified with *; additional challenges from [97,101,117], identified by[a].

> distinction between promotional prospectus and critical evaluation become progressively more obscure ([23], p.71).

Although the "Nuclear Renaissance" never entered a building phase, the response to the announcement of loan guarantees took on the feel of a frenzy with a flood of applications equal to ten times the amount set aside for the loan program [142], and talk of more than doubling the size of the U.S. fleet in a short period of time [5]. While vendors in the second ("Nuclear Renaissance") or third (SMR) nuclear hype cycle were just as aggressive in promoting their product and governments tend to be supportive, the more recent hype cycles exhibits one important difference. The prior failure of nuclear power had created both a sense that claims like this needed to be examined carefully and quickly, eliciting a body of analysts who were willing to do so and rendering customers (utilities) more cautious. Thus, the claimed advantages of SMR technology that went largely unchallenged for half a decade, began to encounter criticism, or at least a more balanced view [10,99,95,136,140,22].

By 2011, as shown in the right hand column of Exhibit 1, every potential benefit was also seen as representing a challenge. Taken together, the counterpoints constitute a very substantial challenge to vendor claims. Some critics of the analysis offered very fundamental challenges to the claimed advantages, noting that "the potential cost benefits of assembly-line module construction may be overstated." [96,100]

- The diseconomies of small unit construction are quite severe, including the surface area of the reactors and containment structures, and lost economies in dedicated systems for control, management, and emergency response and the cost of licensing and security.
- The economies of mass manufacturing are 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 and a massive book order create 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.

## 3. The rush to market

Throughout its history, commercial nuclear power has suffered from a "rush to market" syndrome, where complex technology is deployed in substantial amounts before the bugs are worked out. The rush to market is a central issue and problem for nuclear technology because the complex, capital intensive technology is slow to market and must compete against other technologies that deploy more quickly and scale faster.

This rush to market contributed to the crash of the Great Bandwagon Market, and plagued the "Nuclear Renaissance."

> 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 ([23], p. 154–155).

With a technology as complex as nuclear reactors, prototypes and real-world experiences are crucially important before full scale deployment is contemplated. Komanoff emphasized that in putting a safe product into the market design 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 ([80], p. 27).

While these factors seem obvious with respect to large reactors, the discussion below indicates they apply to SMR technologies

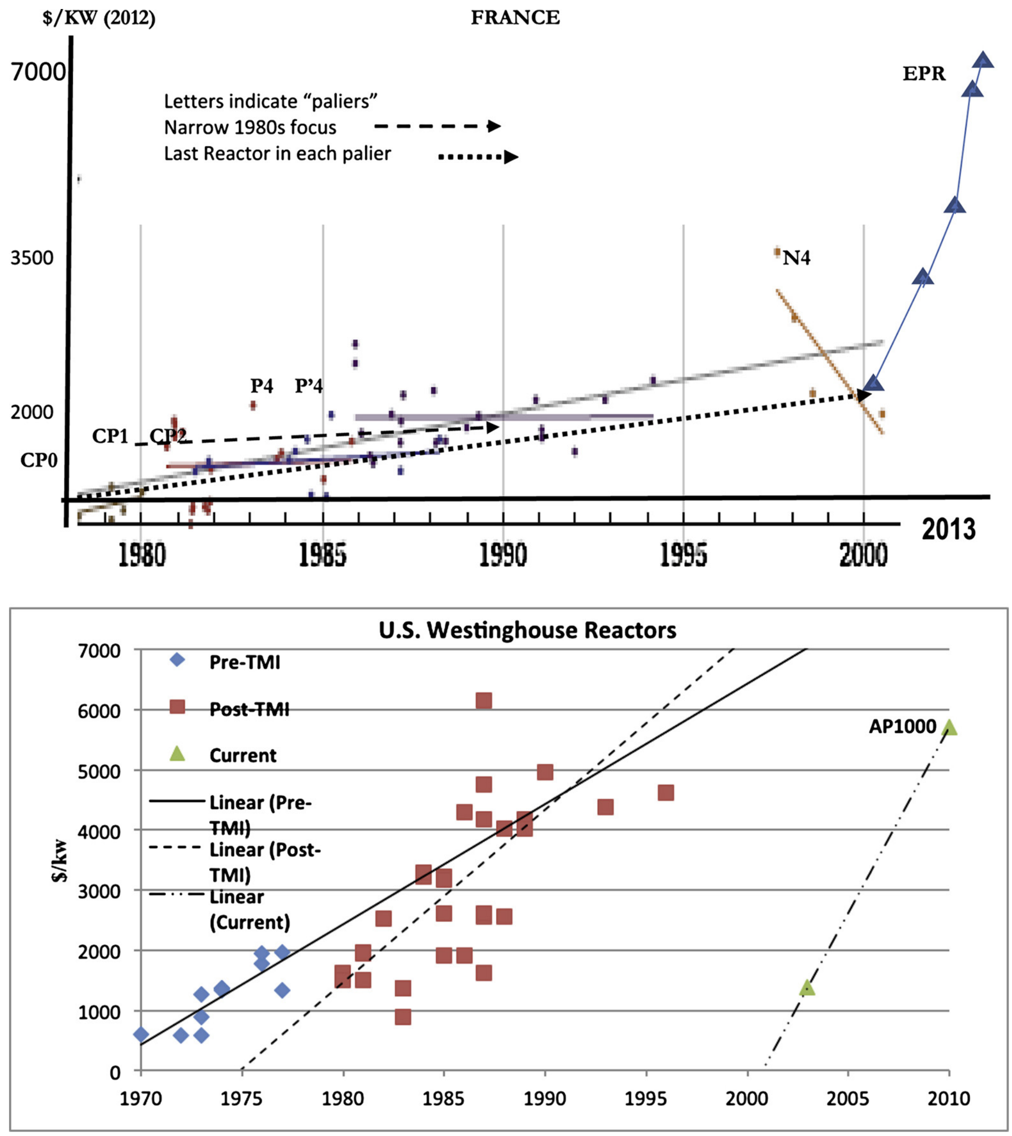



**Exhibit 1.** Overnight costs within technologies (PWR).

Sources: [18,32,34].

as well. The lesson has not been learned and SMR technology has not escaped from the problem of the rush to market. Moreover, SMR technology has an additional factor pushing for speed – the urgent need to respond to climate change. Technologies that require a decade or more to begin significant deployment forego what is increasingly seen as the most critically important period for a response.[70]

Even when analyses that advocate deployment of SMR technology give a nod to the challenge of ensuring that the technology is safe and recognize the time it would take to make it ready for deployment is substantial, they dramatically underestimate the nature and extent of the task. Ingersoll, 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. ([68], pp. 589–603, 591–600)

Ingersoll concluded that it would take up to 10 years to perfect the design. Yet his framing did not even necessarily include building a prototype or going through a demonstration phase, which epitomizes the mistake that Bupp, Derian, 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. . . [T]he 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. ([68], p. 600, emphasis added)

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 ([157], pp. 27–28).

In spite of the call for caution in the rollout of a new technology, a frequently cited University of Chicago study [125] combined high initial cost estimates 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 (5.4 GW) by 2020 for each design and production assembly line – and then assumes a steady stream of production of 12 units per year [91,48]. In essence, the Chicago study envisions full production in the time others think it would take to just get the design right.

A number of factors lie behind the rush to market. Vendors believe that they need a large book of orders to achieve economies of scale and reap the rewards of learning. Vendors and customers do not want to fall behind others and may also be responding to the fact that there are alternatives that will prove to be more attractive and a slow roll out renders investment vulnerable.[9]

## 4. Learning processes and cost projection

Major claims about how to overcome the cost disadvantage of SMR technology rely on the claim that learning will lower costs. These claims are made with reference to other industries [125], but the evidence from the nuclear industry does not support the optimism. In this section we review evidence from France and the U.S. that bears on the question of learning in the nuclear sector. In France nuclear energy constitutes the highest fraction of electricity generation of any advanced industrial nation. The United States still has the largest number of operating commercial nuclear power plants. Taken together, France and the U.S. represent almost half of all reactors built in market economies.[10] Understanding the challenge of cost escalation, cost estimation and learning in these two nations represents a substantial knowledge base about the evolution of nuclear reactor construction costs.

The recent release of formerly confidential data on French nuclear construction costs has stimulated a new round of analysis of nuclear cost escalation and cost estimation [61,120,18,31,32,34]. Our earlier analysis [34] was the only study to directly compare France and the U.S., but the analysis by Rangel and Lévêque [119,88] affirmed the findings on the causes of nuclear cost escalation.

> This component represents what [31,32] 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. ([118], pp. 12–14)

After affirming the earlier findings, Rangel and Leveque parse through their data in search of cost trends within subsets of reactors ([118], p. 16) Similarly, [18] focuses on a very narrow set of reactors to draw inferences about the containment of cost escalation. They both argue that a positive learning effect can be seen and explained by standardization, which is a good direction to look in order to overcome the cost escalation curse [118].

> [W]e 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 [32,61]...
> 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 ([118], pp. 14–15).

While our earlier analysis found a hint of learning when looking at individual U.S. reactor builders, ([32,34]) 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, as discussed below. 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.

Caution is needed in drawing lessons about the potential for learning because the advice is based on a very narrow range of observations,[11] but large changes in technology have been associated with large increases in cost, which is the challenge that SMR technology faces.

Exhibit 1 shows the escalation of French and U.S. nuclear reactor construction cost that lies behind these observations. Time on the *X*-axis serves as a proxy for industry experience and reactor size, as both scaled up over this period. To enhance the comparability of the cost histories between France and the U.S., we include only U.S. pressurized water reactors.

- The size of the learning effect is relatively small and statistically weak and the other negative, cost-increasing effects of adding a reactor reduce or eliminate the positive, cost-reducing benefits of learning.
- Introducing new technologies raises the cost significantly, to the point at which the reduction of cost within the technology as more units are added does not offset the increase in cost associated with introducing the technology. 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 European Pressurized Reactor (EPR) – is well above the cost of the last technology.
- The dangers of extrapolating beyond the analysis are substantial because of both the size and direction of the effects is radically different.
- In the case of the French and U.S. experiences, nuclear reactors were scaling up by 60 percent, which may be very different than scaling down by 75–90 percent, which is what the SMR technology does.
- In the case of the French and U.S. experience the analysis is projecting a reduction of 25 percent in cost over a relatively small number (10) of reactors, while in the case of SMRs analysts are projecting much larger reductions over a much larger number of units (50+).

These observations tie directly into the debate over SMR technology because SMRs constitutes a relatively large change in the

[9] Bupp and Derian ([23], pp. 74–75) describe these factors for the Great Bandwagon Market. [37], notes similar motivations for the "Nuclear Renaissance."

[10] 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.) [54].

[11] Boccard's ([18], p. 452) 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. Focusing on the uniform technology in a short period, as Boccard does, can be misleading. 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".

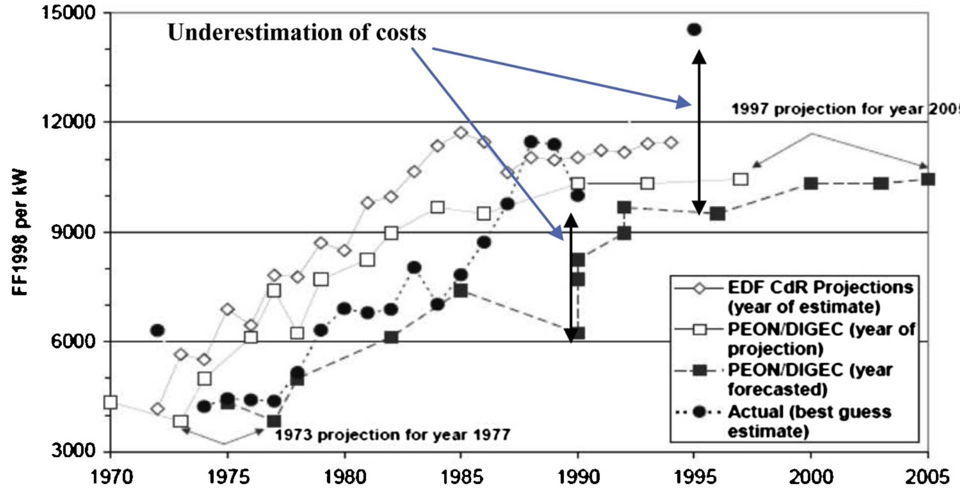



**Exhibit 2.** French cost underestimation.

Source: [61].

design. The expectation based on history is that the initial costs will be much higher and, even with learning the final cost will still be higher than the previous technology.

The upper graph in Exhibit 1 shows graphically how the analysis of the French data arrives at the conclusion that there is a learning effect and why it must be treated carefully. 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. However, introducing new designs dramatically increases costs.

Exhibit 1 includes the official cost estimates for ongoing construction of the new French EPR ([129]:50) 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.

Although the trend line for U.S. "Great Bandwagon Market" reactors as shown in the lower graph in was much higher, 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. The gap between the initial estimates of the cost of new reactors and the current estimates for the reactors under construction in U.S. is almost as large as the gap for the French EPR.

Boccard ([18], p. 452) 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. The first three of these would be relevant to the projected cost of SMR technologies.

## 5. The persistent underestimation of costs

Over the course of almost five 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 to improve their cost projections. Referring to Exhibit 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 ([61],p. 30)

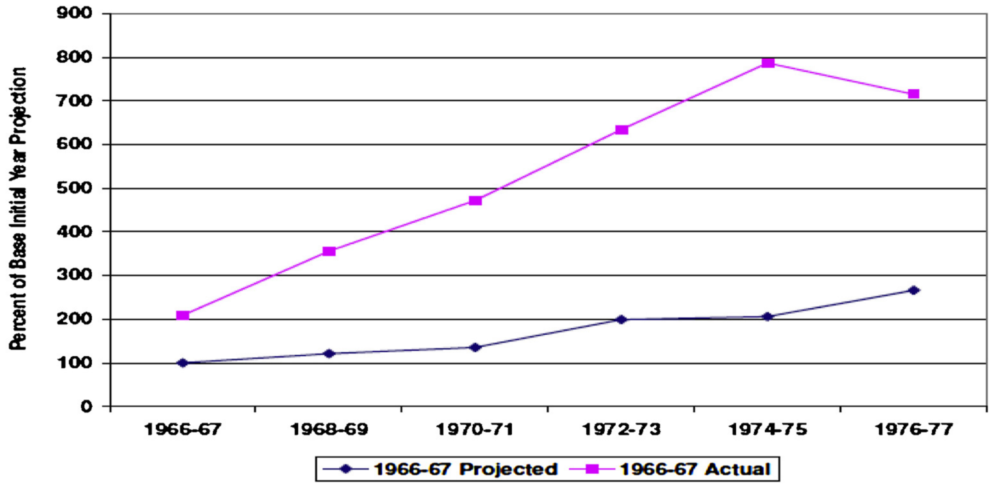
Exhibit 2 shows the gap between projections and actual costs for all of the reactors completed in France. As bad as the projection of the N4 technology costs was in France, the dramatic difference between the initial estimates of the new French EPR reactor (as shown in Exhibit 1, above) and the current estimates, would make it the worst underestimate in the French experience.

Bupp and Derian identified the same problem of persistent cost underestimation as follows:

> 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. ([23], p.79)

The U.S. data, as summarized in Exhibit 3, shows a pattern similar to France. 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 (as shown in Exhibit 1, above). If we included the full range of technologies in the U.S. the inability to estimate costs would be even greater.

The failure of cost projections is part of the nuclear hype cycle. Vendors produce extremely optimistic projections of cost. Government agencies, mandated to promote the technology, fund friendly academic studies to validate hypothetical and theoretical cost projections, but they never live up to the promise in reality.




Source: [52].

**Exhibit 3.** U.S. cost underestimation.

Ironically, 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. [126,146] Moreover, the low cost estimates of the "Nuclear Renaissance" were driven by assumptions about cost-reducing processes – economies of scale, learning by doing, and regulatory relaxation – that vendors said would kick in during both the "Great Bandwagon Market" and the "Nuclear Renaissance," but never did. The current hype cycle surrounding SMRs is based on the hope that the cost-reducing processes that have failed to appear in the past will finally arrive.

## 6. Relaxation of licensing and safety regulation

The fact that licensing and safety regulation loom large in the advantages claimed for SMR technology should not be surprising, safety has been the central issue driving nuclear economics since the earliest days of commercial nuclear power. The recent study of French construction costs confirmed earlier findings on U.S. costs:

> [I]t 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 [31,32] for the U.S case. . . 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 ([118], pp. 16–17).

Given the challenging nature of SMR economics the claim that regulatory requirements in licensing and safety can be reduced takes on greater importance. 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. Table 2 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.

**Table 2**
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: [100,101,97,135,118,117].

Widespread dispersal and close proximity to population centers was one of the key factors that triggered increased oversight of safety during the Great Bandwagon Market [34]. Close proximity to population centers required higher safety margins to reduce the probability and mitigate the impact of accidents. 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" ([139], p. 9). Retrofitting was expensive, so the battle with the safety regulator was engaged.

The push to relax regulatory oversight for SMRs 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.[12] The strategy of short

[12] [34], reviews early reactions through late 2011. More recent summations and recommendations can be found in [55,151,152,103].

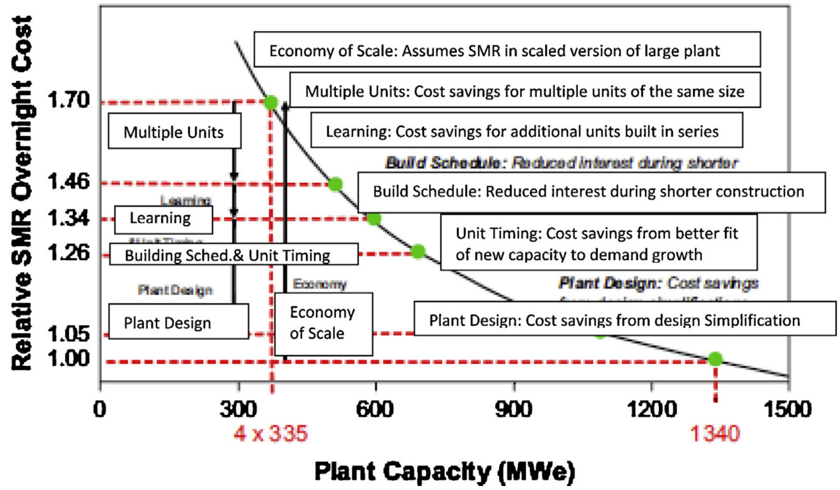



**Exhibit 4.** Economic Factors that Contribute to Offsetting the Economy of Scale for a 4-unit SMR plant compared to a single large reactor plant. Source: [68], Fig. 4.

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. The claim for regulatory relief sounds like more of the same, particularly in light of the fact that 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.

It is also important to keep another aspect of the context of the safety debate in mind. The SMR advocates argue for a relaxation of safety regulation but insist 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) ([33]). They are unwilling to test the proposition that less safety regulation is better by accepting full private responsibility for safety.

## 7. The economic challenges of SMRS

At the start of the SMR hype cycle, as suggested in the Ingersoll quote above, the assumption was that the large reactor "Nuclear Renaissance" technologies would succeed. Large, low cost "Nuclear Renaissance" reactors would meet the demand for large central station power. SMRs, exhibiting similar costs per kWh, would meet additional needs for smaller units. Selling this argument to policy makers and potential customers faced a major challenge.

After half a century of claiming that bigger is better because of economies of scale, the initial challenge for SMR advocates was to explain how the diseconomies of scale suffered by SMRs compared to large reactors would be overcome (see Exhibit 4). 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 output basis as they are spread across larger units. Economists say they exhibit economies of scale.[13] Because SMRs are small, they forgo the benefits of economies of scale and suffer diseconomies of scale.

Exhibit 4 presents this cost analysis. While the exhibit is from Ingersoll, it reflects the exact analysis and numbers originally put forward by Westinghouse. The analysis presents a series of steps of cost reductions based on theoretical calculations and analogies to other industries.[14] The vendor's promotional claims were regurgitated repeatedly and the hypothetical economic process became gospel among the advocates of SMRs.[15] About half of the lost economies are assumed to be made up by modularization and learning, the other half results from speed of design and construction.

Skepticism about the basis for the cost projections discussed in the previous Section was not restricted to critics of nuclear power. In fact, a debate has arisen within the industry over whether the goal of cost parity with large nuclear reactors adopted by the advocates of SMR technology is achievable.[16] The experts directly involved in the industry (regulators and senior management employees) believe SMRs will cost more than the current generation of reactors, with regulators projecting the highest cost (30% above current large 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 projected the lowest costs by far, utilities had higher cost projections, and independent analysts had the highest projections [34].

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 [24]. Decommissioning costs are projected to be three times as high [91,92]. Also, as pointed out by some analysts, because of the smaller size of SMRs and the fueling pattern that is envisaged, SMRs would require 30–40 percent more fuel and produce correspondingly more radioactive spent fuel [59,117], implying higher fueling and waste disposal costs.

The challenge of nuclear cost projection for SMR technologies can be seen by juxtaposing three studies conducted by researchers

[13] 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.

[14] The mass production and savings were hypothesized based on the experience in other industries, not rooted in the nuclear sector [126].

[15] See note 7.

[16] The difference cited are from [1]. Similarly broad ranges of opinion are reflected in [6,7].

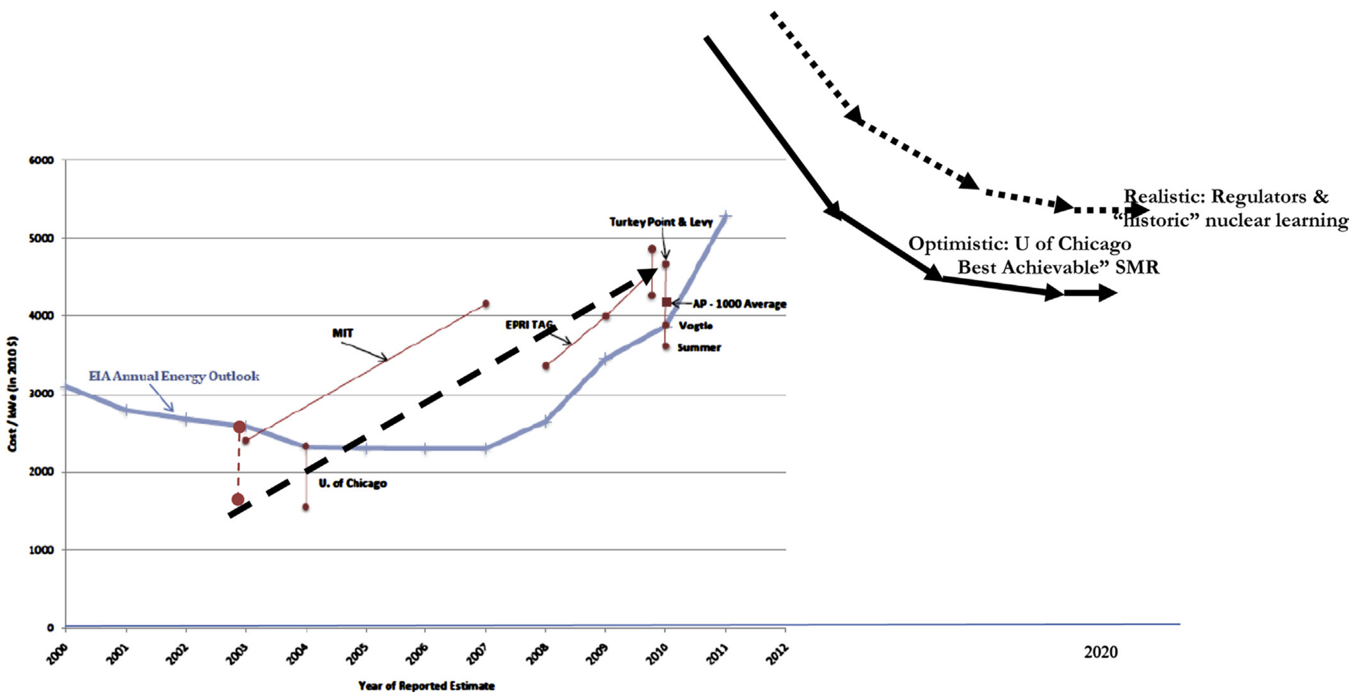



**Exhibit 5.** University of Chicago recap of enthusiast/utility estimates of overnight cost for new GW – scale nuclear plants: 2000–2010 and SMR cost projections. Sources: [146,127]. Low estimate is derived from [104,105,126], R., Goldberg, S., 2011. *Small modular reactors – key to future nuclear power generation in the U.S.* Energy Policy Institute at Chicago, University of Chicago, p. 19.

at the University of Chicago (see Exhibit 5).[17] In 2004, as the hype around the "Nuclear Renaissance" was heating up, under contract with the Department of Energy, the University of Chicago prepared an analysis of nuclear costs, compared to coal and natural gas. Individual cost estimates, largely from vendors and consultants, yielded very low estimates. Seven years later the University of Chicago prepared another analysis that sought to explain why the original cost estimates were so far off the mark [126]. (Note that MIT had gone through a similar process, as shown in Exhibit 5.)[18] At the same time, the University of Chicago prepared an analysis of the cost of SMRs [125].

The University of Chicago SMR cost estimates were substantially higher that the estimates put forward half a decade earlier. This might reflect that fact that the initial estimates of SMR costs were tied to the extremely low estimates of large "Nuclear Renaissance" 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. First, SMR technology will suffer from material cost increases because the underlying diseconomies of scale of SMRs suggests that they embody as much material per MW of capacity. Second, just as the design of the first "Nuclear Renaissance" reactor took 16 revisions to pass muster,[19] it is likely that overly optimistic assumptions about how quickly new designs can be approved by regulators will be proven wrong in the case of SMR technology because of the novel characteristics of these designs.[20]

The dramatic increase in projected costs for "Nuclear Renaissance" technologies shines a spotlight on the World Nuclear Association's claim, noted at the start of Section II that "the use of diverse pre-fabricated modules to expedite the construction of a single large reactor is not relevant." While SMR technology involves a much higher level of modularization than was proposed for the "Nuclear Renaissance" technologies, many of advantages of modularization and standardization were claimed for the new approach to large reactor construction, so the experience should not be considered totally irrelevant. The benefits were not realized, which is reflected in the dramatic escalation of cost for those reactors that entered construction.[21]

Exhibit 6 shows the SMR cost challenge in broader historical context. It plots the actual overnight costs of the reactors completed during the "Great Bandwagon Market," the projected and ongoing costs of the "Nuclear Renaissance" reactors and the projected costs of SMRs based on the University of Chicago study (plus a realistic scenario). 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 fifty-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 II.

17 [146,126,131], used Westinghouse's cost estimates for the AP1000 as the example. These estimates were reported in the [146], report and identified by [62], as one of the early estimates. Westinghouse employees were in the forefront of the SMR estimates, see [25].

18 [104,105].

19 The AP1000 under construction in Georgia and South Carolina.

20 A direct comparison of the SMR technology to nuclear renaissance technologies using a number of characteristics (Neutron Spectrum, Coolant/moderator, Fuel, Economy of Scale, Economy of Mass Production, Use of Proven Technology, Plant Simplification, Modular Construction, High Thermal Efficiency, Passive Safety [46] suggest to sue that that SMRs do not enjoy a great deal of advantage on the supply-side.

21 [64], before it started building, the nuclear industry promised its new generation of plants would be constructed using giant Lego-like modules that make building faster, cheaper and produce a higher-quality result. Instead, the Louisiana factory building these modules has failed to master quality control rules, stick to schedule or replicate the approved designs, adding time and significant cost to first-of-their-kind projects.

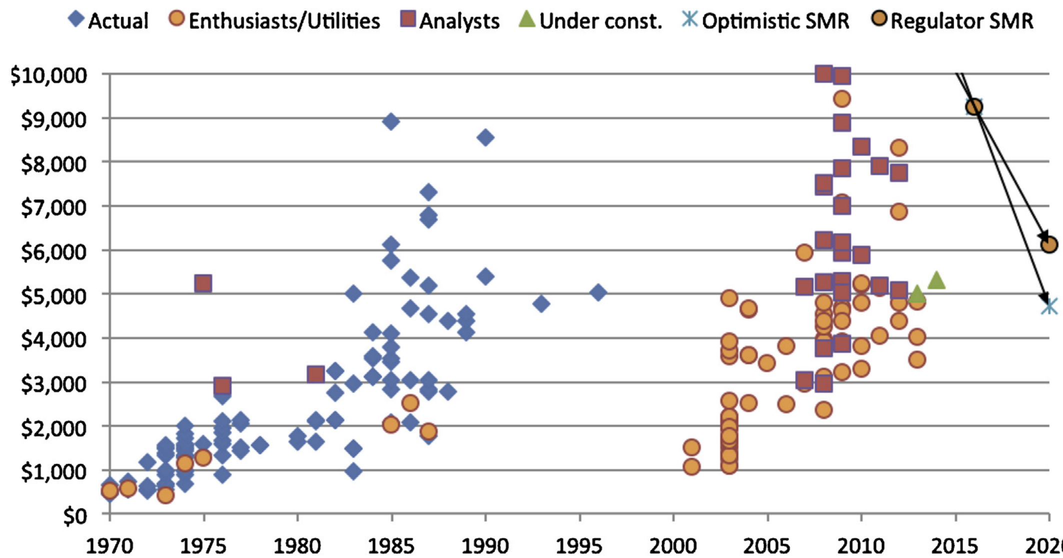



**Exhibit 6.** Actual and projected overnight construction costs of U.s nuclear reactors with SMR projected costs.

Sources: [34,126]

The bottom line on SMR technology is clear. It is not likely to enjoy any advantage in the cost per unit of output compared to large reactors, and probably be more costly. There is no advantage to be had on the cost side.

## 8. The size of the undertaking

The advantage claimed for the size of the units produced is also suspect, both at the level of the individual units and the effort to create an assembly line. We will deal with the latter first.

Although each individual SMR is smaller, the commitment necessary to drive the costs down, the cost of starting an assembly line, i.e. getting it to operate at the projected costs per unit of output (reactor), is huge. With an average overnight cost of more than $6500/kw and the University of Chicago study calling for 54 100 MW units (5.4 GW), the total for each design/production assembly line would be almost $36 billion. At the less optimistic cost projections, the total would be closer to $45 billion. When Westinghouse stepped back from SMR development, it declared it needed a book of orders for 30 to 50 reactors [91]. Given the relatively large size of the reactors (225 MW), the size of the order book would be 6.75–12.25 GW and the cost would be well above $36 billion. Moreover, if the goal is to have two assembly lines to create a modicum of competition, the total cost would be $72 billion. At the less optimistic cost estimates the total cost would be in the range of $90 billion.[22]

To appreciate the enormity of this undertaking, we can compare the cost of getting the assembly lines running at their "efficient" cost levels to the total additions to capacity that are projected for the U.S. electricity sector until 2020. Table 3 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 [96]. Large domestic subsidies are likely to be necessary to move the deployment forward.

[22] Makhajani ([101], p. 5), "A hundred reactors, each costing $900 million, including construction costs ([9], Slide 10), would amount to an order book of $90 billion, leaving aside the industry's cost escalation."

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 [32].

## 9. Demand side characteristics of SMR technology

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. SMR advocates are forced to claim that it beats other technologies. Yet, SMR advocates focus largely on a comparison between large and small reactors, arguing that SMRs have smaller total capital commitments, shorter construction times, and smaller unit size, making them more flexible, better able to meet small load increases more quickly and easier to finance compared to large reactors. Typically, the characteristics of other non-nuclear alternative resources are never considered.

Once all of the alternatives are factored in, however, there is no reason to believe that SMRs possess a unique set of characteristics that will drive demand, even in unique circumstances. As shown in Exhibit 7, when the size and construction period for the alternatives are factored into the analysis, SMRs do not fare well at all. While SMRs are more attractive than large reactors, coal and IGCC, they are less attractive than every other alternative on virtually all of the claimed sources of advantages.

If we move beyond these basic characteristics of the technology to consider other characteristics, the conclusion is much the same. Although there may be some non-electric applications in which SMRs gain some advantage [93], there are other non-electric applications, like desalinization, that may favor the alternatives and alternatives with storage have attractive possibilities for grid independence [14,111,4]. Nuclear power has significant disadvantages in terms of security [75], proliferation risks [78] and continues to suffer from unique environmental problems [136,116]. Based on a non-commodity, local source of power, renewables have a large

**Table 3**
SMR capital needs compared to renewable deployment thru 2020.

| Source of estimate | | | |
|---|---|---|---|
| EIA | Capacity added (GWe) | Overnight cost ($/kw) | Total cost ($, billions) |
| 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: [53], Appendix A. Author's calculation for SMR, per text.

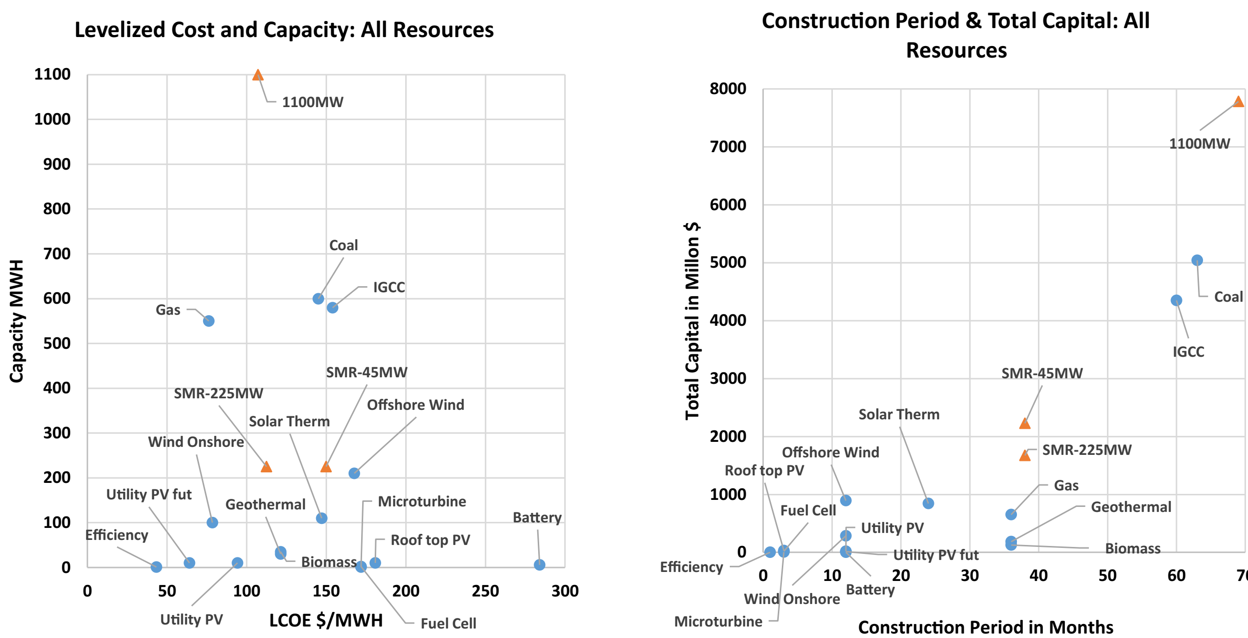



**Exhibit 7.** Putting the SMR size flexibility advantages in perspective.
Sources and Notes: This analysis combines the most recent estimates of Lazard [87]. *Levelized Cost of Energy Analysis – Version 7.0*, June, with the most recent expert analysis of SMRs. I have included 225-MW SMRs at 105% of large nuclear, which is the optimistic projections and 45-MW SMRs at 140% 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.

advantage in macroeconomic impacts ([90,127,71,115,19]). As a result, in multi-attribute rankings and evaluations, the main renewables (wind, solar, hydro) and efficiency are much more highly rated [136,77,148] and have consistently been so for decades.[23]

## 10. Cost trends and competition

Although we have included the levelized cost of electricity on one of the axes in Exhibit 7, cost and cost trends deserve more attention. 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. 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.

Exhibit 8 presents levelized cost estimates for a full range of base load and peaking technologies from Lazard. Needless to say, there are many such estimates available.[24] We choose one source to preserve consistency in assumptions. We believe 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.

23 [136], 646...640. The same is true of older comparisons. [144], evaluating [113,26,66,133].

24 [37], provides a framework for comparing estimates.

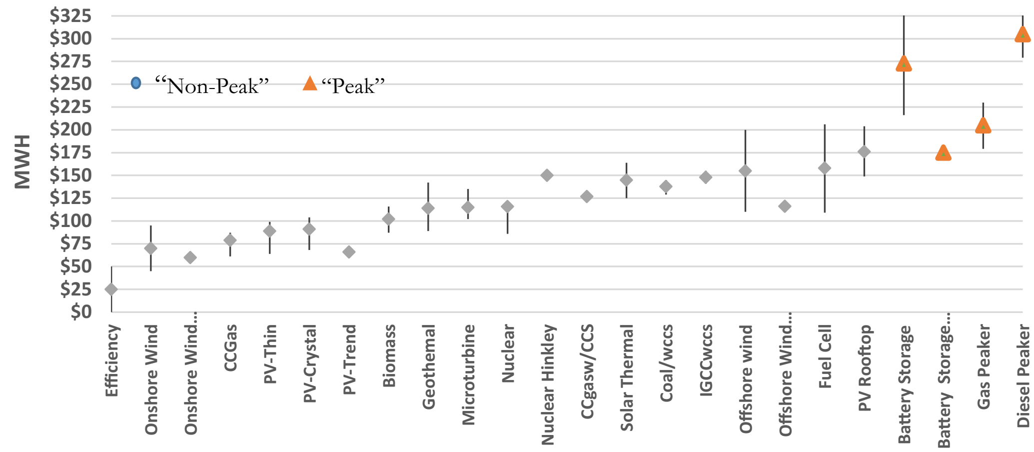



**Exhibit 8.** Levelized cost: full slate of options with trends.

Source: [87] plus trends for wind and battery 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.

We include estimates for SMR technology based on the earlier discussion of how much higher the cost per unit of output was expected to be. We also include a recent estimate for the cost of nuclear from the EPR, which is based on the contract signed by the UK government to build the Hinkley reactor.[25] This is consistent with the estimates of the French EPR discussed earlier. We have also included trend estimates for wind, solar and storage, since the SMR costs are depicted at the longer term "efficient" level. The solar trend is based on Lazard, wind and storage are from other analysts identified in the Exhibit sources. The message that this analysis sends is quite clear. There are a large number of alternatives that are likely to be considerable less costly than nuclear, even in a low carbon environment and even if the nuclear technology is small and modular rather than large.

The severe cost disadvantage that nuclear power, large or small, faces is even more apparent when cost trends are taken into account (see Exhibit 9). Renewable technologies have been exhibiting declining costs for a couple of decades and these trends are expected to continue, while nuclear costs have increased and are not expected to fall. Renewables have been able to move rapidly along their learning curves because they actually do 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. They afford the opportunity for a great deal of real world development and demonstration work before they are deployed on a wide scale. These are the antithesis of how nuclear development has played out in the past, and the push for small modular reactors does not appear to solve the problem.

Within the past year, a bevy of independent, financial analysts – [86,28], Credit Suisse [49,50], McKinsey and Company [58], Sanford Bernstein Parker and Chang [122], the Motley Fool [108], Morningstar [16,57], and Barclay's [8,85,154] have heralded an economic revolution in the electricity sector. A quarter of a century of technological progress has led to the conclusion that over the course of the next decade a combination of efficiency, renewables and gas will meet the need for new resources and more importantly, render the antiquated base load model largely obsolete[85,86]. 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 in the near and mid-term, with growing evidence that prospects for high penetration renewable scenarios for the long terms are also quite good.[26],[73,74,42–45]

These expectations for potential growth of alternatives and efficiency, bring us back to the most fundamental challenge that nuclear power has failed to overcome in its 50 year history. It simply cannot win the competition to meet demand.

Looking at the pattern of generation resource acquisition in the 1970s and 1980s, we have challenged the oft repeated claim that a slowing in the growth of demand was the key factors that undermined the nuclear "Great Bandwagon Market" of the 1970s. Over the course of the 1970s and 1980s, twice as much fossil fuel-fired capacity was brought online than orders for nuclear capacity were canceled (see Exhibit 10). If nuclear were economically competitive with coal, it would have displaced a large part of that power. If nuclear power were cost competitive, the "Nuclear Renaissance" would not have failed so badly and the industry would not be desperately seeking and demanding support for a new technology to save it.

## 11. Conclusion: the pullback from SMR technology development

This analysis has shown that all of the four factors that Ingersoll identified as creating the conditions for a "Nuclear Renaissance" and the dozen characteristics that suggested small modular technology would play a large part in that renaissance have turned

[25] [60], "EDF to miss its own deadline for Hinkley Point nuclear decision as EC state aid investigation drags on," *The Telegraph*, 10 Mar, after pointing out that the project is being heavily scrutinized, the article puts the guaranteed price at £92.50/MWH which works out to over $150/MWH.

[26] See for example, [65,15,114,138,27,98,128,76,156]. There are a growing number of scenario analyses at the global ([72,74,42,44,21,45,29]).

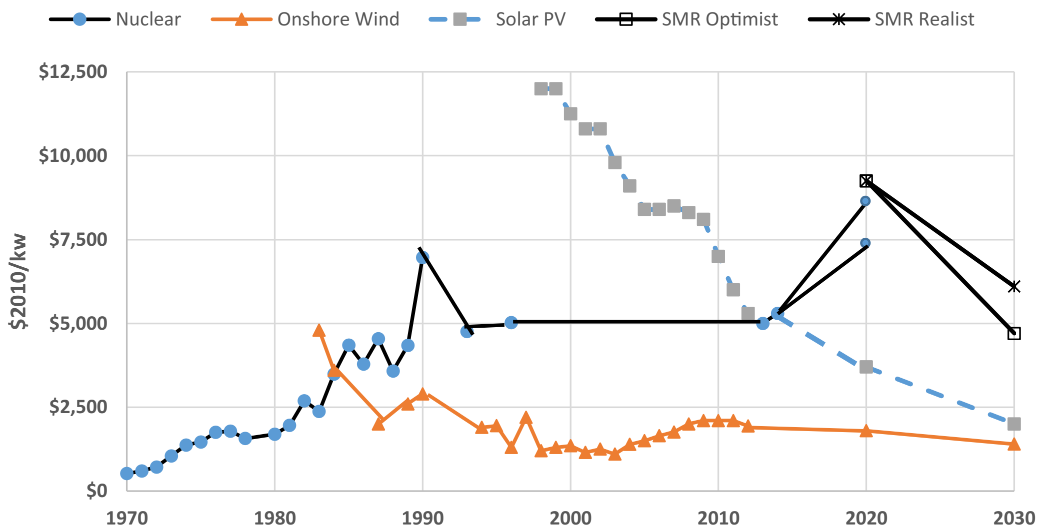



**Exhibit 9.** Cost trends: nuclear, wind and solar.
Sources: Barbose G, Darghouth N, Weaver S, Wiser R. *Tracking the Sun VI: An Historical Summary of the Installed Price of Photovoltaics in the United States from 1998 to 2012.* Lawrence Berkeley National Laboratory; 2013, July. Wiser R, Bolinger M. *2012 Wind Technologies Market Report.* U.S. Department of Energy; 2013, August.

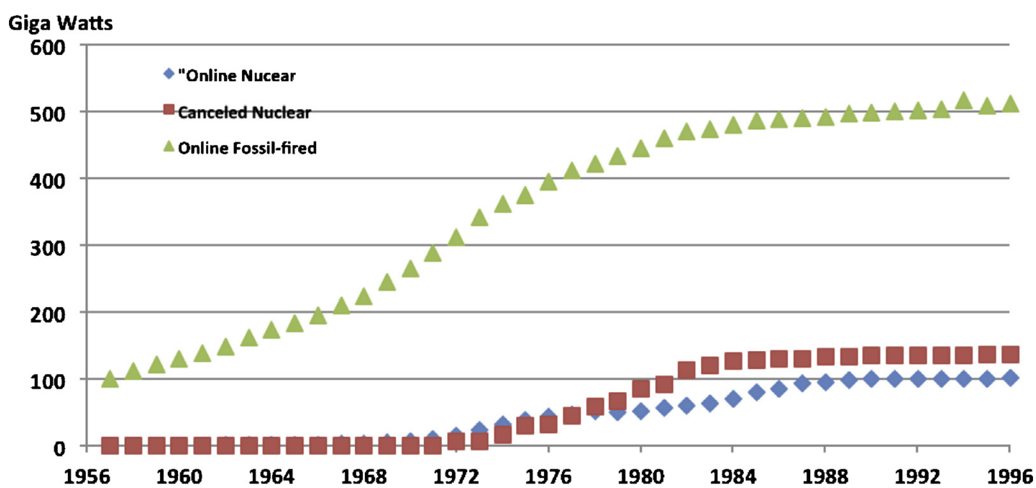



**Exhibit 10.** Completed and canceled nuclear capacity compared to fossil-fired capacity: 1963–1996.
Sources: Koomey J. Was the Three Mile Island accident in 1979 the main cause of US nuclear power's woes? *Bull Atomic Sci* 2013;[82,34].

sharply against nuclear power. In fact, we have argued that, looking at the long history of commercial nuclear power, this outcome is not merely repetitive, it is endemic and may be inevitable.

The failure of nuclear economics is not just bad luck.

Nuclear power is inherently uneconomic because it relies on a catastrophically dangerous resource that is vulnerable to human frailties and the vicissitudes of Mother Nature.

The severe threats to public safety posed by nuclear power and the evolving demands of safety result in an extremely complex technology that requires long lead times and large sunk capital costs.

The technology suffers constant cost escalation and does not exhibit cost reducing processes that are observed in other industries.

Therefore, any nation that claims to have the wherewithal (technical expertise and economic resources) to build a "safe" nuclear reactor will have the wherewithal to meet its needs for electricity with alternatives that are less costly and less risky. Thus, at present and for the foreseeable future, it is a virtual certainty that nuclear power is not going to be the least cost option or close to it, even in a low carbon utility sector. [35]

Given this dismal picture of the prospects for nuclear technology, large and small, it is not surprising that SMR technology has stumbled getting into the starting gate, with a dramatic reduction in interest from two of the leading developers.

Babcock & Wilcox, one of the firms that had received a federal SMR subsidy, stepped back from the development of SMR technology [48,51] 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." [124] The extent of the pullback by B&W 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 [63]. The company declared it "still expects to license mPower reactor by the mid-2020s" [63].

> 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 [48].

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., also announced it was stepping back from development of small modular nuclear technology [90,3]. 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.

Westinghouse used language that is similar to the Babcock and Wilcox explanation, not only in blaming cheap gas, but also in declaring that it did not want "to get ahead of the market." [90] In the case of Westinghouse, their caution was tied to the failure to find orders for its AP600, a medium sized reactor that had been licensed fifteen years earlier [90] and its claim that it needed a large book of orders, 30–50 reactors. 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"[27] and much larger subsidies would be necessary to move the technology forward.

The declarations of confidence in SMR technology could not hide the fact that in less than a decade its development was–"grinding to a halt".[28] The rapid and stunning collapse of the SMR hype is extremely important in the policy context [89]. The failure of SMR technology makes it impossible to ignore the huge scale that nuclear power demands to succeed. Shifting that need up the supply chain to a manufacturing facility does not eliminate its importance. The problem that utilities have in swinging the financing and development of large reactors is replaced by the even bigger problem that vendors have, but it is essentially the same problem. Westinghouse and B&W are big names in the nuclear space, had thrown a great deal of weight and money into advancing SMRs as the next big thing and the savior of the nuclear industry, but they failed.

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 failure to find customers and investors is the ultimate rejection in a capitalist economy. But, as noted in the introduction, with nuclear power the ultimate fate will be determined in the political marketplace, so the 50-year debate is likely to continue.

[27] 2,12, a leading advocate of nuclear power used this phrase.

[28] 102,121, "who had authored positive study of SMR at Navigant, admitted that even the low estimate of 4.6 GW by 2030—seems optimistic now."

## References


1 Abdulla A, Azevedo IL, Granger Morgan M. Expert assessments of the cost of light water small modular reactors. Proc Natl Acad Sci U S A 2013;110(June (24)).
2 Adams R. Westinghouse's roderick shifts resources from SMR to AP1000. AtomicinsightsCom 2014;February.
3 Adams R. Small modular reactors—US capabilities and the global market. ANS Nucl Café 2014;April.
4 Akikur RK, et al. Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: a review. Renew Sustain Energy Rev 2013:27.
5 Alexander L. The real reason for fear. Washington Times 2009; October 9.
6 Anadon LD, et al. International workshop on research, development, and demonstration to enhance the role of nuclear energy in meeting climate and energy challenges. Venice, Italy: International Center for Climate Governance Island of San Giorgio Maggiore, April 7–8; 2011.
7 Anadon LD, Nemet GF, Verdolini E. The future costs of nuclear power using multiple expert elicitations: effects of RD&D and elicitation design. Environ Res Lett 2013:8.
8 Aneiro M. Barclays downgrades electric utility bonds, sees viable solar competition. Barons Blog 2014. May 23.
9 Babcock & Wilcox Company. B&W mPower small modular reactor: creating the future of nuclear power. EFCOG executive council semi-annual meeting, December 5; 2012.
10 Banks GD. SMR Deployment Faces Challenges Despite National Interest A Summary of Findings from the November 14 CSIS Workshop on SMRs, CSIS, December 18; 2013.
11 Barber Wayne. As expected, B&W to slow its small reactor development program. Elect Light Power 2014;April.
12 Barker J. Big push for small modular reactors grind to a halt 2013. December.
13 Bastasch M. McCain: no global warming action until the left supports nuclear power. The Daily Caller 2014. March 3.
14 Belouda M, et al. Integrated optimal design and sensitivity analysis of a standalone wind turbine system with storage for rural electrification. Renew Sustain Energy Rev 2013;28.
15 Bettencourt LMA, Trancik JE, Kaur J. Determinants of the pace of global innovation in energy technologies. PLOS ONE 2013; 8(October (10)).
16 Bischof A. Morningstar Utility Observer 2014. February.
17 Black G. Economic and employment impacts of small modular nuclear reactors. Center for Advanced Energy Studies; 2012. June.
18 Boccard N. The cost of nuclear electricity: France after Fukushima. Energy Policy 2014;66.
19 Branker K, Michael P., Joshua MP. A review of solar photovoltaic levelized cost of electricity. Renew Sustain Energy Rev 2011:15.
20 Breakthrough Staff. Top climate scientists urge support of nuclear power: letter calls for 'fresh approach' to nuclear in the 21st century. Oakland, CA: The Breakthrough Institute; 2013. November.
21 Budischak Cory, et al. Cost-minimized combinations of wind power, solar power, and electrochemical storage, powering the grid up to 99.9% of the time. J Power Sources 2013:225.
22 Bullis K. Can small reactors ignite a nuclear renaissance? Technol Rev 2013;March.
23 Bupp IC, Derian J-C. Light water: how the nuclear dream dissolved. New York: Basic Books; 1978.
24 Carelli MD, et al. Economic features of integral, modular, small-to-medium size reactors. Prog Nucl Energy 2010:52.
25 Carelli MD, et al.Economic comparison of different size nuclear reactors, Cancún, Quintana Roo, México, del 1 al 5 de Julio 2007.
26 Chernik P, Caverhill E. The valuation of externalities from energy production, delivery and use. Fall 1989 update. A report by PLC, Inc. to the Boston Gas Co; 1989.
27 Chmutina Ksenia, Goodier Chris I. Alternative future energy pathways: assessment of the potential of innovative decentralised energy systems in the UK. Energy Policy 2014;March:66.
28 CITI Research. Shale & renewables: a symbiotic relationship; 2012. September 12.
29 Cochran Thomas B, et al. Fast breeder reactor programs: history and status. International Panel on Fissile Materials; 2010. February.
30 Conti D. Nuclear power industry under siege, FirstEnergy exec warns. Chicago Tribune 2014. April 9.
31 Cooper M. The economics of nuclear reactors: renaissance or relapse. Institute for Energy and the Environment, Vermont Law School; 2009.
32 Cooper M. Policy challenges of nuclear reactor construction: cost escalation and crowding out alternatives. Institute for Energy and the Environment, Vermont Law School; 2010. September.
33 Cooper M. Post-Fukushima case for ending Price-Anderson. Bull Atomic Sci 2011. October.

34 Cooper M. 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. 2012.
35 Cooper M. Public risk, private profit, ratepayer cost, utility imprudence: advanced cost recovery for reactor construction creates another nuclear fiasco, not a renaissance; 2013. March.
36 Cooper M. Renaissance in reverse: competition pushes aging U.S. nuclear reactors to the brink of economic abandonment. Institute for Energy and the Environment, Vermont Law School; 2013. July.
37 Cooper M. The economic feasibility, impact on public welfare and financial prospects for new nuclear construction, for Utah heal 2013. July.
38 Cooper M. The unavoidable economics of nuclear power. Corporate Knights 2014. January 22, 2014.
39 Credit Suisse. Nuclear... the middle age dilemma? Facing declining performance, higher costs, inevitable mortality 2013. February 19.
40 Cunningham N. Small modular reactors: a possible path forward for nuclear power, American security project 2012. October.
41 Daniels S. Exelon warns state it may close 3 nukes. Crain's 2014. March 1.
42 Delucchi MA, Jacobson MZ. Providing all global energy with wind, water, and solar power, part II: reliability, system and transmission costs and policies. Energy Policy 2011:39.
43 Delucchi MA, Jacobson MZ. Response to a critique of Jacobson and Delucchi's proposals 2012.
44 Delucchi MA, Jacobson MZ. Providing all global energy with wind, water and solar power, part I: technologies, energy resources, quantities and areas of infrastructure, and materials, part II: reliability, system Transmission costs and policies. Energy Policy 2011:39.
45 Delucchi MA, Jacobson MZ. Meeting the world's energy needs entirely with wind, water and solar power. Bull Atomic Sci 2013;69(13).
46 DeWitte, Jacob, N.D. Small Modular Reactors 101, MIT Energy Club Nuclear Community.
47 Downey J. No sale: Babcock & Wilcox can't find buyer for generation mPower. Charlotte Bus J 2014. February.
48 Downey J. Westinghouse slows small reactor development. Charlotte Bus J 2014. February.
49 Eggers D. A thought... energy efficiency: the reality of slower power demand growth, Credit Suisse 2013. February 11.
50 Eggers D, et al. A Thought... the transformational impact of renewables, Credit Suisse 2014. December 20.
51 Electric Energy Online. B&W announces restructuring of small modular reactor program 2014. April 14.
52 Energy Information Administration. An analysis of nuclear power plant construction costs, Washington, DC, January 1 1986.
53 Energy Information Administration. Annual Energy Outlook: 2014, Washington, DC 2014.
54 Europe Nuclear Society. Nuclear Power Plants Worldwide 2014.
55 Eurosafe Forum. Experience Feedback on the Fukushima Accident, November 8 2011.
56 Fairley P. EC sees heavy price tag to UK nukes, Spectrumieeeorg, February 3 2014.
57 Forbes.com. Morningstar, 3 Utilities Most Likely to Fall in Death Spiral, According to Morningstar, April 10 2014.
58 Frankel D, Ostrowski K, Pinner D. The disruptive potential of solar power: as costs fall, the importance of solar power to senior executives is rising. McKinsey Quart 2014. April.
59 Glaser A, Hopkins LB, Ramana MV. Resource requirements and proliferation risks associated with small modular reactors. Nucl Technol 2013.
60 Gosden E. EDF to miss its own deadline for Hinkley Point nuclear decision as EC state aid investigation drags on. Telegraph 2014. March 10.
61 Grubler A. The costs of the French nuclear scale-up: a case of negative learning by doing. Energy Policy 2010:38.
62 Harding J. Economics of nuclear power and proliferation risks in a carbon-constrained world. California Energy Commission; 2007. June 28.
63 Henderson B. B&W scales back its small nuclear reactor project, charlotteobserver.com. By Bruce Henderson The Charlotte Observer; 2014.
64 Henry R. Promises of easier nuclear construction fall short. AP 2014. July.
65 Hoffert MI. Farewell to fossil fuels? Science 2010:29.
66 Hohmeyer O. Social costs of energy consumption: external effects of electricity generation in the federal republic of Germany. Berlin: Springer-Verlag; 1988.
67 Hultman N, Jonathan K. Three Mile Island: the driver of US nuclear power's decline? Bull Atomic Sci 2013. May.
68 Ingersoll DT. Deliberately small reactors and the second nuclear era. Prog Nucl Energy 2009;51.
69 Ingersoll D. Deliberately small reactors and the second nuclear era. Oak Ridge National Laboratory; 2010. June.
70 IPCC. Working group III, mitigation of climate change, fifth assessment report 2014.
71 Islam MR, Mekhilef S, Saidur R. Progress and recent trends of wind energy technology. Renew Sustain Energy Rev 2013;21.
72 Jacobson MZ, Delucchi MA. Providing all global energy with wind, water and solar power, Part I: technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Policy 2011;39.
73 Jacobson Mark Z, et al. Examining the feasibility of converting New York State's all-purpose energy infrastructure to on using wind, water and sunlight. Energy Policy 2013.
74 Jacobson MZ, Howarth RW, Delucchi MA. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. Energy Policy 2013:57.
75 Johansson B. Security aspects of future renewable energy systems: a short overview. Energy 2013:61.
76 Johnson EP. The cost of carbon dioxide abatement from state renewable portfolio standards. Resour Energy Econ 2014;36(2).
77 Karakosta C., et al. Renewable energy and nuclear power towards sustainable development: characteristics and prospects. Renew Sustain Energy Rev 2013:22.
78 Katarzyna S. A wind-power fuel cell hybrid system study model of energy conversion for wind energy system with hydrogen storage. Akureyri, Iceland: The School for Renewable Energy Science; 2009.
79 Kessides IN. The future of the nuclear industry reconsidered: risks, uncertainties, and continued promise. Energy Policy 2012:48.
80 Komanoff C. Power plant escalation: nuclear and coal capital costs, regulation, and economics. Van Nostrand; 1981.
81 Koomey J, Hultman N. A reactor level analysis of busbar costs for US nuclear plants, 1970–2005. Energy J 2007.
82 Koomey, J., Was the Three Mile Island accident in 1979 the main cause of US nuclear power's woes?, 2011. June 24.
83 Kuckro R. Power players muster force for electricity market reform. E&E 2014. April 21.
84 Kusnetzov V. Options for small and medium size reactors (SMRs) to overcome loss of economics of scale and incorporate increased proliferation resistance and energy security. Prog NuclEnergy 2008:50.
85 Lacey S. Wall street firms step up warnings 2014.
86 Lacey S. Wall street firms step up warnings about distributed energy's threat to utilities. Greentech Media 2012. May.
87 Lazard. Levelized cost of energy analysis – version 7.0 2013. June.
88 Lévêque F. Estimating the costs of nuclear power: benchmarks and uncertainties. Interdisciplinary Institute for Innovation, Working Paper 13-ME-01, May 2013.
89 Lewis M. Are small modular reactors a better nuclear solution, or just more of the same? Thomasnet News 2013. February 27.
90 Litvak A. Westinghouse backs off small nuclear plants. Pittsburgh Post-Gazette 2014. February 1.
91 Llera E. Forecasting job creation from renewable energy deployment through a value-chain approach. Renew Sustain Energy Rev 2013:21.
92 Locatelli G, Mancini M. Competitiveness of small-medium, new generation reactors: a comparative study on decommissioning. J Eng Gas Turbines Power 2010:132. October.
93 Locatelli G, Mauro Mancini M. Competitiveness of small-medium new generation reactors: a comparative study on decommissioning. Proceedings of the 17th international conference on nuclear engineering, Brussels, Belgium, Paper 75254, July 12–16 2009.
94 Locatelli G, Bingham C, Mancini M. Small modular reactors: a comprehensive overview of their economics and strategic aspects. Prog Nucl Energy 2014:73.
95 Lokhov A, Cameron R, Sozoniuk V. OECD/NEA study on the economics and market of small modular reactors. INPRO dialogue forum on global nuclear energy sustainability: licensing and safety issues for small- and medium-sized reactors (SMRs), Headquarters, Vienna, IAEA, 29 July–2 August 2013.
96 Lyman E. An examination of the safety and economics of light water small modular reactors. Energy and Water Development Subcommittee, Committee on Appropriations, US, Senate 2011. July 14.
97 Lyman E. Small isn't always beautiful: safety, security, and cost concerns about small modular reactors. Union of Concerned Scientists; 2013. September.
98 Maia T, et al. Envisioning a renewable electricity future for the United States. Energy 2014;65(1).
99 Maize K. Are SMRs U.S. nuclear power's last, best hope? Power Mag 2014. May 1.
100 Makhijani A, Boyd M. Small modular reactors no solution for the cost, safety and waste problems of nuclear power. IEER, PSR; 2010.
101 Makhijani A. Light water designs of small modular reactors: facts and analysis. IEER; 2013.
102 Martin R. mPower pullback stalls small nuclear. Forbes 2014. February, 28.
103 Masahiko A, Rothwell G. Lessons and policy implications. Energy Policy 2013;53.
104 Massachusetts Institute of Technology. The Future of nuclear power: an interdisciplinary MIT study 2003.
105 Massachusetts Institute of Technology. Update of the future of nuclear power: an interdisciplinary MIT study 2009.
106 McMahon J. Exelon pins nuclear hopes on small modular reactors. Forbes 2014. May 13.
107 Moody JR. The economics of small modular reactors. James R. Moody & Associates; 2012. August.
108 Murphy S. Forces are mounting against utilities like never before. Motley Fool 2014. January 29.
109 Mycoff CW, et al. Section IV.1. Methodologies and decision criteria for demonstrating competitiveness of SMRs. Paper for IAEA TECDOC

strategies to demonstrate competitiveness of SMRs in world markets 2007.
110 Nei Nuclear Notes, "NEI's Paul Genoa Hits 10 Markets in Radio Media Tour on Small Modular Reactor," 2013. April.
111 Nogueira CEC, et al. Sizing and simulation of a photovoltaic-wind energy system using batteries, applied for a small rural property located in the south of Brazil. Renew Sustain Energy Rev 2014:29.
112 Northey H. Groups oppose top climate scientists' call to embrace nuclear power. Greenwire 2014. January 8.
113 Ottinger R, et al. Environmental costs of electricity. Oceana, NY: Pace University Center for Environmental Legal Studies; 1990.
114 Petkovi D. Adaptive neuro-fuzzy maximal power extraction of wind turbine with continuously variable transmission. Energy 2014:64.
115 Pleßmann G, et al. Global energy storage demand for a 100% renewable electricity supply. Energy Procedia, 8th International Renewable Energy Storage Conference and Exhibition, IRES 2013 2014.
116 Rabl A, Rabl VA. External costs of nuclear: greater or less than the alternatives? Energy Policy 2013;57.
117 Ramana MV, Mian Z. One size doesn't fit all: social priorities and technical conflicts for small modular reactors. Energy Res Soc Sci June 2014:2.
118 Ramana MV. Laura Berzak Hopkins, and Alexander Glaser. Licensing small modular reactors. Energy 2013;61.
119 Rangel LE, Lévêque F. Revisiting the nuclear power construction costs escalation curse, Interdisciplinary Institute for Innovation, Working Paper, 12-ME-08 2012.
120 Rangel LE, Lévêque F. Revisiting the nuclear power construction costs escalation curse. Int Assoc Energy Econ 2013, third quarter.
121 Martin R. mPower pullback stalls small nuclear, Navigant 2014. April 25.
122 Parker MW, Chang F. Bernstein energy power blast: equal and opposite... If solar wins, who loses? Bernstein Research 2014. April.
123 Pearce D. The Dictionary of Modern Economics. MIT Press 1983.
124 Roanaoke.com, Ruiter. Layoffs coming at Babcock & Wilcox as mini-reactor program scaled back, April 17 2014.
125 Romm J. Those who want to see nuclear power play a bigger role in climate action, think progressorg, November 4 2014.
126 Rosner R, Goldberg S. Small modular reactors – potentially key contributors to future nuclear power generation in the U.S. Center for Strategic and International Studies; 2011. December 1.
127 Rosner R, et al. Analysis of GW-Scale overnight capital costs, EPIC, University of Chicago, technical paper, November 2011.
128 Santiago K, et al. A strong argument for using non-commodities to generate electricity. Energy Econ 2014;May:43.
129 Schiffman R. Is nuclear power the answer on climate change? Reuters; 2014. January 10.
130 Schneider M, et al. The world nuclear industry status report 2013 2013. July.
131 Scully Capital Services. Business case for new nuclear power plants: bringing public and private resources together for nuclear energy, mitigating critical risks on early orders for new reactors. Briefing for NERAC; 2002. October 1.
132 Shropshire D. Economic viability of small to medium-sized reactors deployed in future European energy markets. Prog Nucl Energy 2011:53.
133 Shuman M, Cavanagh R. A model of conservation and electric power plan for the Pacific Northwest: appendix 2: environmental costs. Seattle, WA: Northwest Conservation Act coalition; 1982. November.
134 Sovacool B, Nugent D, Gilbert A. Construction cost overruns and electricity infrastructure: an unavoidable risk? Electric J 2014. May.
135 Squassoni S. Small modular reactors: contours of proliferation/security risks, proliferation prevention program center for strategic & international studies. Platts 4th annual small modular reactors conference, Washington, DC, May 29–30 2013.
136 Stein EW. A comprehensive multi-criteria model to rank electric energy production technologies. Renew Sustain Energy Rev 2013:22.
137 Hadid Subki M. Common issues and challenges in development and deployment of small and medium-sized reactors (SMR). 22nd TWG Meeting on GCR, IAEA, 28–30 March 2011.
138 Sueyoshia T, Gotob M. Photovoltaic power stations in Germany and the United States: a comparative study by data envelopment analysis. Energy Econ 2014;42(March).
139 Tomain JP. Nuclear power transformation. Bloomington: Indiana University; 1988.
140 Tomich J. Small nuclear reactors generate hype, questions about cost. St. Louis Post dispatch; 2012. April 25.
141 Tucker W. America's last nuclear hope small reactors may save us yet. Energy Spectator 2011. March.
142 Turmelle L. Group warns more nuclear power plants may shut down. New Haven Register 2014. February 14.
143 U.S. Department of Energy. DOE announces loan guarantee applications for nuclear power plant construction 2008. October 2.
144 U.S. Congressional Office of Technology Assessment. Studies of the environmental costs of electricity. Washington, DC: September; 1994.
145 U.S. Department of Energy. N.D. Small modular reactor home page, http://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors
146 University of Chicago. The economic future of nuclear power: a study conducted. University of Chicago; 2004. August.
147 Upton J. Enviros and climate scientists continue their fight over nuclear power. Grsitorg 2014. January 10.
148 Verbruggen A, Laes E, Lemmens S. Assessment of the actual sustainability of nuclear fission power. Renew Sustain Energy Rev 2014;32.
149 Vine D, Juliant T. Climate solutions: the role of nuclear power. Center for Climate and Energy Solutions; 2014.
150 Von Hoene Jr WA. Minding the energy gap, what's at stake for U.S. nuclear plants. United States Energy Association; 2014. April 23.
151 Wang Q, Chen X. Regulatory failures for nuclear safety – the bad example of Japan–implication for the rest of world. Renew Sustain Energy Rev 2012;16.
152 Wang Q, Chen X, Yi-chong X. Accident like the Fukushima unlikely in a country with effective nuclear regulation: Literature review and proposed guidelines. Renew Sustain Energy Rev 2013;17.
153 Wikipedia. Political economy, http://en.wikipedia.org/wiki/Political_economy
154 Wirl F. Taxes versus permits as incentive for the intertemporal supply of a clean technology by a monopoly. Resour Energy Econ 2014;36.
155 World Nuclear Association, N.D., Small modular reactors home page, http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Small-Nuclear-Power-Reactors/
156 Zheng C, Kammen DM. An innovation-focused roadmap for a sustainable global photovoltaic industry. Energy Policy 2014;67.
157 Zhitao L, Fan J. Technology readiness assessment of small modular reactor (SMR) designs. Prog Nucl Energy 2014;70.

## Further reading

158 Azevedo IM, Morgan G, Ahmed Abdulla ND. Investigating the economic viability of small, modular reactors. Pittsburgh: Department of Engineering and Public Policy, Carnegie Mellon University; 2014.
159 Cooper M. Nuclear safety. Post-Fukushima case for ending Price Anderson. Bull Atomic Sci 2012.
160 Environmental Protection Agency. Regulatory impact analysis for the proposed standards of performance for greenhouse gas emissions for new stationary. Washington, DC: Sources: Electric Utility Generating Units; September 2013.
161 IPCC. Working group III, mitigation of climate change, fifth assessment report 2014.
162 Mitenkov FM, Averbakh BA, Antyufeeva IN. Economic effect of the development and operation of serially produced propulsion nuclear power. Atomic Energy 2007;102(1).
163 Standard & Poor's. Utilities make some progress on new nuclear power, but hurdles still linger 2009. March 9.
164 U.S., Department of Commerce, International Trade Administration. The commercial outlook for U.S. small modular nuclear reactors. Washington, DC; 2011. February.