SMRs - Economies of Scale v Economies of Volume

Why SMRs?

Interest firstly in the US and now in the UK in Small Modular Reactor (SMR) designs is driven by the very high cost and long duration of projects like the one planned for Hinkley Point. Such projects are just too large for even the largest utility. Also, they take too long to be able to respond to changes in market demand. Because of their smaller scale, (less than 300MWe), the project investment for an SMR will also be smaller and it is expected that they can be built more quickly. SMRs can be built where the level of demand is smaller, more in line with their power output. Or, if the level of demand is larger (more than a GWe), a number of SMRs can be constructed using their modular features to provide the level of power required, constructing a series of power plants rather than one large reactor.

In 2014, the case for SMRs in the UK was examined both by Parliament [1] and by industry [2]. Each concluded enthusiastically that SMRs based on the well-proven light water reactor technology should be considered for the next phase of UK nuclear investment, after the 12 large reactors planned for construction during the next twenty years. However, they agreed that the economic case for SMRs has yet to be made, that they can actually produce lower cost electricity than the current range of 1000+MWe reactors.

Economics Drivers

Nuclear power economics depend on three broad types of cost, in the approximate proportions:

Project investment	66%
Operations and maintenance	16%
Fuel and waste	17%

The unit fuel and waste costs of SMRs will be similar to larger reactors. There are some specific manpower challenges in operations and maintenance costs. The prime factor for SMRs, like their larger cousins, will be the high cost and long duration of construction. Doubts about the economics of SMRs are first and foremost doubts about construction cost. Unless these costs can be reduced as reactors become smaller, SMRs will not be economic.

Two major factors drive the costs of reactors: power scaling and progressive learning.

1. Power scaling is well known in the energy sector. As units of a similar design increase in size, their cost rises more slowly and that unit costs fall.

$$\text{Cost/Power} \propto (\text{Power})^{a}$$

- where a is the scaling index - taken to be in the range -0.6 to -0.3 [3], or -0.5 to -0.3 [4].

This effect could make the unit capital cost of a 200MWe SMR more than double those of a 1000MWe reactor. But doubts have been raised about the correctness of the scaling index values employed in these scaling estimates. Many of the cost studies relate only to the US and specifically to the early part of the programme in 1970s. Some of the data appears to be either from non-nuclear sources, or from other estimating methods [5]. More significantly, the method separated reactor scale and construction duration as independent variables to arrive at the scaling index values given above.

This strong power scaling effect is shown not to be present in later and larger studies of the cost of US reactors [6]. It is clear that larger reactors take longer to build because they are more complex. Therefore scale and duration are not independent. When these two variables are combined the effect of scale on cost is much smaller than previously thought. Power scaling effects may even be negligible because all the predicted savings from increases in size are offset, either by extended construction duration or additional safety enhancements required for these larger reactors.

Similar cost trends with low or negligible cost scaling are seen in other published studies, e.g.: France, Japan, UK, Canada and S Korea, covering almost 200 of the over 400 power reactors built. Nuclear power scaling effects are either small, or are completely absent.

2. Opportunities for learning and productivity improvement arise from the larger numbers of SMRs required providing a fixed quantity of power. Series production of a common design leads to lower costs. Also, there is the potential for enhanced learning from factory construction, made possible by their smaller size. Manufacturing learning leads to progressive improvements in productivity and progressive reduction is cost, expressed as:

Man-time cost falls at a fixed rate % (y) as volumes double

- where y % production time saving for b doublings of units or volume, with y - Wright Progress index. Learning rate = 1-y being in the range 10-30% [7].

Learning rates of double digit percentage are seen across many manufacturing industries, including those that have relatively low volumes and large sizes similar to nuclear power. Two summary studies (see Table) covering many other investigations and industries supported this effect.

However, the nuclear Industry learning rates are much lower [10] 3-5%. The question is why?

Industry	Learning Rate	Source
Aircraft	19%	Chen & Goldberg [8] Appendix A
Shipbuilding	10-15%	Man-time learning
Semi-conductors	20%	
PV	20-35%	
Wind turbines	4-12%	
Gas pipelines	4-24%	McDonald & Schrattenholzer [9] pg. 257 Learning rates based on overall cost, include all types of improvement
Gas turbines	10%	
Coal Power	8%	
GTCC	26%	
Wind	17%	
Ethanol Prod.	20%	
Solar PV module	20%	

Industry Learning Rates

Many observers have commented on the low productivity of nuclear construction, caused by the constant evolution of reactor designs with many local/site-based variations. The US built 100 reactors with very few the being the same. Also, the long periods between projects, their geographic dispersion and the desire to employ local staff, mean that lessons learned on one project are forgotten and then have to be learned again on another project. The constant drive to increase the scale of nuclear reactors tests the limits of knowledge and manufacturing on each new reactor.

Also, the large size and complexity of construction sites inhibits communication, coordination and learning. Finally, the stringent and intensive quality processes required by nuclear safety, challenge the skills and experience of construction staff, most of whom have never built a nuclear power station before. It may be said that nuclear construction provides ideal conditions for forgetting rather than learning! SMRs seek to address this issue by designing reactors for manufacture in factories and assembly on site.

SMR Designs

Much of recent development in SMR design has been in the US led first by Westinghouse with variants ranging in size from 50-225MWe. NuScale and mPower gained US DoE funding for their reactor designs. All of these are integral PWRs with the core, steam generators, pumps and pressuriser integrated into one large and long vessel. Most designs make some use of natural circulation cooling, either as in NuScale for power operation, or otherwise for decay heat removal. These two design ideas: integral construction and passive cooling are significant ways of reducing cost. Also the same factory that constructs reactor vessels can make the other components and the assembly is delivered to site either by barge, or in the US, on a railcar. Similar features are present in other SMR designs from Russia (VBER 300), China (ACP100) and S Korea (SMART).

NuScale SMR – 45MWe

Until SMRs are built in sufficient volumes, it will remain unclear whether they have conquered the cost problem. However, a study at Carnegie Mellon [11] has thrown some light on the progress being made. Comparative estimates of the cost of both the Westinghouse and NuScale SMRs and a current large reactor by 23 experts, showed a wide range of values. However, based on the average of estimates, cost scaling effects have been largely offset – scaling index -0.2 (50 MWe) to -0.1 (200 MWe). Learning rates are expected to be in the range 7-9% and the experts agreed that SMRs would be significantly shorter in time to construct: 36 months, as opposed to 60 months.

Conditions for Success

If these studies show what is possible, what are the conditions for SMRs to become competitive against today's large reactor designs? Simple modelling of SMRs cost trends compared with mature large reactor designs, gives some useful indications [5]. The larger number of SMRs required to provide an amount generation capacity with their better learning and productivity, offsets any power scaling effect. Some examples are shown in the Table below:

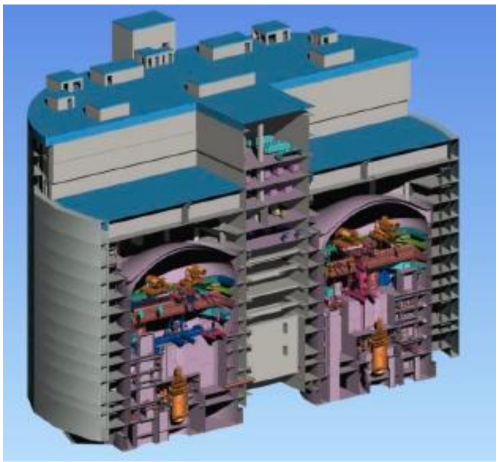
	Specific Power Scale	Overall Learning	Break-Even Capacity	Comment
Conventional assumptions	-0.35	3%	>100GW	Not economically feasible
Low power scaling & Learning	-0.2	3%	>100GW	Ditto
Low power scaling , Mid Learning	-0.2	7.5%	2.8GW for 200MW 15GW for 100MW	Significant contribution of lower construction interest for viability
Low power scaling, High Learning	-0.2	10%	1GW for both 100 & 200MW	Very competitive costs – unit size: determined by supply chain needs.

SMR Scaling & Learning Conditions

With values of the power scaling index in the range -0.35 to -0.2, it is not possible for SMRs to be lower in cost than conventional large reactors without enhanced rates of learning. If learning rates are at least 7.5% and power scaling index is relatively low (-0.2), SMRs can achieve lower unit investment costs than large reactors. The generating capacity and number of reactors to achieve such lower costs is not large: 2,800MWe (14 off 200MWe reactors) for low scaling (-0.2) with a mean value of 7.5% learning rate. Every reactor beyond this number will have lower unit capital costs than a mature large reactor and these costs will continue to fall as more SMRs are produced.

Designing for Learning

The design focus of current SMRs appears to be on the reactor system. This is understandable both because it is the natural interest of nuclear engineers and because of the need to gain safety acceptance of the concept. Safety issues have at their heart the design of the reactor and its systems for the control of power, cooling and the containment of radioactivity. However, the reactor system is less than a third of the costs of a typical nuclear power plant. All parts of the plant need to be considered to achieve the target learning rates applied to the whole project cost.



CNNC - ACP100 MWe

SMR designs are evolving and as yet none have been built. The layout of the reactor containment and power plant buildings will continue to change. Current reactor arrangement such as the Chinese ACP100 shown here and also others designed in the US, seem to surround an integrated and engineered reactor system with a conventional reactor containment building. This is most likely to be constructed using site-based methods. If so, the high costs of the building and associated mechanical, electrical and control systems will prevent achievement of the defined economic targets for scaling and learning.

US designed SMRs have considered the issues of transporting large reactor components between factory and site. However, it is less clear that the means of off-site manufacture and transport of the rest of the plant has been considered so thoroughly. Also, the transport system in the US with its many wide rivers and generous gauge rail systems is not replicated elsewhere, either in Europe or in many other countries around the world. If SMRs are to access wider global markets, transport considerations need to be assessed more broadly.

The means and methods of manufacturing learning are well understood. Learning results from aspects such as having a common design which is manufactured repeatedly in the same factory, together with strong economic incentives to improve productivity. The methods of cost reduction are well known. These include: design with the production processes in mind, use of modern tools, automation, jigs and fixtures, production arrangement designed for flow, integration of the supply chain for material and component supply and the measurement of production performance, with regular feedback of metrics and their improvement.

The question is not whether it is possible but rather: How will the nuclear industry change from its fragmented design and construction approach, where some parts of the power system are designed to precision standards (reactor core and vessels) and other parts (containment building and the related systems) are left to site teams to detail and construct?

Linked questions include: How will a sufficient volume of SMRs be ordered and produced if the designs remain specific to a single country? This depends on safety regulation. How can a SMR design be made the almost identical for different countries each with their different safety regulations and standards?

Conclusions

SMRs can in principle be designed to compete with larger reactors on capital costs. SMR designs need to meet two conditions. They must have simplicity at the heart of their concept which allows much of the complexity of modern reactors to be avoided and will result in a lower power scaling effect. Also, SMRs must be designed at the outset for factory construction and the design-for-manufacture approach must be applied across the whole power plant, not just the highly engineered reactor and turbine systems.

Meeting these economic conditions will allow us to address the industrial questions which then become the keys to competitive SMRs. Can SMRs be made in high volumes, constructed in many countries and in ways that satisfy a variety of regulatory systems?

Other industries such as civil aerospace have made this major transition, in the decades starting in the 1960s, from many high-cost bespoke designs to standard and economically efficient aircraft and mass air-travel.

If positive answers can be found for nuclear power to these business problems, rather than engineering and scientific questions, SMRs will have a bright future. More significantly, at least one way of dealing with the perennially high cost of nuclear power will start to be realised.

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