By Tony Roulstone


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Making Nuclear Competitive Again

Identifying the keys.

THOUGH NUCLEAR POWER STATIONS ARE being completed at a rate of three or four each year in China and Russia, there are many reasons why none have been completed in Europe or America since 2000. This changed in 2023 when the French designed EPR at Olkiluoto 3 in Finland started operating.

Competitive Nuclear Power

While safety, waste, sustainability, and operating costs are important issues for nuclear power, the key issue is capital cost. Unless nuclear power produces energy that is competitive with other forms of energy, the case for nuclear cannot be made, and no new nuclear power stations will be completed.

The nature of the energy market has fundamentally changed in the last 25 years. Then, the competition for electricity production was between coal and gas. Now, it is competition with renewables such as solar, wind, and hydro. Even cleaned-up gas power (equipped with carbon capture and storage) could be part of the future energy market if competitive.

The question is: Why is nuclear not competitive? The answer is considered in four parts as follows:

- why the current types of reactor cost so much
- nuclear industry's response based on
    - smaller reactor designs, making use of production engineering methods
    - advanced reactor technologies
- the use of production systems for nuclear construction.

Nuclear Construction Costs

About 70% of the energy costs for a nuclear project relates to its construction: How much does it cost to construct? How long does it take to build? These are the two main issues to be addressed in making nuclear competitive. In the past, the main ways of tackling cost have been as follows: first, larger and larger reactors, and second, in the East, improved production engineering approaches, including standardization of designs.

Know-how for efficient nuclear construction in the West was lost by lack of use for more than 25 years. The industry was left with economies of scale. Larger units were expected to have lower unit costs. This idea has propelled the industry for 50 years. Reactor sizes increased from 300 to 400 MWe in the 1970s through 900–1,000 MWe in the 1980s to 1,400–1,700 MWe now. The idea originated in coal-fired power stations where the costs of the main equipment—boilers and turbines—did not increase in line with size. But as nuclear power stations became more complex, reactor and turbine equipment made up a smaller part of the overall cost. Now, the evidence for the cost scaling of nuclear power plants is

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less strong. For example, France built 30 900-MWe units in the early 1980s followed by 24 1,200-MWe units, and as reported by its Finance Ministry, very similar but larger units did not cost less. Also, statistical analysis of U.S. and French reactors built since 1980 indicates that though there is a small cost scaling effect, larger units took longer to build, wiping out these apparent savings. The overall effect of the two countervailing effects means that building larger and larger units has not been a route to lower unit cost.

What is the status of large reactor designs: EPR being built in France, Finland, and the United Kingdom; AP1000 in the United States; and APR1400 from South Korea in the United Arab Emirates? Table 1 shows publicly available cost and schedule information on modern Western large reactors. They have very high construction costs and long build schedules—in the case of AP1000 and EPR, much in excess of the original estimates. While these designs are more efficient and should be even safer than older designs, they are just too costly: they have capital costs in excess of US$10,000/kilowatt electrical (kWe); have overly high energy costs—more than US$150/megawatt hour (MWh); and take too long to build: 10+ years. For private investors and utilities, they are too large, too expensive, and too uncertain to consider.

South Korea has been building the same type of reactor for many years—based originally on CE System 80—now developed into APR1400. KEPCO has performed much better by standardizing its design and by retaining the know-how for nuclear construction from a regular sequence of reactor builds. Follow-on units of EPR and AP1000 should benefit from some repetition and construction learning, leading to lower costs. Also, there may be better ways of managing project risk, such as asset return models, which are being investigated. Nevertheless, it is clear that the energy cost of new Western nuclear power is much too high—perhaps treble the raw energy costs (levelized cost of energy) of renewables.

The Nuclear Industry's Response

The nuclear industry's response has been small modular reactors (SMRs), generally 50–500 MWe of power output. These designs have often been developed by new players in the industry or by start-ups funded by private equity. Two very different ways of tackling the cost problem are proposed, using the following:

1) well-understood and proven light-water reactor (LWR) technology, focusing innovation and production engineering methods to raise the productivity of nuclear manufacturing and construction—i.e., conventional SMRs.
2) advanced reactor designs—advanced modular reactors (AMRs)—simplifying the design and the safety case to reduce capital costs.

Both depend on series builds to make their economics competitive. The main application of AMRs is likely to the supply of electricity to the grid. There are other niche applications that will help them get established, such as high temperature industrial heat and hydrogen production, power in remote locations, or even powering direct air capture.

SMR Designs

Within the family of SMRs all based on proven LWR technology, there are two main design strands (OECD 2021) —integral reactors in which the fuel and steam generating equipment are all housed within the reactor pressure vessel. They avoid large bore external piping and the related loss of coolant accidents. Some of these use natural circulation flow, such as NuScale and BWRX-300, allowing them to claim a simplified safety case. But natural circulation cooled reactors are large in size for their relatively small output, somewhat negating these cost benefits. Others, such as NuScale from the United States and NUWARD proposed by EDF, employed an integral design but with pumped coolant flow. NUWARD has been discontinued and is likely to be replaced with a loop arrangement, with steam generators outside the reactor vessel, similar to other SMRs. These conventional but more bulky designs are easier to maintain and are closer to the current reactor experience.

SMRs seek to use their smaller size and production engineering methods to benefit from the larger number of units (the economy of multiples) required to provide the same capacity as a few large reactors. For example, a typical SMR with an output of 300 MWe would require 11 units to provide the same power as Hinckley Point C being built in the United Kingdom. Building these units to a standard design, with the same suppliers and as a linked program, could cut costs substantially—but by how much?

TABLE 1. Recent Western large reactor projects: reported cost and schedule performance.

Project Design	Plan Cost (US$/kWe)	Actual/Est. (US$/kWe)	Plan Years	Actual/ Est. Years
EDF				
EPR Finland Olkiluoto	$2,063	$7,563	5	17
EPR France Flamanville	$2,200	$12,733	5	15
EPR United Kingdom Hinkley C	$6,303	$12,882	6	12
Westinghouse				
AP1000 United States Vogtle	$8,273	$17,727	7	13
KEPCO				
APR1400 United Arab Emirates	$4,643	$6,964	5	9

Est.: estimated.

Squaring the Circle—Smaller Cheaper Reactors

About 70% of the nuclear energy costs result from construction—from capital costs and build duration. Operating costs are less significant, with fuel, waste, and decommissioning unit costs being similar to large reactors. Operating, services, and security unit costs of SMRs can be higher than current designs unless offset by siting several units on the same site where some of these costs can be shared. This is likely to be the norm at least for the early SMR programs.

High-level studies of capital and schedule costs of SMRs on both sides of the Atlantic (Carelli 2010; Roulstone et al. 2020) have considered the economies of multiples—making use of the number of units and the scope for production learning from one reactor system to another. These studies show that SMRs could be competitive with large reactors for high rates of production and for large programs with many standard units.

Studies at Cambridge in the United Kingdom have confirmed this view. They examined the effect of key processes and significant variables on SMR capital costs and hence on energy costs. They show that innovation will be required more in the means of production of SMRs rather than in the technology. LWR technology is well proven with more than 15,000 reactor years of global operating experience. Nuclear safety will always be a top priority, and the high standards of safety will be maintained if SMRs employ the same design methods and reactor technology. SMRs will, however, require a completely different approach to their design and construction.

The breakdown of costs of a typical large reactor in Figure 1 shows that only a minority of overall cost relates to bought-out systems: reactor vessels and equipment, turbine and power conversion, control equipment, and fuel. The majority of costs are site related (more than 60%)—for civil and mechanical construction and related overheads. Looking at the details, indirect labor costs are higher than direct labor costs. These costs reflect the difficulty of construction and the quality standards of nuclear construction.

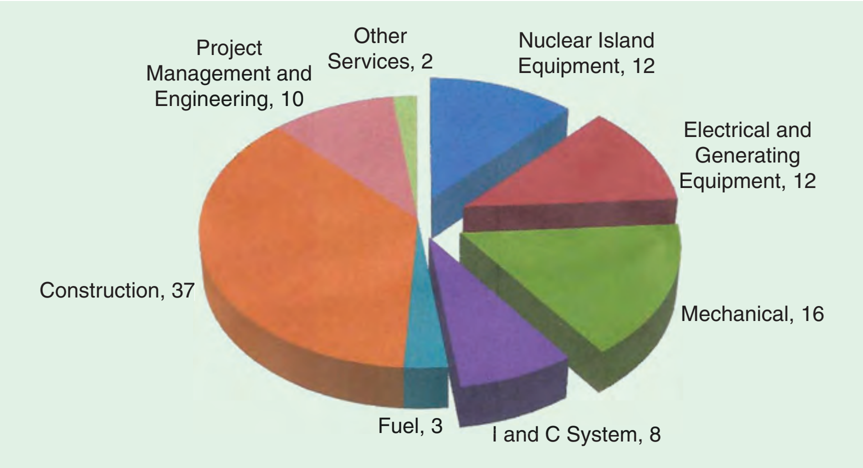

Figure 1. A breakdown of reactor construction cost categories %. (Source: Taken from OECD 7195.)

Industry-standard methods were used to establish a cost baseline for small reactors based on the U.S. costing tool (U.S. Energy Engineers Data Base). Cost data were collected for U.S. nuclear large reactor projects for a period of 10 years up to 1988. The database provides a detailed analysis of about 200 cost centers, including the cost of components, site labor, bulk materials, and overheads.

Power scaling is the idea that for larger sizes of similar components, their cost does not increase at the same rate as their size. This means that unit costs fall as size increases. Power scaling was applied to the large reactor costs using the factor based on experience. These differ for different types of equipment and different commodities. In this case, the cost factors were applied in a more detailed way, at the cost center rather than at the whole plant level as in other studies. This approach provided a factual and transparent baseline for the specific cost of SMRs—built with similar technology and in the same manner as large reactors. As expected, unit costs were higher than large reactors.

There are three broad strategies that can be used to compensate for the small size of SMRs to address their apparent diseconomies of scale: standardization, modularization, and production learning. To ensure that the study was based on experience, the following data from existing power plant construction were used:

- *Cost baseline and breakdown*: U.S. construction Energy Economic Data Base (EEDB)— mean values escalated
- *Build schedule:* Sizewell B large pressurized water reactor (PWR) construction schedule
- *Modularization scheme*: Stone & Webster modularization design study of the 800-MWe three-loop Westinghouse PWR.

Standardization

One might expect that nuclear power plants from a particular vendor would be similar. They are not. Almost none of the 50 reactors built in the United States in the 1980s are the same. This was the result of the way in which nuclear projects are funded and managed—as individual projects. The detailed design of apparently similar units differs because of site conditions, customer requirements, or most often, the different contractors and suppliers used for construction. Detailed design is carried out by contractors for each project during construction. This led to high and variable costs. A more recent example is the U.K. Hinkley Point C project, which is the sixth EPR and is in the fifth year of construction. Nevertheless, large amounts of detailed design work are still being done. This project-by-project approach is wasteful. It slows down construction. It leads to different equipment being installed on each notionally similar power plant. It costs more.

We know from the French nuclear power program and similar more recent projects in Asia that standardization is a powerful idea. Much of the design and safety work does not have to be repeated for each project. More importantly, as the U.K. Energy Technologies Institute (ETI) showed, the standardization of detailed design and construction enables the use of the same supply chain and the same construction teams, reducing costs substantially.

Standardization is not often employed in the nuclear industry because of frequent changes in reactor design and the project-by-project approach, driven by the funding requirements and the desire for localization. A prime example is the U.S. nuclear program. It constructed 100 power reactors with almost none the same. Even when similar reactor designs were employed, there were different contracting teams, different detailed designs, and different construction systems. Costs for the U.S. reactors were very high and highly variable.

The opportunities for standardization are many and diverse. These occur at all stages of construction and commissioning, also subsequently in operation. In other industries, standardization is a prime method of reducing costs. Importantly, it is a prerequisite for the other production engineering strategies.

Modularization

Modularization is common in other industrial sectors; design for modular construction and assembly is used widely in shipbuilding, civil construction, and the oil and gas industries. It is not much used in nuclear power.

The nuclear construction norm is to bring bulk materials—cement, aggregate, reinforcing steel (rebar), piping, and cables—to the site, where they are fashioned into foundations, buildings, process systems, and services, which, together with the specialized vessels, pumps, turbines, and transformers, make up a nuclear plant. This approach is called *stick-built*. Modular design breaks down parts of the overall plant into units that can be built in factories before being transported to the site where they are assembled. The concept seeks both higher construction productivity and shorter site construction schedules. The aim is to transfer work from sites where labor productivity is low—because of congestion, poor working conditions, or a lack of tooling—to factories that provide much better access and working conditions, specialized tooling, and support systems that provide material and components just in time.

Modularization pays off when the work is complex in nature, where it is subject to strict quality requirements, and where it can be repeated again and again for units that can be transported to the site. Successful modularization requires significant up-front design, long-term investment in the supply chain, and a sufficient flow of standard units. Shipbuilding experience shows large productivity gains expressed in the 1–3–8 rule: the production work hours for work in factory conditions, on site, and in situ.

The large size of current reactor designs together with their infrequent project-by-project approach means that either modularization for large reactors is difficult or it fails to pay back its investment. Westinghouse's experience of modularization with AP1000 at Vogtle has not been successful, perhaps because of its lack of experience in modular design and build. Also, it did not have consecutive projects on which to first learn lessons and then deliver the savings. Hitachi has shown the benefits of partial on-site modularization for their large advanced boiling water reactor designs. Over four projects, they achieved both shorter construction schedules and much reduced site construction labor costs.

Modularization both improves direct labor productivity and reduces build duration. The size of the benefit depends on the ability to break the design down into modules that can be fabricated, transported, and then assembled in situ. In this study of modularization, the focus was on factory-built rather than site-built modules: hence the importance of transportation as a constraining factor. AP1000 construction projects have shown that the size of large reactors makes off-site modularization much more difficult. Large reactor modules are bulky and very heavy, making them difficult to transport by road because many sites are not accessible either by river or by sea.

SMRs have a better potential for modularization because of their smaller size. Our study considered a detailed breakdown of the reactor equipment and buildings into modules using the earlier Stone & Webster modularization exercise as a template. The feasibility of transporting modules was assessed using the transport constraints for U.K. roads, which are similar to those of Europe and more restrictive than those for the United States and Canada. Five different categories of modules that cover most of the site work were considered. As the reactor size becomes smaller, more modules can be transported; see Figure 2, which shows the degree of modularization (DoM)—the share of the category by cost—for the different types of the module versus reactor size.

There is a tradeoff between making modules smaller for transport and the increased amount of assembly work required for the larger number of smaller modules. The share of modularization is also affected by the type of modules considered. For example, large concrete and liner modules are more difficult to modularize and less economical to produce off site than mechanical modules. For some types of modules, only a small proportion can be transported due to either size or weight constraints, and for others, the quantity of modules that can be transported is strongly dependent on reactor size. This analysis of transport constraints shows that SMRs with sizes below 450 MWe are better able to achieve high degrees of modularization (60% or more) than larger reactors.

Module size affects the schedule improvement from modularization. In this study and a similar U.S. study of a Westinghouse SMR where much of the plant was modularized, the construction schedule was shortened significantly, even taking into account the added preparation and the module assembly time.

Taken together, the productivity improvements from offsite manufacture and the economic effects of reducing the length of build schedules can be large. Figure 3 shows the total cost of construction, including interest during construction TCIC at 7.8% per annum. The baseline (top line in light red) is for a nonmodular stick-built approach. This line shows the effect of economies of scale for conventional build—as reactor size reduces, TCIC increases for smaller units. Stick-built SMRs are likely to cost more than stick-built large reactors.

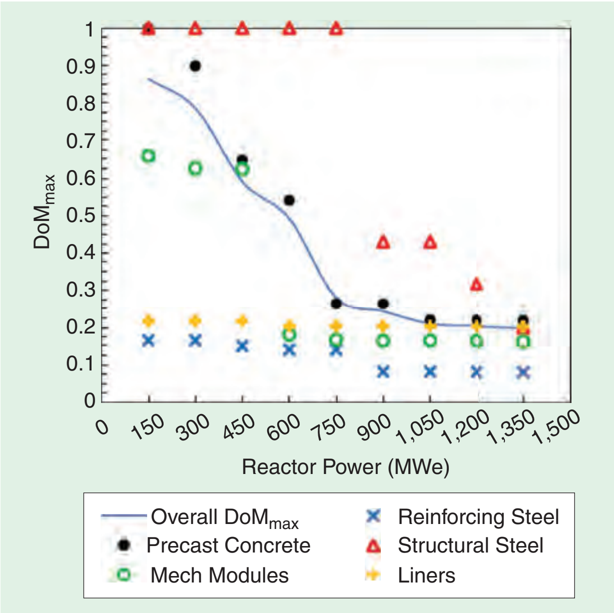

Figure 2. Feasible degrees of modularization for different module types versus reactor output (Roulstone et al. 2020).

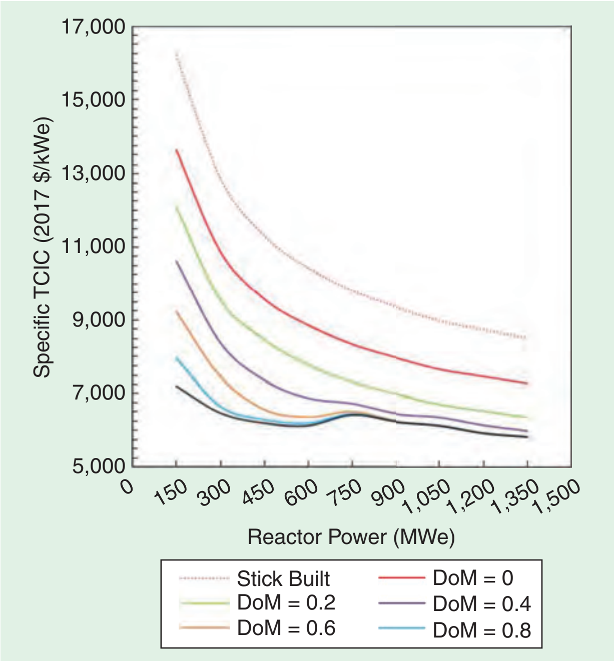

Figure 3. The TCIC for different degrees of modularization versus reactor output (Roulstone et al. 2020).

Increasing levels of modularization DoM, together with the cost reductions from production learning over a 10-GW program of build, allow construction costs to be reduced until the limit of modularization is reached—set by the transport constraints. Improvements in total capital cost are possible even for low levels of modularization mainly due to the shortening of the build schedule and resulting lower overhead and interest costs. For higher levels of modularization, significant reductions in costs are possible but only for reactor sizes smaller than 500 MWe. The minimum cost occurs between 300 and 500 MWe for a DoM of more than 0.6.

Production Learning

Improved productivity through production learning was first noticed in the production of aircraft in the 1930s. Production of the same type of item, component, or system leads to lower labor costs as numbers increase. Subsequently, this idea has been applied to factory-made equipment across almost all industrial sectors. It has led to huge reductions in cost. Production learning is at the heart of the economic revolution in manufactured goods and systems that has been seen everywhere and during the whole of the 20th century (Figure 4).

Reductions in unit cost as production numbers increase result are known as *production learning*. This is the norm in almost all industries. Production learning, sometimes called *learning by doing*, results from improvements in tooling and manufacturing processes and operations. Better practices and related higher productivity are transferred from the initial units to later ones, driven by the need to compete.

Evidence from the energy industry shows that learning is present in all sectors, with a rates learning (cost reduction for a doubling of volume) of 15–20%—except nuclear. This absence is at the root of nuclear power's long-term lack of economic competitiveness. The causes are a lack of design standardization, the small volumes of production, and one-off site-based construction with long periods between projects, when learning is lost.

Figure 4. A production assembly line for gas turbines.

SMRs, designed for modularization and for high degrees of factory build, have the scope for and can access savings from production learning. Rather than perhaps 30% of the overall cost being made in factories for a stick-built reactor, this could be as high as 60% for SMRs. Also, the larger numbers associated with their small size encourage production learning through higher production volumes, and importantly, increased production rates.

The studies used models of production learning applicable to large low-rate production derived from aircraft manufacture but calibrated to the limited nuclear data. We looked at the effect of program scale, production rate, and supply chain configuration on SMR economics: in this case, a 250-MWe reactor system in Figure 5, which shows the total cost of construction ($/kWe) including interest at 9.6% and 2018 prices for a 10-year program of standard builds. The study identified US$6,600/kWe (TCIC) as the measure of energy cost parity with a large reactor such as AP1000.

Small programs of 5 GW (20 units in total) over 10 years (2 units pa) may never achieve cost parity. The higher production numbers and production rate need 4 and 8 units pa to ensure that SMRs can fully offset the economies of scale enjoyed by larger reactors. This also shows the importance of supply chain configuration. Production learning effects were strongest when the supply chain was stable, well aligned, and with incentives both for continuous cost improvement and for sharing this between suppliers and reactor vendors.

These results provide evidence of the scale and rate of build required for a successful SMR program. They are similar to those of the earlier study of SMR economics by the University of Chicago.

Economic Comparisons

These analyses have shown that SMRs can be competitive with large reactors. Can they go further and be competitive with other forms of zero-carbon energy? Can the techniques of standardization, modularization, and production learning reduce costs to match the energy costs of renewables?

This question is in two parts.

1) How low could SMR total capital costs be reduced?
2) How do SMRs compare with the future costs of renewables, including their system costs?

The breakdown of total cost, including interest during construction (TCIC) for a 250-MWe SMR in Figure 6, shows on the left-hand side that a stick-built SMR, constructed as a one-off project, would cost more than US$14,000/kWe compared with an equivalent figure for a large reactor of just over US$8,000/kWe. Applying the principles of standardization and modularization with the linked schedule gains would reduce total capital costs by 58% to a level where they are competitive with a large reactor on a first-of-a-series basis (i.e., ignoring, in both cases, first-of-class costs). Production learning for a 10-GW program produced at 8 units pa would further reduce capital costs to below US$4,000/kWe, which is equivalent to an energy cost [levelized cost of electricity (LCOE) at 7%] of US$62/MWh. The production learning contribution is relatively small because of the large modularization savings that had already reduced the direct and indirect labor content by a large amount. If the savings from modularization were found to be lower, the learning-by-doing opportunity would then be larger.

Such an SMR program has large development and first-of-a-kind costs for safety analysis, development, and demonstration, which could be several billion U.S. dollars. Amortizing these initial costs over a 10-GW build program increases the unit capital costs by about 8%, adding a similar amount to the cost of energy.

Looking at the sensitivity of SMR energy costs (LCOE) to discount rate and reactor size, in Figure 7, we see that energy costs could be as low as US$70/MWh at a 7% rate of interest. Also, reactor powers in the range of 250–400 MWe appeared to be optimal. These results indicate that SMRs could be competitive with both large reactors and perhaps also with other zero-carbon sources of electricity.

What is the equivalent figure for renewables? While standalone energy costs for wind and solar are low, both are intermittent. They don't provide energy when the sun is not shining and when the wind is not blowing. For a like-for-like comparison with other types of energy, one needs to include the costs of backup supply and grid reinforcement. Whole system costs are significantly higher when renewables supply more than half of the demand. Additional costs include connection, profile, and backup costs. For example, standalone 2040 U.K. energy costs of renewables are thought to be in the range of US$40–50/MWh. Studies by the U.K. Royal Society (Royal Society 2023) indicate that the additional system costs are in the range of US$40–50/MWh, making system energy costs US$80–100/MWh (at 2021 prices, US$/£1.3). SMRs would therefore be competitive with renewables with costs in this range.

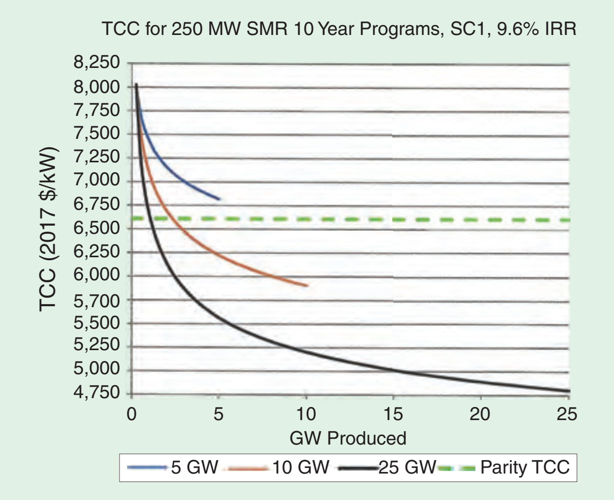

Figure 5. Learning curves for the total cost of construction ($/kWe 2018 prices) learning curves
(Roulstone et al. 2020).

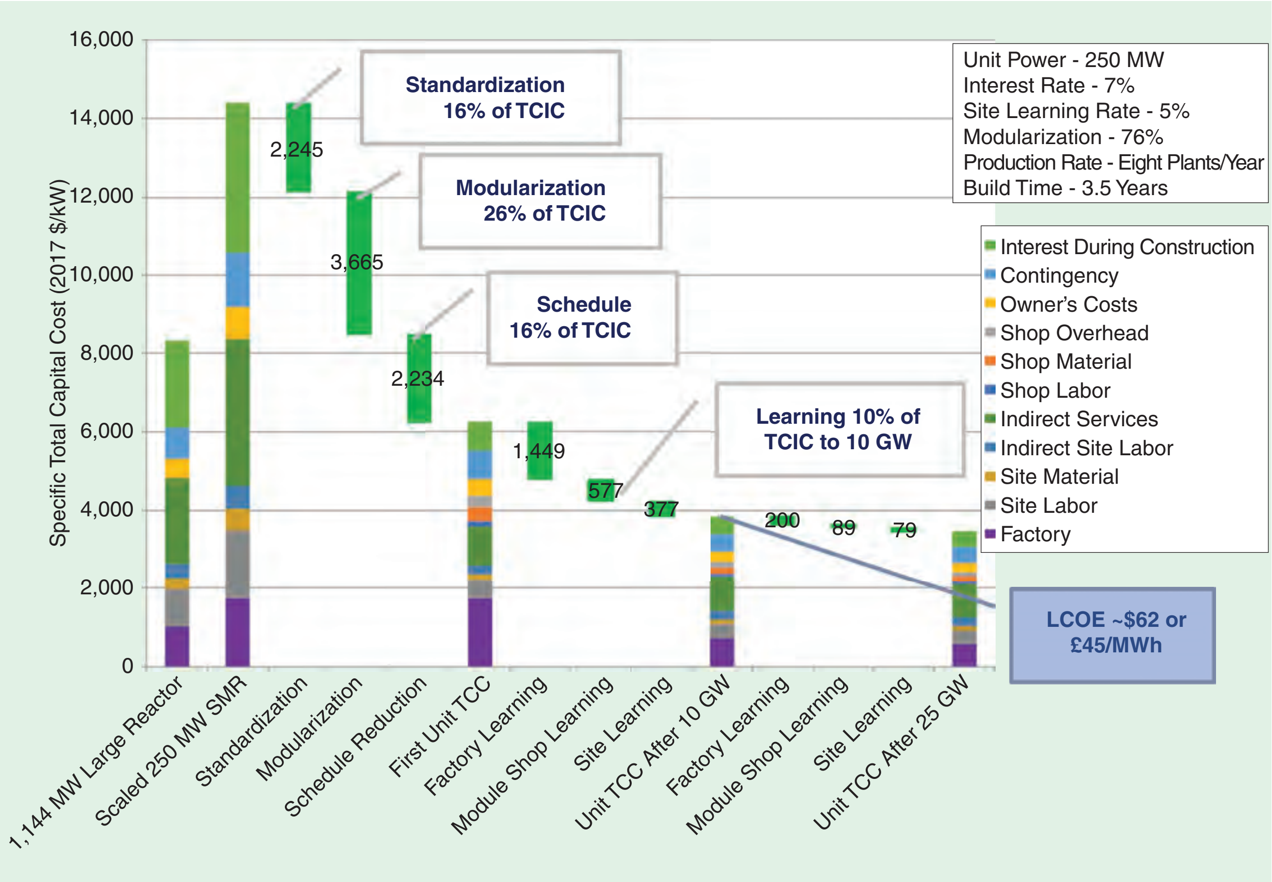

Figure 6. The distribution of total capital costs savings for 250 MW SMR (2018 prices) (Roulstone et al. 2020).

AMRs

AMRs employ a range of nuclear technologies and core coolants (OECD 2021) that have been not used in commercial reactors. They offer more sustainable, proliferation-resistant, safer, and more competitive nuclear energy.

Many AMR designs are proposed. Table 2 compares a selection of the leading designs, listed by coolant type—high-temperature gas, liquid metal, or molten salts. High-temperature gas reactors use carbon dioxide or helium as the coolant. Liquid-metal reactors use sodium, or in some cases, a lead-bismuth mixture, which does not react chemically with water. Various molten salts are proposed based on fluoride salts, often with lithium and/or beryllium to improve neutron economy; otherwise, they use chloride salts.

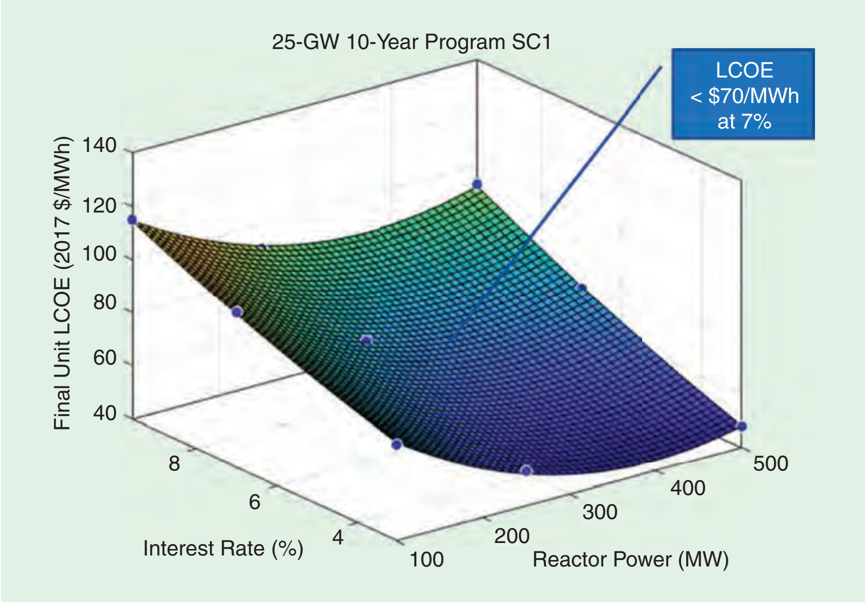

Figure 7. SMR energy costs (2018 prices) versus project interest rate and unit size (Roulstone et al. 2020).

The use of higher fuel enrichment is common in AMRs. Fuel enrichment for thermal neutron systems is 5–8% [low enriched uranium (LEU)], and for fast neutron systems, it is 10–20% (high-assay LEU). In some cases, plutonium is substituted for enriched uranium. Fast neutron reactors can extract much more energy from the fuel with the possibility of breeding huge amounts of fuel, following reprocessing. Some fast reactor designs also use thorium as a fuel with similar objectives. All these AMRs have higher coolant outlet temperatures than current LWRs, leading to higher power conversion efficiencies. These higher temperatures make AMRs attractive for some types of industrial heating, such as chemical processing.

Each design type has ways of simplifying the system design compared with current LWRs, with the aim of much lower capital costs. Because LWRs have high core power densities, they need to be actively cooled after shutdown. The continuing fission product decay-heat can damage or destroy the reactor, as happened in 2011 at Fukushima. Gas-cooled reactors are designed to avoid this problem with their much lower power density. Small gas-cooled reactors using ceramic fuels can cool themselves purely by heat loss from the reactor vessel—as demonstrated recently in China by HTR-PM. This walk-away capability allows the designer to do away with complicated active cooling systems in current designs. However, such designs are constrained to about 200 megawatts thermal (MWt)/100 MWe in size.

Leaders in commercializing gas-cooled AMRs are X-energy, with potential projects in Saskatchewan and Texas, and HTR-PM in China. Also, the Japanese project high-temperature engineering test reactor (HTTR) has demonstrated the highest temperatures (950 °C). It is targeting industrial applications such as steel and hydrogen production.

Both liquid-metal-cooled and molten salt-cooled reactors are unpressurized, hence removing one of the key issues affecting LWRs—coolant leaks leading to core damage. The safety argument is simplified, and no complex coolant injection systems are needed. Both types require higher fuel enrichment. Also, there are potential questions about reactor stability in some configurations. Also, it is not yet clear whether large and expensive containment structures are needed to contain the effects of accidents and to protect the reactor from external threats.

The Gates-funded Natrium fast reactor project at Kemmerer in Wyoming is the most mature liquid-metal-cooled reactor project with work on site underway. It is followed by ARC-100 in New Brunswick. While there is much interest in molten salt-cooled reactors, there is less experience with this technology. Terrestrial Energy of Canada (IMSR) and Moltex (SSR-W) in New Brunswick appear to be the closest to commercial projects.

AMR designers often claim much lower capital costs. Recent INL studies (INL 2024), which used similar methods to those mentioned previously, showed the scope of cost improvement for high-temperature gas and liquid-metal fast reactors using production engineering

TABLE 2. Summary data for representative AMRs and demonstrators.

Design	Type/Fuel	Coolant/Temp	Power (MW)	Status
X-Energy (United States)	Thermal/LEU	Helium/750°C	200 MWt 80 MWe	Active project, Dow Chemicals
HTR-PM (China)	Thermal/LEU	Helium/750°C	250 MWt	Working prototype Twin unit 250 MWe
EH HTGR (Japan/United Kingdom)	Thermal/LEU	Helium/950°C	30 MWt	Demo for larger unit and hydrogen production
Natrium (United States)	Fast/HALEU	Sodium/510°C	345 MWe	Active project, Wyoming
ARC-100 (Canada)	Fast/HALEU	Sodium/510°C	286 MWt 100 MWe	Design and safety, based on EBRII
W-LFR (United States)	Fast/HALEU or Pu/U	Lead/630°C	950 MWt 400 MWe	Design for prototype
newcleo (Italy/France)	Fast/Pu/U	Lead/550°C	500 MWt 200 MWe	Early design
IMSR (Canada)	Thermal/LEU	FLiBe Salt/585°C	440 MWt 195 MWe	Design and safety, coal repowering
SSR-W (United Kingdom/Canada)	Fast/HALEU or Pu/U	Cl Salt/590°C	750 MWt 350 MWe	Design and safety, New Brunswick project
Kairos (United States)	Thermal/HALEU	F Salt/585°C	310 MWt 140 MWe	Design and safety
Copenhagen Atomics (Denmark)	Thermal/HALEU/Th	FLi Salt/560°C	100 MWt	Early design, ammonia production
Thorcon (United States)	Thermal/HALEU/Th	FBe Salt/700°C	550 MWt 250 MWe	Design and safety, based on MSRE

methods. These lower cost estimates (US$4,000/kWe in 2050 at current prices) are based on high-level design studies rather than reactors that have been built. They must be tested on fully developed designs that have withstood the challenge of safety regulators and have been constructed and operated as a prototype. Once AMRs have reached this level of maturity, their claims of much lower capital costs will become clearer.

From One-Off Projects to a Production System

If a thorough application of the principles of standardization and modularization provides the opportunity for LWR-based SMRs to be competitive, a question arises: How is this to be accomplished? The SMR concept is more about building a new production process than about new reactor technology. It uses reactor technology, for which there is both extensive experience and a good record of safety. What is new is the following:

- the size of the program and the number of customers to build a viable program (10 GWe)
- the scale of funding (US$1–2 billion per unit), which is capable of being provided by private capital once the build schedule risk is understood
- reactor vendors being responsible for the whole power plant design, controlling design standardization
- suppliers focused on continuous cost reduction over a period of years and a large number of units.

SMR programs will involve radical change for an industry that both is ill prepared and has been weakened by limited funding and low levels of activity for many years. Leadership will need to come from new places and take the industry in new directions, as described by Flyvbjerg and Gardner in *How Big Things Get Done*.

It is the ability to optimize and control the design and construction production system that delivers the improvements in performance. Production systems are used in other sectors to improve the performance of capital goods manufacturing, from ships and aircraft to trucks and cars.

This production system idea is not novel. In the 1990s, British Airports Authority (BAA) developed a production system to deliver Terminal 5 at Heathrow—costing perhaps US$10 billion in today's terms. BAA completed the new terminal on time and close to the budget by using computer-aided engineering, just-in-time delivery, long-term relationships with their suppliers, and production management. The key feature of BAA's approach was that for six years before the start of construction in 2002, they developed their supply chain, the production system, and their own management team. Similarly, Anglian Water adapted the approach for its investment program, making extensive use of modular designs and standard components. Over a period of 10 years, the unit costs of infrastructure fell by

TABLE 3. Characteristics of one-off nuclear projects versus production systems.

	One-Off Projects	Production Systems
Product development	Unique project designs are completed before the supply chain is in place. Suppliers complete detailed engineering during project delivery.	There are standard designs for a series of projects done with the suppliers. The engineering is done by the suppliers working together before construction begins.
Process development	Processes for manufacture and assembly are developed by individual suppliers.	The processes are developed with the product by the integrated team of suppliers.
Supply and logistics	Each supplier is responsible for its own supply and logistics.	The supply and logistics are integrated with the process and provided for all suppliers.
Organization and culture	The fragmented organization is held together by contractual commitments. There is a new organization for every project. Every supplier works to optimize its own outcomes.	The integrated organization is held together by commitments to improve performance. The same organization and supply chain work together and learn from project to project. The whole organization works together to outperform its targets.
Information architecture	Each supplier holds its own information about design and production and guards it for fear of it being used against them.	Common systems provide information about design and production that can be accessed in real time by all suppliers.
Governance and metrics	The vendor's commercial managers coordinate the work through the subcontracts with suppliers. The objective is to deliver a project on time and budget.	An alliance board drawn from the vendor and the suppliers manages the team. The objective is to deliver a series of projects faster, cheaper, and more predictably.
Execution	The execution is heavily focused on scheduling, contracting strategy and management, and risk management and project controls.	Map, model, and control the production system. This uses the five levers of production systems performance: product design, process design, capacity, inventory, and variability.

30%. The approach has been codified as Project 13 (Institution of Civil Engineers 2017).

But before applying the ideas to a program of SMRs, it is important to understand how a production system differs from the current management systems for one-off nuclear projects. The six key features of a successful production system (based on Project 13 principles) are shown in Table 3. It compares the main characteristics of traditional project management with a production management system for a nuclear power program.

Nuclear power is able to address the serious and persistent cost and schedule problems by adopting standard designs and production systems. Combined with programs of reactors designed for modular construction in specialized production facilities, this would enable nuclear power to regain competitiveness and allow it to play a much more significant role in addressing climate change.

The key to making these process changes and delivering attendant benefits lies in reforming the industry—changing the mindset from one project at a time to a series of projects delivered by a production system. Because of the history of poor performance and construction managers' project-based experience, change will not be easy. But it is essential for nuclear to be cost-competitive and to play a meaningful role in future energy.

Conclusion

Nuclear power in the West has economic problems caused by the scale of current projects, their one-off nature, and the lost know-how of nuclear construction. AMRs and SMRs are two very different ways of addressing the cost and build timescale challenges of nuclear power.

AMRs seek to simplify the design and hence the safety case by the use of intrinsic safety features. The success of this approach needs to be demonstrated by building and operating prototype units on which a commercial design will be based. SMRs make use of their smaller size and their higher unit numbers to make use of production engineering methods from other industries to radically reduce capital costs and build durations.

We know that off-site modularization improves labor productivity, cuts build time, and lowers project risk. Modularization effectiveness is dependent on both commodity type and the plant size/output of the reactor system. Large reactors are unable to access many of the modularization benefits because of their size and transport constraints. Their high funding needs often drive them to be built one at a time.

SMRs can have shorter build schedules, and a schedule of three to four years seems possible. Production learning for a large SMR program with a high build rate could reduce capital costs to as low as US$4,200/kWe—with energy costs of US$100/MWh at current prices. This would be competitive with both large reactors built as a program. Also, they would be competitive with renewables—US$98-US$125/MWh, at current prices.

Competitive nuclear power using SMRs appears to be feasible. SMRs have the potential to enable nuclear power to make a much greater difference in climate change, making use of their dependability and zero-carbon output. The questions are now less about the economics of individual projects and more about the establishment of programs of build and about process change in the nuclear industry—the deployment of completely different construction philosophies, production systems, and supply chains. These changes will be a huge challenge for the nuclear industry.

Reactor vendors are developing SMRs, and power utilities are keen to deploy them. However, the willingness of the industry to pursue the production systems on which economic success (and hence funding) depend is less widespread and less assured.

For Further Reading

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