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Small modular reactors

Can building nuclear power become more cost-effective?

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Bracchium

UNIVERSITY OF LEEDS

NUCLEAR AMRC

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Executive summary

This study was commissioned by the Department of Energy and Climate Change (DECC) as part of a technical economic assessment of nuclear small modular reactors (SMRs). Like many new technologies, the expected cost of the first of a kind (FOAK) SMR will be higher than that of more mature existing nuclear technologies. This study looks at the opportunities to reduce the cost of nuclear build, as well as the cost of operation, and the extent to which SMRs can become cost-effective.

There are three key findings from the study:

By manufacturing 10 units per annum, SMRs could achieve levelised cost parity with large reactors at 5 gigawatts electrical (GWe) of total deployment:

- Substantial capital expenditure (capex) savings come from moving build activity away from a construction site (where the plant will ultimately be situated) and into higher productivity factories, where serial manufacture promotes improved effectiveness and efficiency through learning by doing.
- The effect of learning has the potential to reduce the capex of SMRs by 5% to 10% per doubling of production; the potential rate of learning for large reactors is 1% to 5%, due to lower proportions of factory build and lower production volumes.
- An 8% learning rate for SMRs will deliver 20% levelised cost reductions, achieving cost parity (based on levelised cost of electricity - LCOE) with large reactors at 5GWe of cumulative deployment, when comparing a generic SMR with a generic nth of a kind (NOAK) large reactor (excluding nonrecurring costs such as the Generic Design Assessment - GDA). At a learning rate of 5%, parity will not occur until after 15GWe, while at 10%, it will be achieved at approximately 2GWe.
- Stronger rates of learning (8% or more) assume a robust delivery programme with production in volume, design standardisation, modularisation and a consistent supply chain. Modularisation, manufacturing and assembly should be considered from the outset so that the benefits can be realised in full.

SMRs offer construction schedules of three to four years, with improved certainty of the schedule duration compared with large reactors:

- Construction schedule durations have been reduced by a year for large reactors built repeatedly to a single design and making use of modularisation, advanced construction methods and a consistent construction supply chain.
- Construction schedule lengths of three to four years are expected to be achievable for an SMR unit after the FOAK (with an extra year for the FOAK); for large reactors, this is considerably longer.
- Schedule improvements are driven by a reduction in scale, an increase in modularisation and factory build, and learning through experience.

One-off capex reductions of up to a further 20% can be achieved for SMRs:

- Additional cost savings are driven by the application of methods such as building information modelling (BIM), increased modularisation and factory build, use of advanced manufacturing techniques and processes, and a strategic decision to install multiple reactors on a single site.
- SMRs can achieve capex reductions of up to 20% where the opportunities haven't already been exploited; the potential opportunities for large reactors are not expected to be as high.
- These methods should be considered within a reactor design from the outset in order to realise the savings. Potential cost reductions for large reactors are limited by their increased design maturity and associated lack of design flexibility, as well as by their larger scale and lower proportion of factory build.

In addition to these capex reduction strategies, a number of opportunities exist to achieve savings in the operation of a reactor. While the specific cost of operating SMRs is expected to be higher than large reactors (due to the staffing levels required in order to meet safety regulations), this could be partially offset by their greater potential to benefit from operating cost reductions:

- Operational learning can drive an increase in power availability and the associated revenue generation by up to an estimated 10%. Learning can be accelerated for SMRs, with a higher number of reactor years for the same output as large reactors. The benefits are achieved through standardisation of design, operations and the supply chain. Learning is also fostered by a utility running multiple reactors.
- Furthermore, a decision can be made prior to construction to co-site multiple reactors, with the potential to reduce operating costs by 7% to 14%. The possibility of operating multiple reactors from a single control room (shared controls) can also offer a means of delivering additional savings over and above this, if the safety case can be proven.

An important driver for the requirement for SMRs is the changing shape of the UK's national grid, specifically with the planned closure of thermal power stations. These currently play a role in adapting to the changing power output from intermittent renewables. Consequently, a much greater range of load balancing power capacity will be required in 2030. Nuclear plants that currently expect to run as base-load power will require additional support or incentives to operate at reduced loads. The relative ability of SMRs to vary their power output (to 'load follow') has been assessed in comparison with large reactors:

- It is expected that SMRs will be at least as able to load follow – varying output by at least 5% of maximum power per minute, with a potential increase in power range – due to their inherent technical features (lower core power densities and shorter cores).
- SMRs also have the potential for more flexibility across a fleet through taking one or more reactors offline while keeping the rest in operation (though restarting the reactors may take considerable time).

With the change from delivering large reactors as construction projects to the serial manufacture of SMRs, the UK has an opportunity to develop 55% to 70% of the supply chain, with a value of 55% to 70% of capex. Building on existing capability and capacity in nuclear and across other industries, the UK could become competitive and capture substantial value. It would require action by both the UK Government and industry to maximise this.

There are substantial challenges in relation to deploying an SMR in the UK, and demonstrating its cost effectiveness, by 2030:

- Technical readiness of the vendors' designs
- Progressing the licensing of designs through the GDA process of the Office for Nuclear Regulation (ONR)
- Costs associated with bringing an SMR design to market
- UK supply chain capability and capacity limitations
- Achieving the optimal conditions for NOAK cost reduction

In order to realise the potential of SMRs in the UK, and to ensure that they are deployed quickly, an integrated development programme must be designed covering FOAK and series production of NOAK. The UK Government, utilities, the ONR, SMR vendors and the supply chain all have an important role to play.

An integrated FOAK to NOAK programme, with a view to realising long-term cost reduction, must commence in advance of the GDA (the regulatory process will be a key factor in determining the overall length of the programme) so that the extensive planning activities can be completed. A robust road map is needed to define key activities. These will include:

- Agreeing an investment strategy to help to ensure industry and vendor readiness
- Producing a utility strategy
- Developing a clear approach for taking designs through the assessment process

Companies also need to build project plans that can secure financial backing in order to deploy a new nuclear build programme based on SMRs and meet the UK Government's energy and climate change objectives.

SMRs in brief

First SMR is 30% more costly

The LCOE for the first SMR will be 30% more than for a NOAK large reactor (excluding GDA costs).

Cost parity could be achieved at 5GWe

LCOE parity with a NOAK large reactor could be achieved at 5GWe of deployment, assuming factory build of 10 units a year.

Serial manufacture can drive down cost with 8% learning rate

Capex can be reduced by a rate of 8% (with a range of 5% to 10%) for each cumulative doubling of factory production of SMRs.

Construction schedule is reduced to three to four years

SMRs offer a shorter construction schedule (three to four years) than that expected for UK large reactors.

Up to a further 20% one-off capex savings

The application of advanced techniques and processes and co-siting of reactors can further reduce SMR capex.

Higher operating costs could be offset

Operational efficiencies could offset the higher operating costs expected for SMRs.

SMRs have ability to vary power output

SMRs can offer improved load following ability in comparison with large reactors, although it is not economical within the current market.

UK could develop 70% of supply chain

Action can be taken to capitalise on the SMR manufacturing supply chain, with a potential value of 70% of capex.

SMR programme

A robust, integrated development programme needs to be initiated prior to the GDA in order for SMRs to be commercially deployable by 2030.

Contents

1 Context: UK nuclear power in 2016 and beyond

- Today, 18% of the UK's electricity is supplied by nuclear power generation, of which up to 85% is likely to be shut down by 2030.
- Sixty-one percent of the UK's electricity currently comes from fossil fuel generation, which is expected to reduce to 25% by 2030[1]; this will be replaced by intermittent renewables, increasing the requirement for a flexible power supply.
- If the UK is to share in the build of nuclear, the supply chain will need to be developed, as the last new build was Sizewell B, completed in 1995.

Nuclear power currently provides 18% of the UK's electricity supply[2] through 15 reactors at 8 sites, built between 1967 and 1995[3] (Figure 1). Nuclear is a dependable source of low-carbon, base-load electricity.

No new reactors have been built since then, and the UK's nuclear fleet is ageing: seven of the eight sites are expected to shut down by 2030.

In order to reduce this shortfall, the UK has delivered a number of initiatives to enable the replacement of existing power plants with a new fleet of large reactors. The UK's new nuclear build projects, using existing large reactor technology, have long development times and are yet to have agreed full financing at the time of writing.

Between 1977 and 1990, France showed that a nuclear fleet can be built quickly and relatively cheaply through the repeated build of a consistent reactor design. More recently, Japan and South Korea have had similar success in construction where they each used a standard design and advanced construction techniques.

There are barriers to replicating this success in the UK. Our current plans for building competitive large reactors include multiple designs which will be produced in low volumes by multiple developers.

There is currently considerable interest in new SMR technology, which the industry and others have claimed is a possible alternative for delivering a nuclear programme to increase generating capacity more quickly, with the potential for lower costs and a lower funding risk. While this could be complementary to a large reactor build programme, delivering both simultaneously could impact the potential to make either more cost-effective.

The economics of SMRs are a balance. Cost per megawatt is initially higher due to their smaller size, but capex for each SMR becomes lower with added volume due to factory learning effects. Further assurance that cost reductions will be delivered is required for SMRs to be seen as economically competitive with large reactors and other low-carbon sources of energy: for example, through deployment of a FOAK and the delivery system of the NOAK in the UK (or abroad).

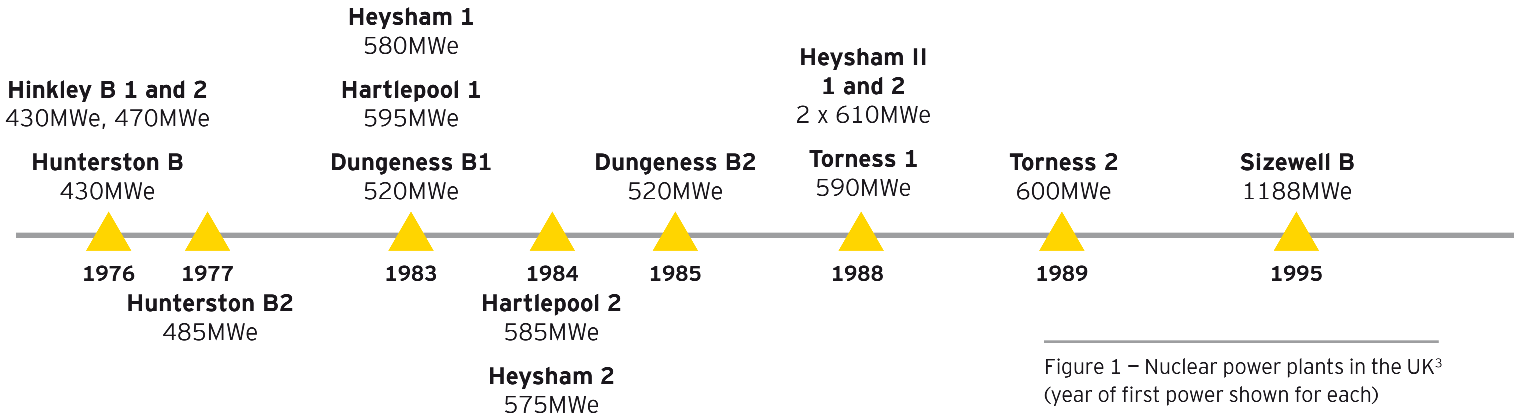


Figure 1 – Nuclear power plants in the UK[3] (year of first power shown for each)

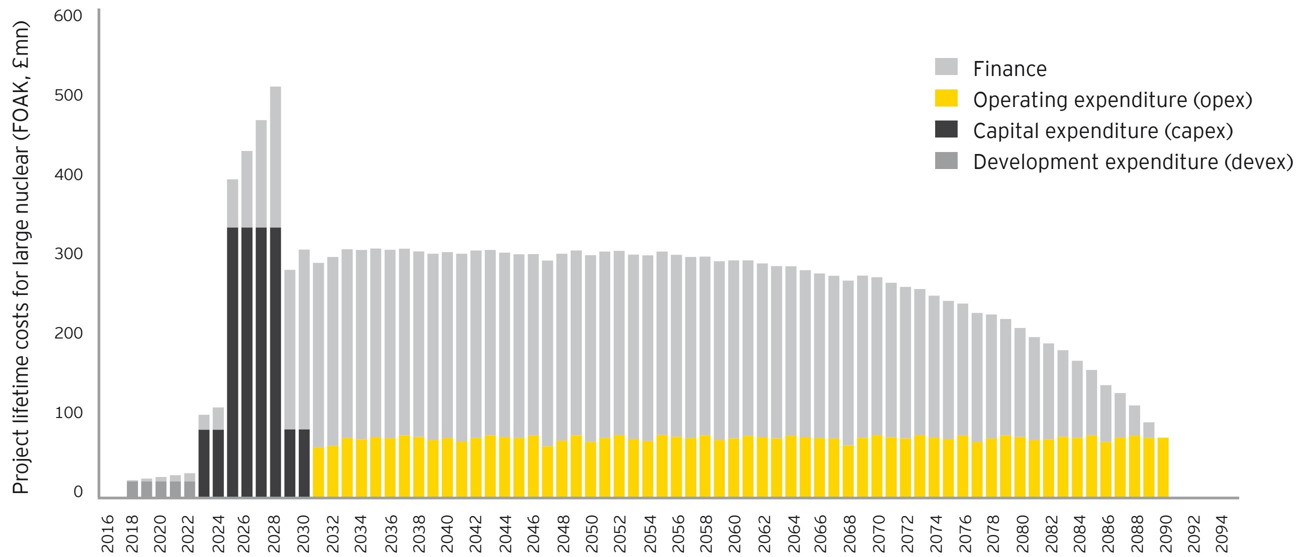


Figure 2 - Breakdown of un-discounted lifetime costs for a general FOAK large reactor[4]

The majority of cost associated with nuclear power is the capex (and the related finance cost) needed to build the asset (Figure 2) which, in the case of a large reactor will last for 60 years.[4] There is potential to address the capex in all nuclear facilities through the application of modularisation and factory build, advanced manufacturing, BIM, advanced construction methods and co-siting of multiple reactors on a single site.

By 2030, there will be different demands of the UK's energy system due to the growth of renewables and reducing fossil fuel generation. This may require increased generating capacity with the ability to vary power output (or load follow) to support increased renewable generation. While new large reactors are all technically capable of load following, within limits, there is a significant economic implication, with costs mostly fixed but generating revenue proportional to the electricity sold. It is expected that SMRs will offer improved load following capabilities compared with large reactors, with increased flexibility across a fleet of multiple SMR units, through using faster rates or a larger range of load following.

Finally, the operational costs per megawatt electrical (MWe) of SMRs may significantly increase in relation to large reactors through diseconomies of scale. This could be mitigated through co-siting and shared control and improved operational performance.

The key question is: to what extent do these opportunities make SMRs an economically viable option?

1. DECC, *'Updated Energy & Emissions Projections'*, Annex J - Total Electricity Generation by Source (2015).
2. World Nuclear Association, *'UK Country Profile'*, www.world-nuclear.org, accessed Jan 2016.
3. EDF Energy, *'Our Power Stations'*, www.edfenergy.com/energy, accessed Feb 2016.
4. DECC, *'Cost of Electric Generation Data'*, provided by DECC, Nov 2015.
5. EDF Energy, *'Nuclear New Build'*, www.edfenergy.com/energy/nuclear-new-build-projects, accessed Jan 2016.

2 Cost: levelised cost reductions of 20% possible for SMRs at 5GWe

- Aviation, shipbuilding and other energy industries have delivered 20% learning rates.
- Nuclear has historically achieved minimal learning through on-site construction of large reactors; Japan and South Korea have improved this, with rates of 5%, through design standardisation, modularisation, advanced construction methods and consistent project delivery.
- Stronger learning of 8% to 10% could be achieved for SMRs, with their greater proportion of factory build (45% to 60%), in comparison with large reactors (30% to 35%).

What is a learning rate?

A progressive increase in efficiency and effectiveness can be achieved by building experience and learning how to perform a process and use tools to deliver a product. The learning rate is the cost reduction realised in this way, for every cumulative doubling of production.

For many years, factories have been shown to achieve high rates of cost reduction across a range of diverse industries and different products.[6] Learning rates, with their compound effect, are a powerful mechanism for sustained manufacturing cost reductions.

Experience shows that optimal conditions lead to learning rates of 20% and above. Figure 3 presents the rates achieved across a variety of different industries. For example, in aircraft manufacturing, learning rates of 18% to 20% have been realised.[7] The aircraft manufacturing industry is characterised by high levels of standardisation and factory build, and production rates of hundreds per annum.

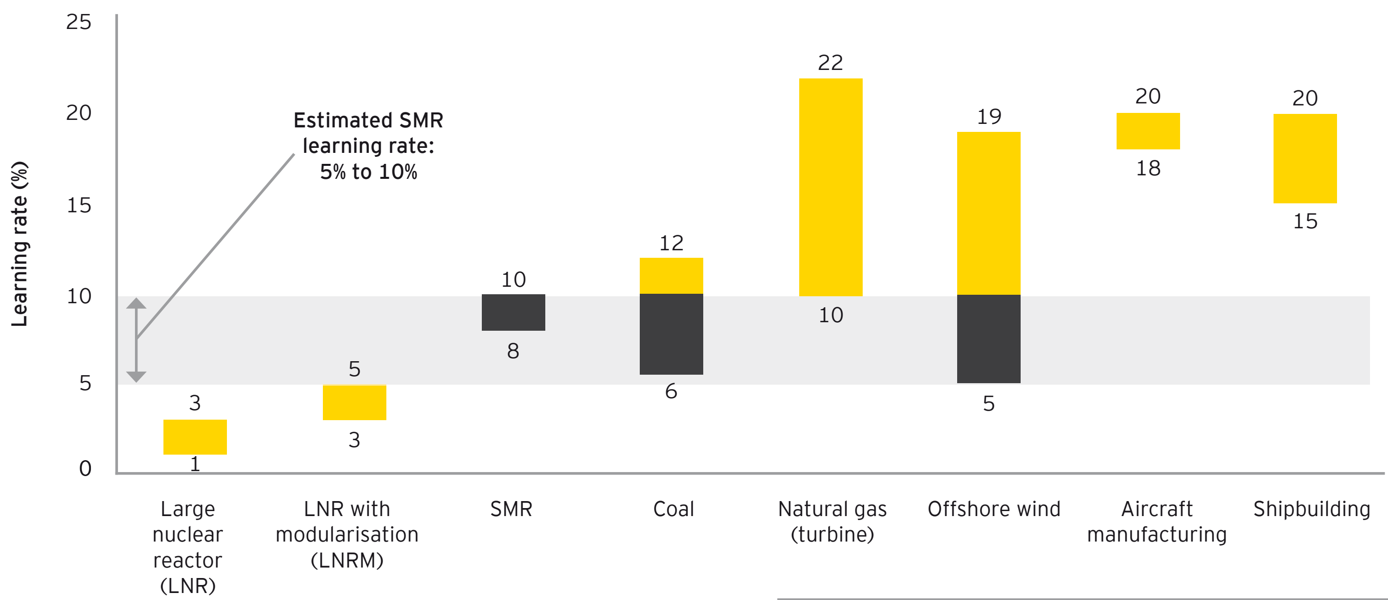
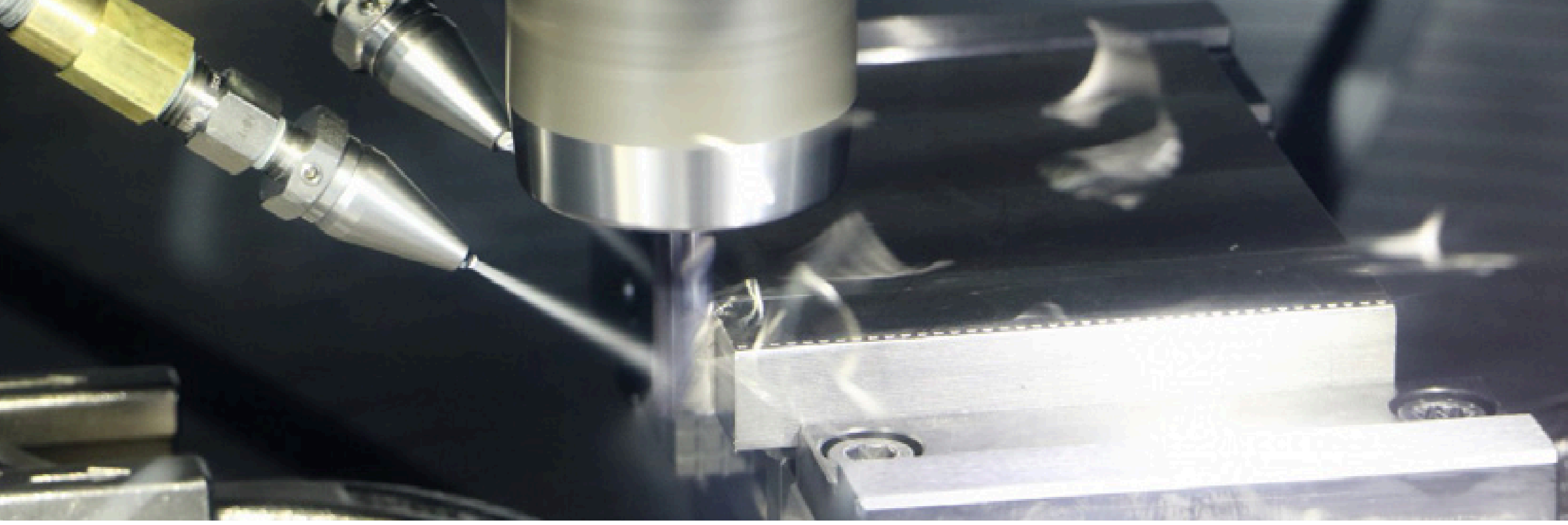


Figure 3 - Learning rate benchmarks from across different industries[9]

A. Both Japan and South Korea used a single design, Advanced Boiling Water Reactor (ABWR) and Pressurised Water Reactor (PWR) respectively



Learning rate	Production rate	Construction and supply chain	Design standardisation	Regulatory stability	Factory manufacturing *(as a proportion of plant cost)*	Industry examples
1% to 3% (Weak)	<1 pa	Local multiple contractors, weak competition	Many local variations	Construction delays	~30%	LNR (US, France)
5%	1 pa	Single consistent supply chain	Single consistent design	Delays uncommon	<45%	LNRM (South Korea, Japan)
7% to 8%	5 to 10 pa	Competition between vendors; vendors use consistent supply chains	Single consistent design	Delays uncommon, with shorter schedules	≥45%	Wind turbines
10% (strong)	≥10 pa	Global competition among a small number of vendors; vendors use consistent supply chains	Small number of designs with large enough market to sustain competition	Delays uncommon, with much shorter construction schedules	≥60%	Aircraft manufacturing

Figure 4 - Key factors for learning in nuclear

Nuclear is, by its nature, more complex than other industries, with large reactors constructed in small production volumes, with long construction schedules and regulatory barriers. The US has seen very low learning rates of approximately 1%.[8A] Much like in the UK, almost all large reactors in the US are different designs, and have been stick-built (primarily site-based construction) using conventional construction methods. Japan and South Korea have improved on this, attaining rates of up to 5% by delivering programmes of multiple large reactors of a standard design[A] with modularisation, built using advanced construction techniques by a consistent project delivery chain.

Figure 4 shows the rates achieved in four different scenarios. While, in principle, the learning rate is constant over time, it is sensitive to factors relating to delivery, and will vary accordingly. Learning is maximised through these five factors: modularisation and factory build, high production rates, standardisation of design and a consistent delivery chain, in a stable regulatory environment. In addition, competitive market conditions provide an incentive to reduce costs and help to ensure savings are passed on to the consumers. The learning rate is agnostic to certain fluctuations in cost – for example, commodity price changes – that may not be within the influence of a delivery programme. While commodity prices may affect cost, learning will still have a relative effect on lowering capex. Based on studies of other energy industries,[8B] no upper threshold has been identified for the maximum level of savings achievable through learning.

6. Wright, *'Factors Affecting the Cost of Airplanes'*, Journal of Aeronautical Sciences 3(4) (1936): 122-128.
7. Chen & Goldberg, *'Small Modular Nuclear Reactors: Parametric Modelling of Integrated Reactor Vessel Manufacture'*, Detailed Analysis Vol 2 ANL (2013).
8A. Cantor & Hewlett, *'Economics of Nuclear Power'*, Power Resources & Energy, 10 (1988): 315-335.
8B. Macdonald & Shrattenholzer, *'Learning Rates for Energy Technologies'*. Energy Policy 29 (2001): 255-261.
9. **Large Nuclear Reactors** - Cantor & Hewlett, *'Economics of Nuclear Power'*, Power Resources & Energy, 10 (1988): 315-335; University of Chicago, *'Economic Future of Nuclear Power'* (2004): Chap 3 & 4; **Large Nuclear Reactors with Modularisation** - Roulstone, *'Making SMRs a Reality'*. Nuclear Insider 5th SMR Conference Charlotte NC Apr (2015); **Small Modular Reactors** (SMR) - Rosner & Goldberg, *'SMR Key to Future of Nuclear Generation in US'*, University of Chicago, EPIC (2011); Waddington, *'Small Modular Reactors (SMR) Feasibility Study'*, NNL, Dec (2014); Boarin, Locatelli, Mancini & Ricotti, *'Financial Case Studies on Small-and Medium-Size Modular Reactors'*, Nuclear Technology 178 (2) (2012): 218-232; **Coal, Offshore Wind and Natural Gas** - Rubin et al, *'A Review of Learning Rates for Electricity Supply Technologies'*, Energy Policy, Vol 8 (2015): 198-218; **Aircraft & Shipbuilding** - Chen & Goldberg, *'Small Modular Nuclear Reactors: Parametric Modelling of Integrated Reactor Vessel Manufacture'*, Detailed Analysis Vol 2 ANL (2015).

Modularisation and factory build. Modularisation entails splitting the plant into packages (modules) that can be manufactured in a factory before being transported to site for assembly. This increases the proportion of the plant that can be built in a controlled, efficient and productive factory environment, where higher learning rates can be achieved.

Modularisation must be completed at the design stage so that the plant is split up into packages suitable for manufacture, transport and assembly. SMRs have a greater proportion of factory build than large reactors for two reasons: their smaller scale and level of modularisation.

High production rates. Production of reactors must be in volume, ideally with 10 or more units built per year, in order to deliver strong learning rates. Any lapse of time between producing each unit must be minimised or avoided altogether.

Production rates are reliant on adequate demand, and the sufficient capability and capacity to fulfil that demand through the supply chain. The lower power output and smaller scale of SMRs lend themselves to higher production rates.

Design standardisation. Learning depends on repeated manufacture of a common or standard design. Without standardising the design and minimising changes during and between builds, manufacturing cost reductions will not be optimised.

Strategic decisions by the UK Government or utilities typically determine whether a standard design will be built in series. Shorter delivery time frames expected for SMRs mean they are likely to be less prone to design changes during construction than large reactors.

Consistent supply chain. Use of a consistent set of organisations and personnel for the delivery of components and modules, and of the plant as a whole, can drive quick and effective learning. A single supply chain for the manufacture and assembly of modules prior to delivery to site helps to ensure that volume effects are fully exploited.

Serial manufacture in factories with a permanent workforce is more conducive to consistency in the supply chain than temporary project organisations set up to deliver site-based construction projects for large reactors. The size of SMRs and the high expected rate and volume of manufacture means that they are suitable for mass production, and would therefore benefit from a consistent supply chain and the learning that would result.

Regulatory stability. Safety regulation is complex and highly technical, and often results in costly and time-consuming processes which may lead to significant design changes or schedule delays.[10]

Although intended to meet similar safety standards (such as International Atomic Energy Agency (IAEA) Safety Principles), there is considerable variation in regulations between countries. This is due to different history, methods and local standards. Increased stability in the regulatory environment helps to minimise the impact of the regulatory process on delivery.

The potential for shorter construction schedules will act in favour of SMRs in comparison with large reactors when it comes to a reduced probability of regulation-driven design changes or hold-ups.

Cost type	LNR	LNRM	SMR Weak *<1 unit per year*	 Central (slow) *5 units per year*	 Central (fast) *≥10 units per year*	 Strong *≥10 units per year*
Proportion of spend[14, 15]						
Factory	30%	35%	45%	45%	45%	60%
Site material	15%	15%	12%	12%	12%	10%
Site labour	55%	50%	43%	43%	43%	30%
Learning rates[11,12,13]						
Factory	6%	8%	8%	12%	15%	15%
Site material	0%	0%	0%	0%	0%	0%
Site labour	2%	4%	3%	3%	3%	4%
Blended learning rates	**3%**	**5%**	**5%**	**7%**	8%	10%

Figure 5 - Bottom-up analysis of learning rates for nuclear[B]

B. Both Japan and South Korea used a single design, ABWR and PWR respectively.

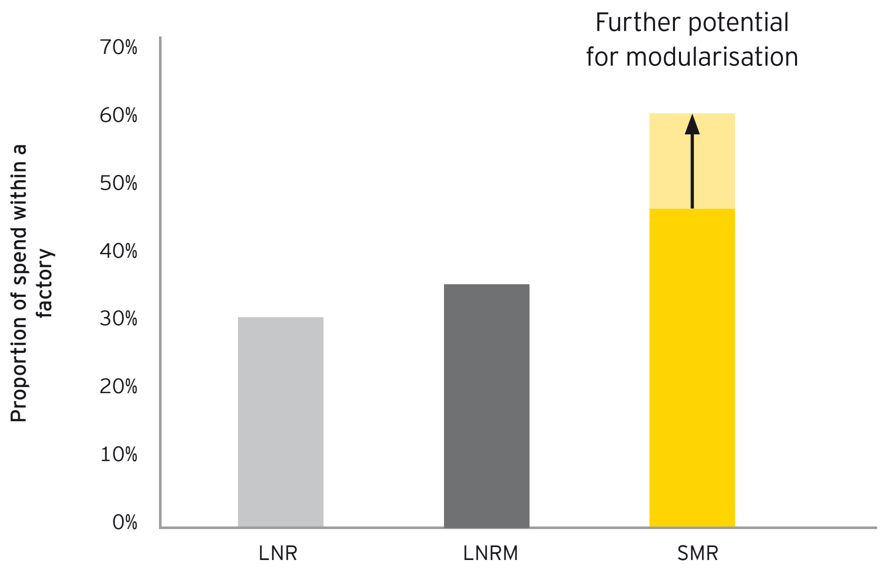


Figure 6 - Proportion of factory build by reactor type

Learning rates

Strong overall rates of learning of 5% to 10% can be achieved in nuclear, specifically for SMRs, while for large reactors, the potential rates are up to 5% with modularisation and up to 3% without. The rates will pertain to an individual reactor design and are not dependent on geographical location of the factory.

The overall learning rates are based on two key elements: the distribution of spend and the learning rates that can be achieved for each type of spend (factory, on-site labour and materials delivered to site). By matching the learning rates with the type of manufacturing or construction work, the overall learning rate for the plant can be calculated. Figure 5 shows the overall learning rates for SMRs in four scenarios – weak, central (slow), central (fast) and strong – in comparison with large reactors with and without modularisation.

- **Factory learning**. Learning rates experienced in a factory environment are considerably higher than those on a construction site due to improved access and better organisation and the ability to standardise production and achieve efficiencies from a consistent workforce. There is evidence from many industries that a well-run factory and supply chain with production rates of more than 10 per year – for example of aircraft and ships – are able to achieve learning rates of at least 15%,[11] as shown in the strong and central (fast) scenario for SMRs. In the weak scenario where the rate of production is low (one unit or less per year), factory learning rates are expected to be 8%.[12] In the central (slow) case, a mid-point of 12% is likely to be achieved.
- **Site labour.** Site-based labour learning in large reactors without modularisation has historically been 2%, which increases to 3% to 4%[12,13] for large reactors with modularisation (as seen in South Korea and Japan). This is due to use of a consistent delivery chain from one project to the next and collaborative working. Given a single, consistent supply chain and regular production volumes (which are both key criteria for delivery of an SMR programme), it is assumed that, for site labour on SMRs, a 3% learning rate is achievable for the low and middle case, and 4% in the high case.
- **Site material.** For the volumes being considered, the learning rates for materials are expected to be negligible.[12] Material prices are expected to be affected more by global prices of basic commodities such as steel, copper and cement.

SMRs will have a greater proportion of spend in a factory than large reactors (see Figure 5): they tend to have a higher proportion of their cost in the reactor vessels and systems, and have more of their systems designed for and made in factories. By scaling factory costs for a large reactor, it can be demonstrated that, based on a typical 100MWe SMR, 45%[14] of the plant can be factory built (as per the weak case). Designing safety and supporting systems for manufacture and supply as modules can increase this factory cost share.

10. Sainati, Locatelli & Brookes, '*Small Modular Reactors: Licensing Constraints and the Way Forward*', Energy 82 (2015): 1092-1095.
11. Quaterman Lee. P.E. Strategos inc, '*Experience & Learning Curves in Manufacturing*' (2014).
12. Delene & Hudson, '*Cost Estimate Guidelines for Advanced Nuclear Power Technologies*', ORNL TM-10071- R3 (1993).
13. EMWG, '*Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*', Rev 4.2 Sept (2007).
14. Cantor & Hewlett, '*Economics of Nuclear Power*', Power Resources & Energy, 10 (1988): 315-335.

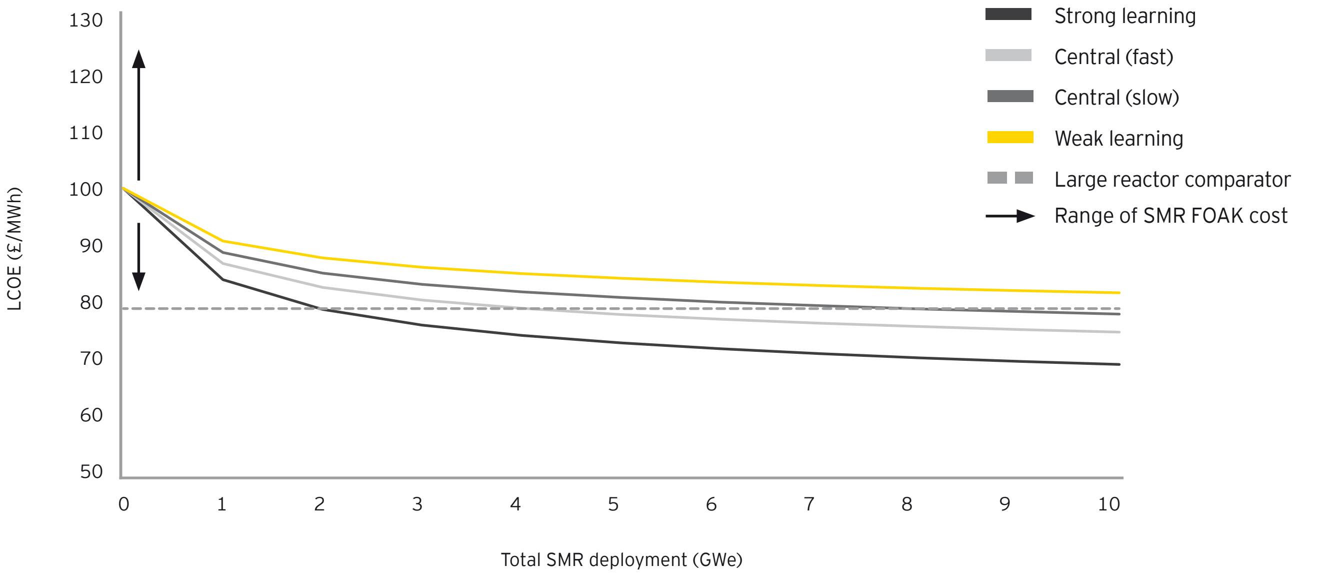


Figure 7 - The effect of learning on SMR LCOE[C]

The high scenario considers a greater application of modularisation and factory manufacture, with a further 15% of the plant costs being translated to factory manufacture, making a total of 60%[15] of the overall cost being factory based. Consequently, SMRs benefit most from the favourable factory learning rate. Up to 30% of a large reactor without modularisation can be factory built; 35% for a large reactor with modularisation.[15] Figure 9 shows an indicative list of components for each reactor type that can be built in a factory. In addition, a higher number of SMR units are required for each gigawatt of capacity compared with large reactors. This means that SMRs will move along the learning curve faster and therefore achieve greater capex reductions for each additional gigawatt.

Cost parity

A generic NOAK SMR would reach cost parity with a generic large reactor[16] that has a LCOE of £79 per MWh (in 2015 prices) through a 20% cost reduction. The estimated point at which parity is achieved, measured in GWe of total deployment, depends on the extent to which the key factors are optimised and undermining factors mitigated:

- With a central (fast) learning rate of 8%, cost parity occurs at 5GWe, and SMRs become less costly thereafter (Figure 7). This is seen as a plausible target for an SMR deployment programme of more than 10 SMR units (with an indicative total output of around 10GWe per annum) neither exceeding possible demand (if the global market is exploited)[17] nor delivery rates.
- In a central (slow) learning scenario with five units produced per annum and a learning rate of 7%, cost parity is reached at 8GWe.
- At the weak learning rate for SMRs, 5%, cost parity won't be achieved until beyond 15GWe. This is expected to occur if SMRs were to be produced at a rate of one unit or less per annum, similar to small reactors.
- At the strongest rate of learning, 10%, cost parity occurs at 2GWe. To achieve this, modularisation would have to be maximised in order to factory build 60% of the plant and deliver production rates of 10 or more per year.

A programme-based approach is required to increase the benefits associated with learning; it is expected to take

SMRs can reach cost parity with large reactors at 5GWe of total deployment. Through a learning rate of 8%, this is achieved by producing 10 or more per year, with 45% of the plant built in the factory. With production rates of five per year and a 7% learning rate, parity is only achieved at 8GWe.

C. The large reactor comparator is based on assumptions provided by DECC for a second of a kind nuclear plant (as expected for any new large reactor built in 2030). This reflects reduced development costs (due to GDA having already been completed), a three-year reduction in construction duration and a 5% learning rate applied to capex. The 5% may be optimistic, based on the low rates of learning achieved historically.

LNR *30% factory spend*	LNRM *35% factory spend*	SMR *45% factory spend*
▶ Reactor pressure vessels	▶ Reactor pressure vessels	▶ Reactor pressure vessels
▶ Steam generators	▶ Steam generators	▶ Steam generators
▶ Controls	▶ Controls	▶ Controls
▶ Reactor protection system	▶ Reactor protection system	▶ Reactor protection system
▶ Pumps	▶ Pumps	▶ Pumps
▶ Cranes	▶ Cranes	▶ Cranes
▶ Turbine generators	▶ Turbine generators	▶ Turbine generators
▶ Condenser	▶ Condenser	▶ Condenser
	▶ Large mechanical modules	▶ Large mechanical module
		60% factory spend
		▶ Mechanical and electrical modules
		▶ Civil modules
		▶ Safety system modules
		▶ Additional control systems

Figure 9 - Indicative factory built components and modules by reactor type

Please note that, if the key assumptions don't hold (around FOAK SMR, large reactor comparator[C] and the learning rate), SMRs may take significantly longer to achieve cost parity with large reactors. For example, in high and low FOAK SMR scenarios of £124 and £86, cost parity is reached at above 15GWe or 1GWe (see Figure 8).

	FOAK LCOE	Cost parity
High	£124	>15GWe
Medium	£101	5GWe
Low	£86	1GWe

Figure 8 - LCOE cost parity for central fast learning scenario with varying SMR FOAK cost

longer and cost more to design and build the FOAK in order to maximise NOAK cost reductions. We have assumed a reduction in the construction schedule from the second of a kind onwards; taking longer to incorporate learnings from the FOAK plant may impact the LCOE of early plant deployment. An SMR programme, focused on enhancing the five key factors, is required to achieve strong learning rates of 8% to 10%. It is possible that higher levels of learning than 10% could be achieved if the program over delivers on the five key factors, therefore reaching cost parity with large reactors after fewer gigawatts of production. Further considerations of the five key factors are discussed overleaf.

15. OECD 7195, *'Nuclear New Build: Insights into Financing and Project Management for LNR'* (2014); University of Chicago, *'Economic Future of Nuclear Power'* (2004): Chap. 3 & 4.
16. Data provided by DECC.
17. Waddington, *'Small Modular Reactors (SMR) Feasibility Study'*, NNL, Dec (2014).

Modularisation and factory build

Modularisation enables a greater proportion of factory build, which increases the learning rate.

Modularisation is primarily constrained as a result of not being considered early enough, lack of design flexibility, module size, the limitations of transportation to site, supply chain skills, infrastructure and relationships. SMRs offer improved design flexibility in comparison with large reactors due to the maturity of designs and smaller scale:

- Modularisation must be considered at the design stage so the plant can be split up into packages which are capable of being manufactured, transported to site and assembled.
- The level and detail of design required for module manufacture will be much greater than for conventional build in order to take account of:
  - Manufacturing processes and, in many cases, manufacturing sources
  - Size of packages that can be lifted and transported
  - Method and cost of lifting and transportation
  - Module interfaces and assembly on-site
- Success in modularisation will require a different range of design, manufacturing skills and quality standards than those possessed by many of the current site contractors.
- The supply chain will shift from delivering construction projects to manufacturing, as a greater proportion of work is moved away from site and into a factory. This will have implications for the UK supply chain, which are discussed further in Section 7 of this report.
- Stable and long-term supplier relationships will be important in reducing transaction costs, driving down manufacturing costs and reducing lead times.
- There will be extra initial costs for establishing and proving the manufacturing facilities and processes. It is expected these will be recovered through revenue from the modules. The investment case for manufacturing facilities will need to be determined.

Production rates

Higher production rates lead to greater cost reductions resulting from learning.

Production rates are primarily constrained by demand and the supply chain capacity: the scale, power output and significant cost of large reactors limit local and global demand; and the demands of large reactor construction on the supply chain also act as a barrier to building more than one reactor per year.

There is uncertainty around the demand for SMRs, although the UK requires 14GWe[18] of new nuclear by 2035, and potentially more, to make a significant contribution to climate change objectives, of which SMRs could play a significant role. In addition, the National Nuclear Laboratory (NNL) estimates that the potential international demand for SMR nuclear generation could be between 65GWe to 85GWe by 2035[19] (with at least some of this expected to be supplied outside of the UK) if SMRs are proven to be cost-effective. Improved production rates could be supported by demand from another country if the UK makes a decision to enter into a partnership in order to develop an SMR. Climate change requirements for low-carbon energy and heat, as well as for flexible power supply through load following, could support much higher demand forecasts if SMR construction becomes more cost-effective than large reactors.

The ability of the UK to serial manufacture high volumes of SMRs is largely dependent on the supply chain, as well as the associated investment case for establishing further skills and infrastructure.

Design standardisation

Standardisation enables higher production rates of a design.

There are a number of limiting factors relating to design standardisation. While most of these are fixed, the SMRs' reduced construction schedules lend themselves to a lower likelihood of design changes being required during construction than large reactors. The opportunity to co-site more reactors also means that local site conditions and therefore design variations, are likely to be reduced.

18. DECC, '*Updated Energy & Emissions Projections*', Annex J - Total Electricity Generation by Source (2015).
19. Waddington, '*Small Modular Reactors (SMR) Feasibility Study*', NNL, Dec (2014).

Factors include:

- Strategic decisions by the UK Government or a utility may determine whether a consistent reactor design, or multiple different variations, will be built.
- Design standardisation is limited by safety regulations, the requirements of which tend to change over time in order to keep risk as low as reasonably practicable.
- Differences in local site conditions (such as ground conditions and accessibility, and temperature of cooling water) will require a certain level of variation in the reactor design interfaces.
- Technical standards (including design, testing, conventional safety and metric versus imperial measurements) are not consistent across international borders. A single standard would unlock the global market by presenting a common design for a number of countries (for which some variation can be accommodated, such as 50 and 60 hertz power supply).
- Harmonisation of safety regulations across different countries could also enable standardisation. Further regulatory review is required to assess the impact of this, and the extent to which it is achievable.

It is important to note that standardisation introduces a risk of common faults or failures to multiple plants.

Supply chain

Learning, with its associated cost reductions, is only possible with consistency in the supply chain.

Various barriers exist to establishing a consistent supply chain for production of reactors. For example, there are limitations to current UK capacity and capability for both SMRs and large reactors (see Section 7). The size of SMRs and the high expected rate and volume of manufacture mean that they are more suitable for mass production than LNR and would hence benefit from greater supply chain consistency and the learning that would result.

Current construction contracts are typically single project, price driven and often let by competitive tender to local non-specialist contractors. This can negate the learning process, accentuate the interfaces between companies and put the focus on the cost of the task at hand, which acts to undermine the progressive cost reduction. Moreover, local contractors may not have developed the required technical skills for nuclear.

The SMR manufacturing supply chain needs to be established around skills, processes and facilities rather than single company costs as in other industries and sectors, such as aerospace and automotive. Investment is also required in facilities, equipment and processes, which necessitates certainty of demand: customers, volume and rates. The number of factories will be largely dependent on the specialisation of the components or modules.

Regulatory stability

Regulatory stability reduces design change and thus enables higher production rates.

Restrictions on improving regulatory stability include a lack of regulatory harmonisation. SMRs will benefit from reduced probability of design changes, or delays at the hands of the regulator, due to the reduced construction schedules:

- Some stability has been brought about in the UK through a design licence period that usually spans 10 years. While close and early cooperation between the ONR and vendor will help to mitigate delays, it will not necessarily improve stability.
- International harmonisation of safety regulation is not regarded as likely to occur in the foreseeable future. In lieu of this, action could be taken to license an SMR in the UK and another country simultaneously, in order to provide a single design that aligns with regulations in both countries. This will enable deployment of a standardised reactor in both countries, aiding higher volumes and learning rates.

There are also opportunities for delivering one-off cost reductions, besides the progressive savings that can be achieved through learning. The additional savings occur through a change in the way that a product is delivered, such as by applying a new manufacturing process or introducing the use of a new construction approach. These areas of opportunity are discussed in further detail within Section 4.

3 Schedule: an SMR can be built on-site in four years

- For large reactors, repeated build of a single design using modularisation and other advanced construction techniques has been shown to reduce construction schedules by 12 months.
- SMRs are expected to have shorter construction schedules per unit compared with large reactors.
- Three to four years can be achieved after the FOAK if a single SMR design with maximised modularisation is deployed in volume in the UK using advanced construction methods.

Construction schedule length is a key driver of cost within highly complex nuclear programmes. Interest payments, another large proportion of the cost of the plant, are also heavily dependent on the delivery time frames.

Historically, nuclear construction schedules have been very long and fraught with schedule uncertainty.

Construction schedule and cost are reduced by smaller plant size and an increase in the level of standardisation, modularisation and other advanced construction methods (such as open-top and parallel construction). Modularisation, for example, transfers site work off the critical path and into a controlled factory environment.

South Korea and Japan have significantly reduced their large reactor construction schedule:[20]

- In South Korea, the time frame was improved from 66 to 55 months by using a consistent project delivery chain to build a fleet of standardised reactors. Figure 10 shows the schedule for the OPR1000 (Gen II PWR) shortening over time.
- In Japan (ABWR) the construction schedule was improved from 60 to 48 months through progressive improvement in modularisation, scheduling and working practices.

In the US, much like the UK, there is a much higher degree of variation across the designs, and use of conventional construction methods. The average construction schedule has been significantly longer and the schedule variance much greater.

PRIS data (Figure 11) shows a clear correlation between reactor size and construction schedule, with time frames of between 3 to 14 years for large reactor builds around the world. This supports estimates that construction schedules for SMRs can be between three and four years.[20]

The trend lines show different approaches of nuclear build:

- **Japan.** Repeated build of reactors with modularisation using advanced construction techniques and a

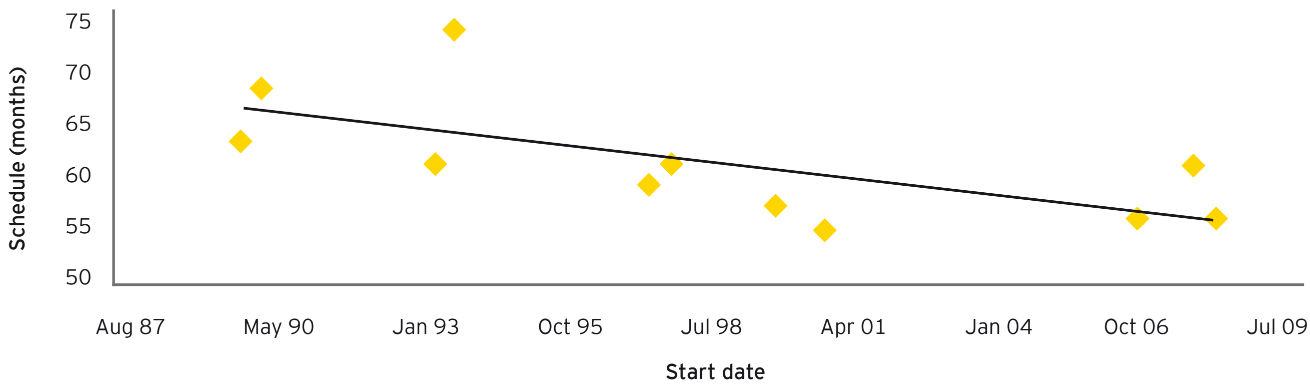


Figure 10 - Construction schedule for South Korean OPR1000[20]

20. IAEA, *'Power Reactor Information System (PRIS) Database Report'* (2015).
21. Rothwell & Ganda, *'Electricity Generating Portfolios with Small Modular Reactors'*. ANL. (2014) pg. 20; Abdullah, *'Expert Assessment of Cost of LWR SMR'*. Carnegie Mellon, PNAS (2013).
Roulstone, *'Making SMRs a reality'*, Nuclear Insider 5th SMR Conference Charlotte NC (2015): April.

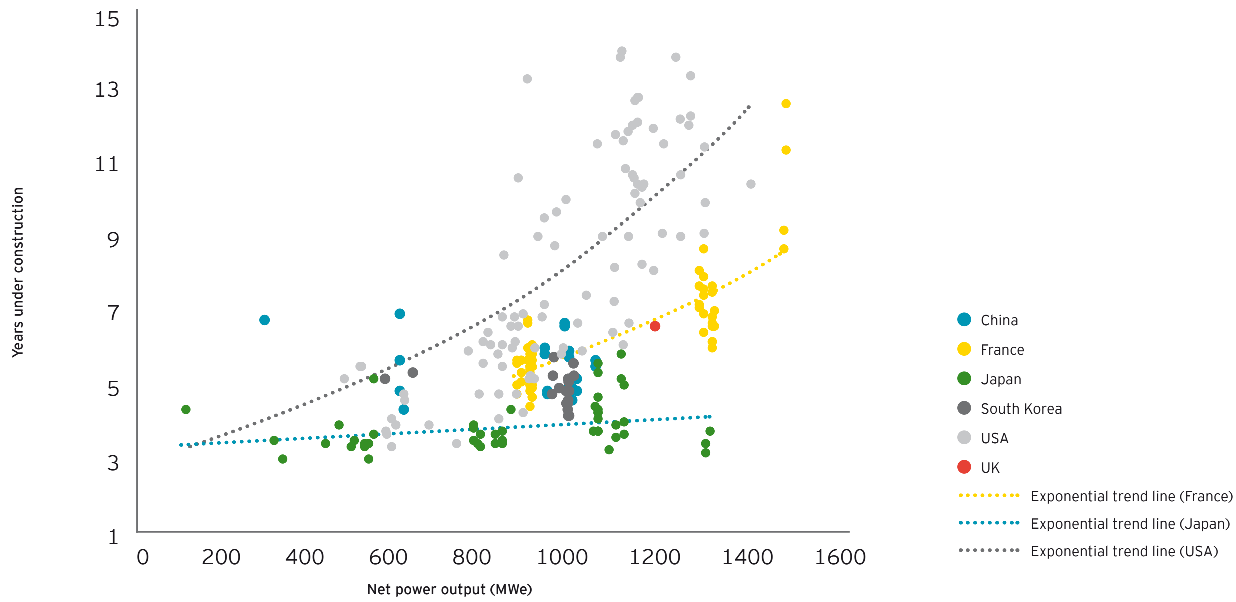


Figure 11 - Effects of size and approach on large reactor (PWR) construction schedules[20]

consistent, integrated project delivery chain, has resulted in an average of three-and-a-half to four-year construction schedule durations. While there is some correlation between reactor size and schedule, this approach has resulted in only slight increases in schedule length for larger reactors.

- **France.** The integrated programme for a single client with co-siting of multiple reactors of the same design on sites has resulted in a rising trend, with an average of around seven years for large reactors.
- **The US.** The strong correlation between reactor size and schedule durations, and high degree of variance, is due to various designs being built across different sites with different supply chains in an uncertain regulatory environment. The average duration ranges from around 7 to 13 years for large reactors, depending on the size.
- **The UK.** Only one PWR has been built: Sizewell B (therefore, there is no trend line). This was built with a similar approach to that taken in the US, and took between six and seven years.

Schedule length is often heavily influenced by regulation. Repeated manufacture of a common design reduces regulatory delays, as occurred in France, South Korea and Japan, as the regulator becomes familiar with the design.

Increased factory production can also reduce regulatory hold points during the build, due to the improved quality and documentation for construction.

Current UK large nuclear construction schedules are expected to be long, with the programme of multiple designs on different sites being similar to the US model.

Research by Rothwell and Ganda (2014) and Abdullah (2013) shows that there is potential for SMRs to achieve a three- to four-year schedule, with estimates ranging from 34 to 40 months.[21] SMRs have a shorter construction schedule (after the FOAK, which is expected to take around a year longer) compared with large reactors, due to their smaller size, combined with the potential for an increase in the level of modularisation and factory build. While the construction schedule of large reactors is longer than for SMRs, they deliver a greater generation capacity per year of build; however, SMRs can be built in parallel to compensate for this.

Only if a single standardised SMR design with maximised modularisation is deployed in volume in the UK, using advanced construction methods, is there potential for these three- to four-year construction schedules, and increased schedule certainty.

4 Capex savings: one-offs of up to a further 20% possible for SMRs

- Nuclear capex can be reduced by up to 20% through:
  - Modularisation and factory build
  - Advanced manufacturing
  - BIM
  - Advanced construction methods
  - Co-siting of multiple reactors
- SMRs have greater potential than large reactors for one-off capex savings as designs are less fixed and, being smaller, are better suited to further modularisation and factory manufacture, as well as to co-siting.
- Potential cost reductions will be small for existing large reactors with their higher levels of design maturity.

One-off capex reductions result from adoption of new manufacturing processes or new tools and techniques proved elsewhere in other countries or other sectors.

For SMRs, benefits of up to 20% can be achieved through five areas of opportunity[D]:

4.1 Modularisation and factory build

4.2 Advanced manufacture

4.3 BIM

4.4 Advanced construction methods

4.5 Co-siting of multiple reactors[E]

A breakdown of the potential cost reductions is shown in Figure 12 (with further details provided in the following sections).

While we have estimated a theoretical cost reduction of up to 32% in aggregate, a saving of up to 20% is considered a more appropriate, conservative estimate for application of all five of these opportunities. This assumes a mid-position for each cost reduction, with co-siting a feature of policy.

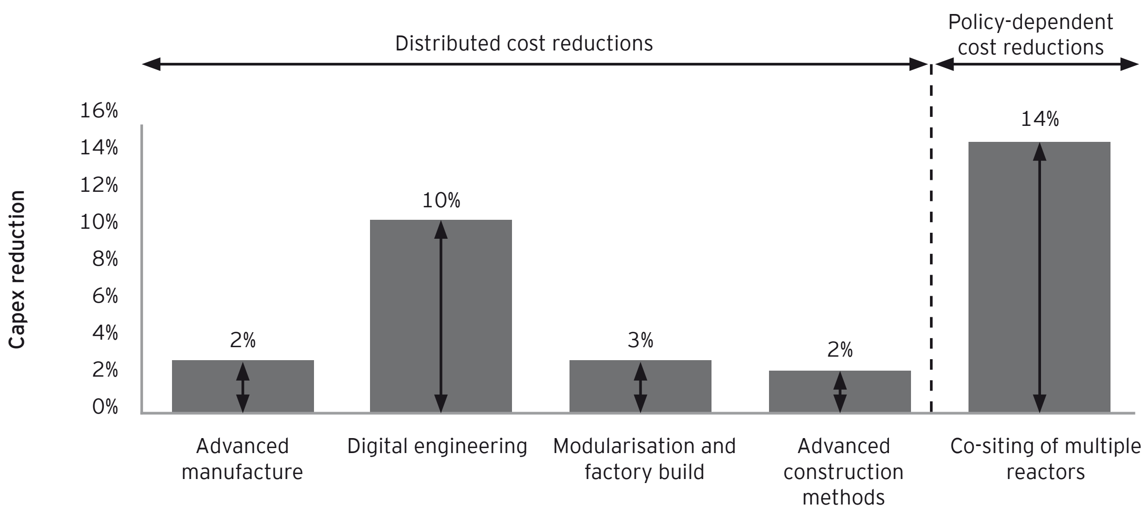


Figure 12 – The potential capex reduction through applying different techniques to SMR[F]

As the maturity of a reactor design increases, the flexibility of design decreases, while level of spend and cost certainty rise. In particular, once the design has been through GDA, any changes may result in substantial additional cost:

- If the one-off capex reduction techniques are applied at the early stages, as is possible for less mature designs, higher cost reductions can be achieved. Consequently, a greater benefit (20%) can be realised for SMRs.
- For mature designs, cost reduction potential decreases. Large reactor designs, which have a high design maturity and therefore high cost certainty, have a far lesser potential for cost savings.

Co-siting can be treated slightly differently to the other four areas, as it relates to a policy decision.

It is uncertain from the SMR vendor responses whether the techniques or processes have been factored into the baseline. In some cases, these may already have been fully applied: for example, most vendors have more than one reactor per site, and are expected to have factored in the associated efficiencies into their baselines. As such, the level of cost reduction is expected to differ with each design, depending on the degree to which the techniques or processes have already been exploited.

In addition to cost reductions, these opportunities can also drive benefits such as scheduling improvements, reductions in delivery risk and quality improvements.

D. The potential cost reduction for large reactors is much less due to their designs being more fixed and their large scale.
E. Co-siting is considered to be different from the other four areas, as realisation of these benefits is dependent on the policy decision to install multiple reactors on the same site.
F. Figures have been rounded.

4.1 Modularisation and factory build

- SMRs can achieve 3% capex savings through labour productivity by moving work from the site and into the factory in modules.
- Success factors include designing the plant for a high level of modularisation early in the design phase using BIM.

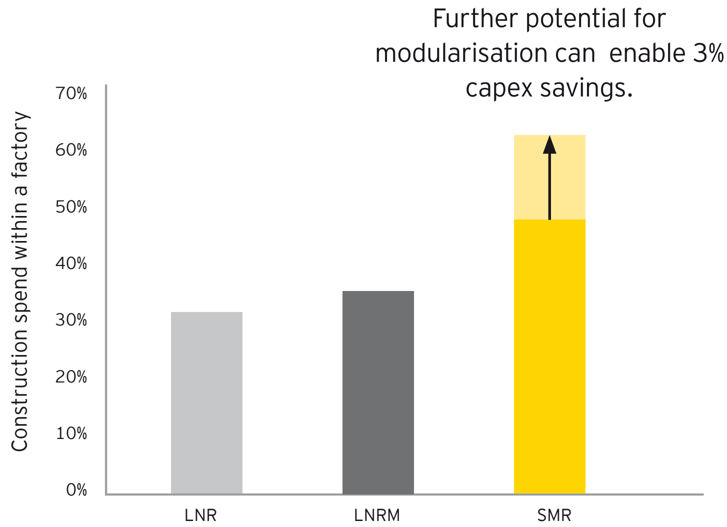


Figure 13 - Percentage of factory construction for different reactor types

Modularisation is a way of simplifying construction by splitting the plant up into packages (modules) which can be factory manufactured, transported to site and assembled in situ, (or close by in an assembly area before being installed). In addition to the progressive capex reductions achieved in a factory through learning (discussed in Section 2), one-off capex savings can be realised as a result of the increase in labour productivity. The General Dynamics Electric Boat case study (on the next page) demonstrates the benefits of modularisation through both learning and one-off capex savings.

The industry is beginning to understand the importance of off-site build. The development of BIM and precision construction techniques has encouraged other industries to use modularisation, which has enabled consideration of this in nuclear. It has been used with success in many industries in the UK and around the world, including automotive, aerospace, ship building and other parts of the construction industry.

Modularisation has been implemented, to some extent, in large reactors on a global level. For example, in Japan and South Korea, it has been shown as a powerful method of reducing the construction schedule, which is a key driver of overall capex. Historically, modularisation has not been exploited within nuclear power plants in the UK. Instead, these have been stick-built on-site, resulting in long build schedules.

Modularisation reduces cost and delivery risk by reducing work on complex construction sites and increasing the percentage of work within a controlled, efficient and productive factory. Production of modules off-site within nuclear-certified factories can reduce the risk of delivery delays due to the improved control and management.

Factories offer:

- A more consistent, permanent workforce
- Improved management and control of processes and activities
- Reduced delivery risk where modules arrive on time at site to a prescribed quality
- Potential to shorten the critical path and reduce site congestion
- Opportunity to apply advanced manufacturing techniques which cannot be applied on-site (these cost reductions are discussed in Section 4.2)

In this way, 20% one-off savings can be achieved on the cost of work moved into a factory.[22] SMRs are expected to be able to increase the proportion of factory build by 15% (from 45% to 60% as shown in Figure 13) through further mechanical and electrical modules, civil modules, safety system modules and additional control system modules. It is therefore estimated that SMRs can achieve a 3% one-off capex saving.

What is modularisation?

Modularisation is a way of simplifying construction by splitting the plant up into packages (modules) which can be factory-manufactured, transported to site and assembled in situ (or close by in an assembly area before being installed).

Case study: General Dynamics Electric Boat[23]

The effective integration of modular designs, advanced manufacturing and construction techniques has proven to be successful in the nuclear defence industry.

In order to maintain affordability, the Virginia-class programme for US Navy attack submarines had to reduce its costs and schedules aggressively. General Dynamics Electric Boat (GDEB) developed a small modular nuclear reactor for use in the Virginia Class through the use of advanced manufacturing, modularisation and construction principles.

General Dynamics attributed the success of GDEB to the implementation of a manufacturing assembly plan which was developed early in the design process that established the construction schedule. This process reduced the number of design changes identified during construction and helped to support the rapid assessment of design concepts to facilitate cost-effective construction.

The redesign of submarine proportions to optimise modularisation, the implementation of new fabrication and manufacturing processes, and the movement of fabrication from a temporary facility on-site to a dedicated factory were stated as other enablers that allowed for cost-saving opportunities.

As a result, the build time was reduced from 84 to 60 months per submarine (28.6%) and the cost per hull was reduced from US$2.4bn to US$2.0bn (16.7%). The latest ship produced by GDEB was delivered eight months ahead of schedule, US $90mn under budget and with 95% modular construction.

22. Hesler W.E., *'Modular Design: Where it Fits'*, Chemical Engineering, Prog 86 (10), 76 (1990); Shelly, S., *'Making Inroads with Modular Construction, Chemical Engineering'*, Vol. 97 (1990).
23. Moody, J., *'General Dynamics Electric Boat'*, www.platts.com (2010), accessed Nov 2015.

Some smaller benefits may be achievable for large reactors where modularisation has not been fully exploited. The one-off benefits of modularisation for large reactors are limited by the size of components and maturity of design (retro-fit of modularisation is unlikely to be cost-effective).

Modularisation requires a far greater level and detail of design than for conventional build, and should consider manufacture, transportation, lifting and assembly. In traditional construction, a lot of the detail can be left until the start of construction, whereas with factory construction, the design needs to be fully detailed before the project is launched, with components and modules designed for manufacture and assembly. This aims to reduce the complexity of the manufacturing and assembly processes and realise improvements in repeatability, quality and cost. For modules, this will mean easier manufacture and on-site installation, but requires significant investment during the design phase to develop and prove modularised designs as well as the manufacturing facilities that will be required to support delivery.

Success in modular construction is as much about a manufacturing management approach as about specific designs and techniques, and improves significantly with experience and repetition.

Transport

Transportation of modules from the factory to site, and lifting them into place, is a key consideration.

Smaller modules can be transported by road relatively easily, subject to the limits of the infrastructure and regulations. UK road transportation regulations stipulate a maximum vehicle weight — up to 150 tonnes for an abnormal load – as well as dimensions, but these vary from country to country.

Transporting larger modules is more difficult. Barges offer a solution, but require that both the factory and site are near the sea (or a river). If feasible, infrastructure such as Marine Off-Load Facilities (MOLFs) is likely to be required, at additional expense.

It is also possible to use temporary on-site factories for nuclear plant build, as Japan and South Korea have demonstrated, but the greater volume and smaller size of SMR modules offer the possibility of accessing the greater benefits from a permanent, specialised factory.[24]

These factors have affected how modularisation is being adopted in nuclear. For example:

- In Japan, ABWRs are at coastal locations, allowing the shipping of large pieces of equipment, which were then assembled in a local temporary factory and finally lifted into place by crane.
- In China, AP1000s at Sanmen used a local factory to make small modules which were then transported by road to site where they were assembled into large reactor units (each weighing 500 to 600 tonnes) and lifted into place by a 2,000-tonne crane.

The choice of reactor concept and consequent component sizes for transportation must be taken in full view of the transport infrastructure of the countries in which it is to be deployed.

24. Zhang, W.J., '*Construction Experience from Modular Nuclear Power Plants*' (2014).

4.2 Advanced manufacturing

- A 2% capex reduction could be achieved for SMRs through the application of advanced techniques.
- Of 14 techniques assessed by the Nuclear Advanced Manufacturing Research Centre (AMRC), 6 have the potential to deliver these savings for SMR manufacture by 2025.
- Success factors include readiness level of the advanced manufacturing technique, reactor design maturity and proportion of factory build.

Advanced manufacturing techniques and processes – such as joining, forming and machining — have been successfully implemented in various industries globally, particularly automotive and aerospace. These have achieved improved material and labour costs, reduced schedule durations, and enhanced quality and safety. Advanced manufacturing could also improve material properties, such as isostatic pressing, which reduces stresses. This can improve the design life of components and reduce operating costs. The benefits are substantially improved in a factory environment.

The safety-driven, heavily regulated and conservative nature of the nuclear industry has resulted in it falling behind other industries in the adoption of advanced manufacturing techniques. Processes require rigorous testing and proof of performance prior to acceptance by the regulator and implementation.

The key considerations when applying these techniques and processes to achieve the associated benefits are:

- **Manufacturing Capability Readiness Level (MCRL)** of current techniques and their respective development rates (the MCRL indicates the maturity of a manufacturing technique or process; a demonstrable safety case is required for certain techniques - such as welding - that considers the long term effect on material integrity, and this must be approved by the ONR before the technique can be applied to nuclear)
- **Reactor design maturity,** as the cost and time commitments associated with redesign are significant and limit the opportunity to reconfigure established designs and supply chains
- **Level of modularisation and factory build** attributed to component size (which affects transport as well as manufacturability) and complexity
- **Supply chain,** including manufacturing and workforce capability and capacity
- **Capital equipment cost** for expensive manufacturing machinery

These factors, and the physical differences between SMRs and large reactors, result in a variation in potential savings. With less mature designs which include a high level of factory build (due to modularisation and smaller components), there is greater potential. Consequently, the savings are greater for SMRs than large reactors.

Fourteen techniques were assessed for in-process savings - against material and labour costs directly associated with the manufacture of components. Six of these have been judged to be applicable to SMR designs and will be ready for production in 2025. Two are applicable for large reactors and will be ready for production in 2022.[G]

The six applicable techniques for SMRs have potential to achieve 2% capex reductions (8% of total manufacturing costs). In comparison, the two techniques applicable for large reactors result in a potential saving of 0.1% of capex (0.3% of total manufacturing). See Figure 14 for breakdown of cost reductions.

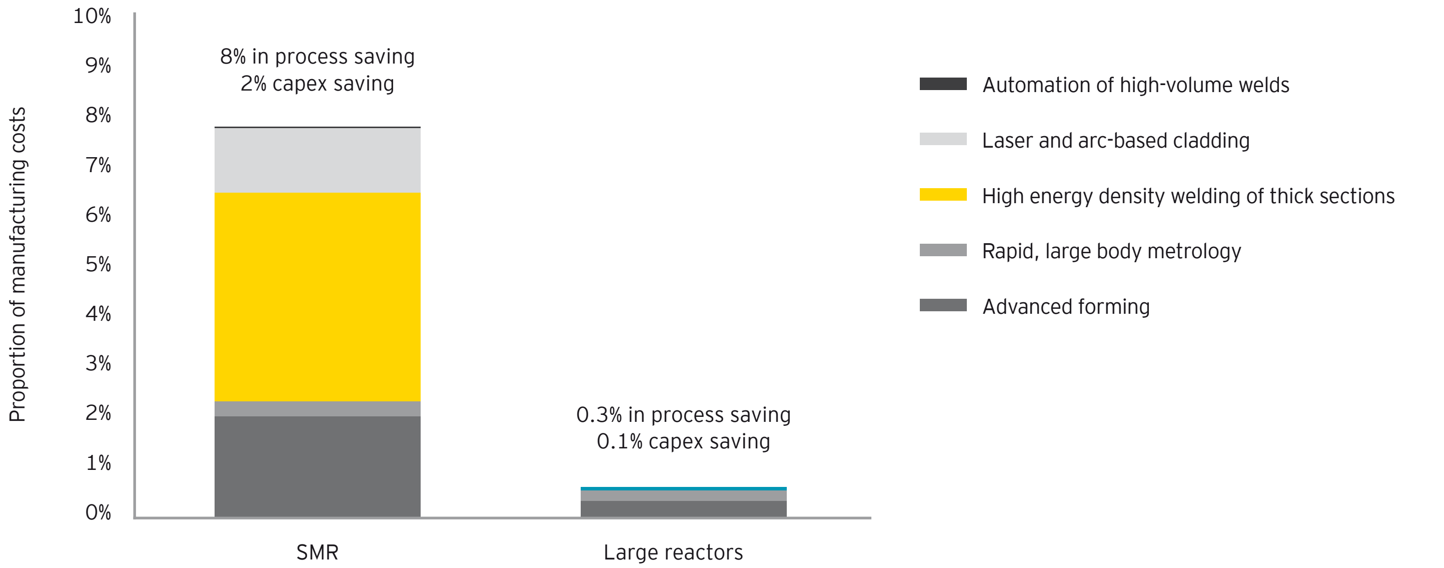


Figure 14 – The potential in-process savings through implementation of advanced manufacturing techniques[H]

Advanced manufacturing assessment with the Nuclear AMRC

Thirty-two advanced manufacturing techniques were identified, with varying MCRLs.

Fourteen of these techniques were selected and assessed based on their potential to improve the current performance of in-factory nuclear manufacturing (for application to SMRs and large reactors for deployment in 2030) relative to conventional techniques.

The cost reductions were evaluated by multiplying X, Y and Z for each component, based on:

- The cost of each component within the nuclear plant (X)
- The addressable spend of each component for application per advanced manufacturing technique (Y)
- The savings achievable through advanced manufacturing relative to conventional methods (Z)

It should be noted that additional cost reductions may be achievable for techniques and processes where:

- Cost reductions could not be evaluated due to a lack of addressable spend per component, for example, metrology
- They can be applied on-site
- They will not be sufficiently developed within the timescales of reactor deployment
- They have not been included within the study

G. To be implemented, the manufacturing technique or process must be sufficiently mature in order to achieve deployment of the reactor by 2030. For large reactors, the technique or process must be ready by 2022, based on an eight-year construction schedule; for SMRs, it must be ready by 2025.

H.The total cost of manufacturing is 30% of total SMR build; therefore, 8% in-process saving as a proportion of manufacturing costs equals 2.4% capex reduction; manufacturing is 20% of total large reactor build, with a 0.3% saving equalling a 0.06% capex reduction (Waddington, 2014, Small Modular Reactors (SMR) Feasibility Study NNL).

NUCLEAR AMRC

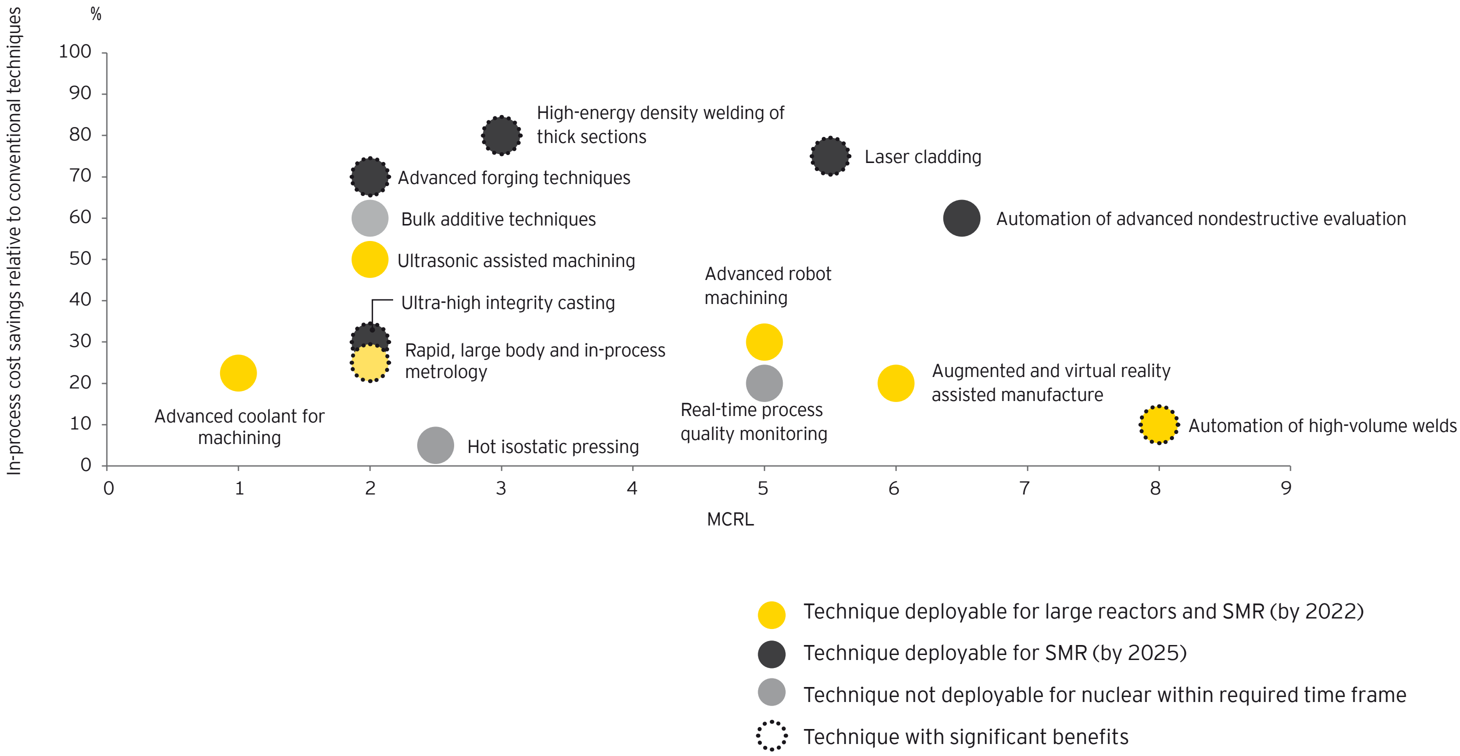
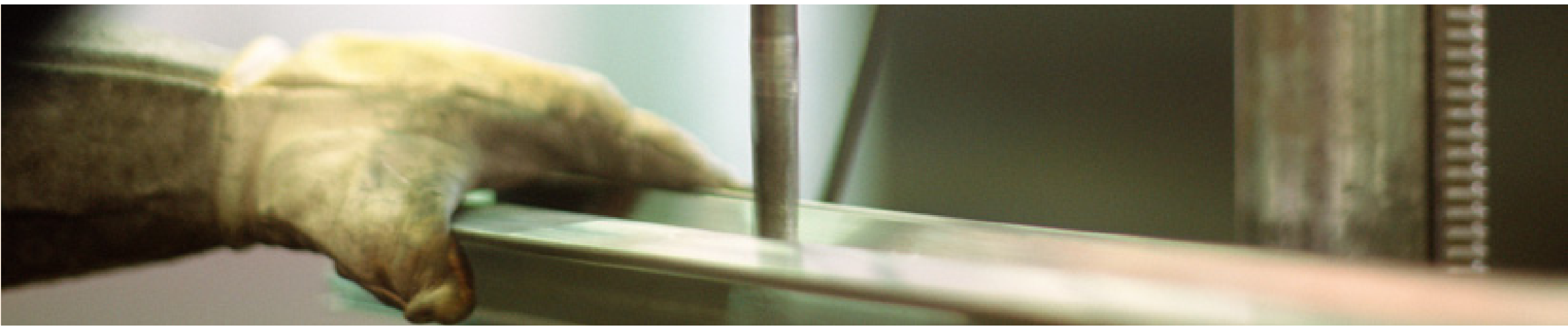


Figure 15 - The in-process savings for each technique against the maturity of the process

By evaluating the MCRL and the cost reductions associated with each process, the advanced manufacturing techniques with the greatest potential for use in nuclear manufacturing have been identified (see Figure 15).

The MCRL gives an indication of the current maturity of a technique or process, but does not capture the rate of development. Consequently, certain techniques can be implemented in time for nuclear deployment in 2030, despite currently having a low MCRL (such as for ultra-high integrity casting and rapid, large body and in-process metrology). The rate of development is demand driven, with MCRLs being accelerated with increased investment.

Six advanced manufacturing techniques may be of significant readiness to be implemented into the designs of SMRs (by 2025), and two for large reactors (by 2022).



The applicability of these six techniques and their in-process savings (as a proportion of manufacturing costs) for large reactors and SMRs are summarised below.

Large	SMR	Technique
0%	4.1%	**High energy density welding of thick sections (laser, electron beam and hybrid laser arc welding)** These joining techniques significantly reduce material costs through the elimination of the need for filler material. The size of components within the plant are most appropriate for electron beam welding. The ability to weld thick sections in a single pass reduces weld process times compared with conventional welding techniques.
0%	1.8%	**Advanced forging techniques** Advanced forging techniques significantly reduce material and processing steps needed to produce high-quality components. The forging process is highly flexible and allows for easy geometric modifications. Forging is limited in large reactor manufacture as the UK cannot currently provide suitably sized components.
0%	0.4%	**Ultra-high integrity casting** Like forging, casting can form complex, high-quality shapes and remove the need for post-cast machining, leading to material and labour cost benefits. Casting can cope with larger component sizes and helps to take the strain off the forging supply chain.
0%	1.2%	**Laser cladding** Laser cladding can be applied to components which come into contact with water to reduce corrosion. There is a reduced heat input compared with conventional cladding, limiting thermal deformation and allowing for dimensional accuracy in the production of components.
0.2%	0.3%	**Rapid, large-body and in-process metrology** The time taken to inspect the physical attributes of parts can be reduced through the use of automation and software. Doing this in-process will reduce the time provision which is usually allocated to metrology, whilst enabling the consistent high-quality recording that is necessary in nuclear manufacturing.
0.1%	0.2%	**Automation of high-volume welds** Automated welding techniques offer cost-saving opportunities through a reduction in processing time, allowing for a higher rate of production. Automation also enables the consistency of high-quality welds.

NUCLEAR AMRC

4.3 BIM

- BIM offers up to 10% capex reductions through simplification of the design and build.
- Potential benefits are dependent on full implementation in the early design stages.

BIM is a combination of Computer Aided Design (CAD) tools and additional functionality, which gives a digital representation of the physical and functional characteristics of a facility. This can be used to collect and share facility information in order to improve decision making over the course of the life cycle.

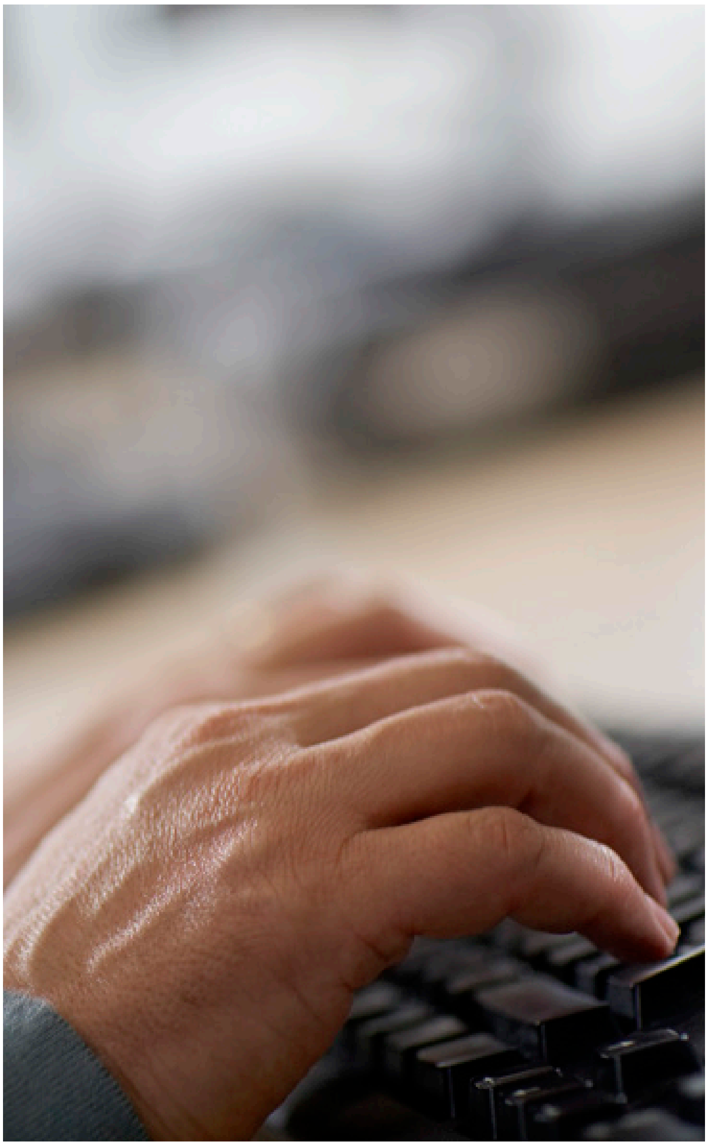
Application of BIM to UK nuclear has so far been limited because the existing fleet was constructed when these tools were not developed, and there are many challenges to retrospective implementation. Some benefits are available to the more recent large reactor designs, although some of these were also designed without BIM.

Application of BIM is expected to have a 10% capex reduction for SMRs, consistent with savings achieved for other industries.[25] In some cases, as much as 20% capex reduction has been achieved (as shown in a UK Government study for projects applying level 2 BIM[26]). For new large reactors, similar benefits would be expected.

Savings at the top of the range will be achieved where the whole project delivery chain uses a single, shared platform from the early design stages. These benefits are achieved through:

- **Reduced rework.** Designers are able to model construction, identifying clashes early in the design phase and allowing the supply chain to communicate more effectively and efficiently. This reduces rework and waste.
- **Improved scheduling capability.** This enables improved supply planning and the better sequencing of tasks, resulting in improved schedule performance and reduced delivery risk.
- **Enabling other techniques.** BIM capability aids the application of modularisation and advanced construction methods.
- **Regulatory paper work.** There is potential to manage and store a significant amount of regulatory paperwork online, such as Life Time Quality Records (LTQRs), which could significantly reduce project paperwork and improve document management.

The benefits of BIM are maximised at the full extent of Level 3 BIM with increased collaboration between different disciplines. The model generated during the construction phase will then be used for through-life management. This degree of capability is still being developed, but is improving quickly. The UK Government is currently aiming to have this mandated for all of its projects from 2019.[27]



25. BIM Task Group, *'Investors Report'* (2012); Holness, G.V.R, *'BIM Building Information Modelling Gaining Momentum'*, ASHRAE Journal 50.6 (2008).
26. HM Government, *'Digital Built Britain'* (2015).
27. NBS, *'BIM Levels Explained'*, www.thenbs.com (2014).

What are the BIM levels?

Level 1

This is object-based modelling in 2D or 3D with a small degree of integration within the delivery chain, such as sharing through a common data environment. Common formats and data standards may be used.

Level 2

This is a situation where all parties own their own 3D CAD model, but these are not all necessarily retained on a shared model. Collaboration occurs through the sharing of information through a common file format, enabling a central federated BIM model (a requirement for all UK Government projects from 2016).

Level 3

This is where full collaboration exists between all disciplines, using a single shared project model held in a central location. This enables all parties to view and modify the model and removes risk of conflicting information.

There are a number of limitations and challenges to the implementation of BIM:

- **No single integrated software package** exists with sufficient functionality to span all requirements of the delivery chain. The nuclear power plant is a complex facility, and its project delivery chain encompasses hundreds of suppliers and contractors. It is uncertain when a fully integrated platform will be developed.
- **Front-end costs of BIM** are higher, without any immediate tangible benefit (as these are not realised until the construction phase).
- **Retrospective application of BIM** to existing nuclear designs is challenging due to high cost, restrictions in capability and lack of as-built drawings that account for changes made during construction. This is especially significant in relation to mature large reactor designs.
- **A skills gap exists** within the UK nuclear delivery chain relating to the use of BIM. Additionally, there is significant inertia to moving away from conventional techniques, which slows deployment.
- **Sensitive information** is contained in designs, which may restrict the sharing of information.

The low design maturity of SMRs provides greater opportunity to exploit the potential of BIM compared with the mature large reactor designs. SMRs can use this technology from the early stages of design and throughout the project delivery chain with the possibility of exploiting Level 3 capability.

Key enablers include:

- Further development of software to establish a package capable of handling all disciplines
- Investment in skills across industry that spans vendors, supply chain, the regulator and operators

Use of BIM can also provide significant operations savings of up to 13%[26] (seen in the construction industry) due to live knowledge accumulation and building management. This improves the ability to conduct maintenance, reducing costs and downtime. Within nuclear, the accumulation of knowledge will reduce uncertainties during the decommissioning phase, reducing costs and risk contingency funds.

4.4 Advanced construction methods

- Capex savings of up to 2% can be achieved through open-top construction, with further savings possible through parallel construction and crane optimisation.
- These opportunities are heavily dependent on consideration of the methods within the design phase.

To reduce on-site construction cost, certain reactor vendors in Japan and South Korea have implemented advanced construction methods progressively over a decade, learning through the construction of a series of reactors. These help to reduce the schedule, manage delivery risk and increase efficiency of workforce, materials and machinery.

The benefits of these construction methods are maximised when they are considered as a core design principle. Additionally, these methods are best utilised in conjunction with other techniques, modularisation and BIM. Parallel construction is further enabled by moving activity to off-site factories, and also using the improved scheduling capabilities of BIM. Crane optimisation and open-top construction also benefit from the 3D modelling available within BIM, and will therefore realise larger cost reductions.

Open-top construction reduces capex by 2%.[28] There are further benefits associated with parallel construction and crane optimisation.[I]

In Japan and South Korea, these methods have been used in conjunction with other measures to improve site productivity in areas such as training and site organisation.

There are challenges and limitations related to applying these methods:

- **Design maturity.** These must be considered from early on in the design process, resulting in limited possibilities of application to mature designs.
- **Design costs.** These will increase as additional design and planning is required for the implementation of these methods.
- **Health and safety.** For example open-top construction requires ongoing crane activity. The increased safety risk associated with personnel working beneath operational cranes is likely to be problematic in the UK.

Based on the limited maturity of designs, there is the greatest potential for application through SMRs. The greater maturity of large reactor designs is expected to be a barrier to achieving savings.

What are advanced construction methods?

1. Open-top construction

Buildings are left open during the construction phase, allowing the engineering components to be installed parallel with civil construction activities, often floor by floor. This technique facilitates easier access for the installation of internal components, reducing the time.

2. Parallel construction

Mechanical and civil works are scheduled to occur simultaneously, reducing the critical path and overall schedule. A greater degree of parallel construction is enabled through modularisation as fabrication of modules and site activity occur simultaneously.

3. Crane optimisation

Careful planning of crane lifts required during construction enables planning for the specification and locations of cranes around the site. Some reactor vendors use a small number of very large 'ringer cranes' situated at the centre of the site to facilitate the flow of modules and the largest lifts.

I. These savings have not been quantified due to limited data. This is partially due to the difficulty of isolating and attributing the cost savings for each technique when they are closely related to other techniques such as modularisation.
28. OECD 2088, 2000, Reduction of Capex of Nuclear Power Plants.

4.5 Co-siting of multiple reactors

- Capex reductions of up to 14%, averaged across all reactors, can be achieved by installing multiple reactors on the same site at the same time, or in close succession.[29]
- Efficiencies are delivered through shared set-up activities and site infrastructure.
- This could prove particularly beneficial in the UK, where a strategic decision can be made to co-site reactors across the limited approved nuclear sites.

Co-siting of reactors can deliver measurable capital benefits. This is due to the potential to share fixed indivisible costs when co-siting additional units next to the first, decreasing the marginal cost per unit by 10% to 15%.[29,30] This equates to a saving of 5% to 14% for SMRs, assuming between 2 and 12 reactors on a single site, with savings averaged across all reactors.

Co-siting economies mainly impact indirect costs from set-up activities and site infrastructure, such as site licensing, land acquisition and connection to the transmission network.[31] Certain direct costs are also affected, as co-siting has proven to deliver better utilisation of site materials and the sharing of human resources.

It should be noted that, in addition to one-off capex reductions, site learning has also been demonstrated through the same contractors involved in the build of all reactors. The accumulation of site-and reactor-specific knowledge improves construction efficiency and reduces capex.

Key factors to achieving the benefits of co-siting are the size of the site and the reactor. There are also a number of critical conditions that need to be met to help ensure that the benefits materialise:

- **Reactors should be built with a schedule to allow sequencing and matching of build phases.** Large lapses of time between build will limit the degree of cost sharing.
- **Reactors should be of the same design.** Variances in design would limit the potential of sharing and negatively impact site learning.
- **Regulatory requirements should be met.** The safety case for co-siting for SMRs must be demonstrated to the ONR as has historically been done for large reactors. Key considerations for the ONR will include:
  - Distance between reactors
  - Separation of building from operating reactors
  - Separation of power supplies
  - Any common faults which could affect more than one reactor

It should be noted that co-siting, in comparison with a more dispersed approach, may result in a greater distance between the source of generation and the consumer. This leads to inefficiencies through loss of power in the transmission system. Further analysis is required to assess the cost of the potential in efficiencies.

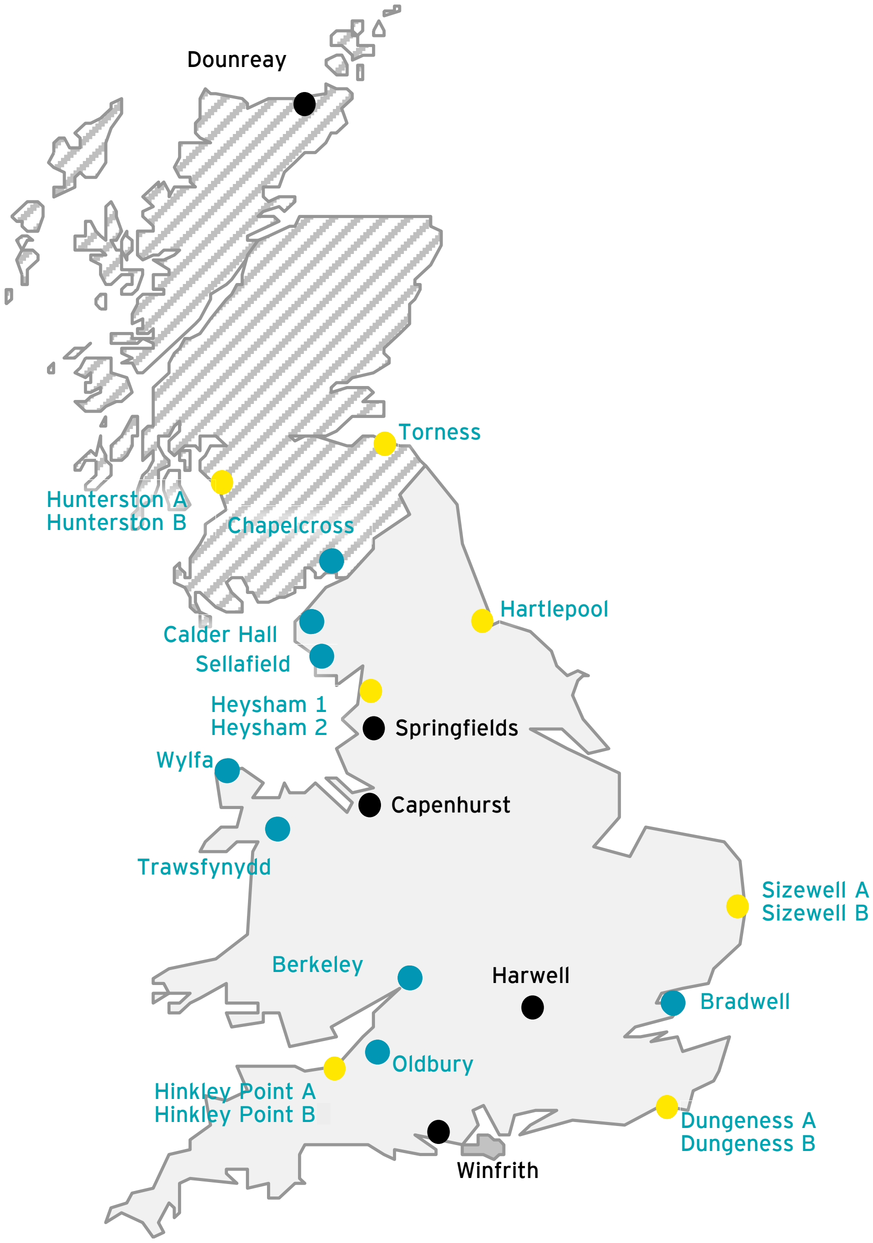
The current UK nuclear site selection process considers a number of diverse criteria, including site size, access to cooling water, proximity to large conurbations, airports and military and chemical installations. The scale of large reactors and their complex safety requirements limit the number of suitable sites. With only three large reactors able to fit on one site, potential for co-siting to optimise use of suitable sites is also limited.

It has been estimated that the bounding limit for deployed capacity of new large reactors in England and Wales is around 35GWe[32] (sites shown in Figure 16).

The small size and lower cooling water requirements of SMRs present opportunities for deployment at a wider range of sites, some of which might have been excluded for large plants. With smaller site requirements and flexible unit configurations, it may also be possible for more than three reactors (the limit for large reactors) to be built on one site.

Additional sites may be made available for SMRs, but these could be smaller, precluding installation of more than one reactor. If these are inland sites, transportation design will become a more serious consideration, to which there may be significant barriers.

There is currently limited research on sites for co-siting of multiple SMRs. These configurations will require larger sites than identified by the Energy Technologies Institute (ETI) for SMRs and could be smaller than the sites identified for large reactors.



Key	
● (yellow)	Existing nuclear power station sites
● (blue)	Closed nuclear power station sites
● (black)	Civil nuclear process and research reactor sites
■ (grey)	Scottish policy for no new nuclear

Figure 16 - Sites in the UK suitable for deployment of nuclear power plants[32]

29. OECD 2088, '*Reduction of Capex of Nuclear Power Plants*' (2000).
30. Boarin, Locatelli, Mancini & Ricotti, '*Financial Case Studies on Small-and Medium-Size Modular Reactors*', Nuclear technology 178 (2) (2012): 218-232.
31. Carelli, Garrone, Locatelli et al., '*Economic Features of Integral, Modular, Small-to-Medium Size Reactors*', Progress in Nuclear Energy 52 (2010): 403-414.
32. Energy Technologies Institute, '*Nuclear: The Role for Nuclear within a Low Carbon Energy System*' (2015).
Locatelli & Mancini, '*Large and Small Baseload Power Plants: Drivers to Define the Optimal Portfolios*', Vol 39, 12, Dec (2011): 7762-7775.

5 Load following: SMRs have the ability to vary output

- By 2030, growth of renewables and reduction in fossil fuel generation may lead to a requirement for additional means of balancing supply and demand for power.
- For nuclear, load following increases the LCOE; nuclear reactors cannot economically load follow within the current electricity market.
- In general, SMRs can offer improved load following ability in comparison with large reactors:
  - Ramp rate of at least 5% of maximum power per minute, with the potential for more flexibility in the power range of load following
  - Because SMRs have lower core power densities and shorter cores

Flexibility of the UK power supply is becoming a more important consideration due to the planned closure of all coal plants. Along with Combined Cycle Gas Turbine (CCGT) and smaller peaking plants, coal plants currently balance national supply and demand. Also, the increased deployment of large amounts of intermittent renewables will require the UK to have a much greater range of load-balancing power capacity.

The combination of daily demand variation of 40% and >30% renewable supply variation means that, by 2030, the grid will have to compensate for up to 70% of its maximum demand. Figure 17 shows a similar effect of the anticipated fluctuations in Germany, where renewables penetration is already high. Demand and supply over a week in 2012 are compared with modelled values for 2020, where the range of variation in a single day is almost 100% of peak demand – the UK is likely to be in a similar situation by late in the next decade.

There are a number of different means of providing varying power supply. However, the range and quantum of the required back-up power is expected to grow, and the scope for steady base-load generation could become more limited. In the absence of strong growth in storage or interconnection, nuclear may not always be able to operate at base-load[33] as is currently the model in the UK.

In France, where there is a high penetration of nuclear (75%[34]), part of the large reactor fleet is required to load follow; in Germany, where there is already a high share of renewables, the large reactors are also capable of load following[35] but seldom do.

Germany is more similar to the UK, where the national grid has to balance a diverse and volatile energy mix over a wide power range in both the short and long term.

Therefore, the questions are:

- Does load following with nuclear make economic sense?
- Can large reactors provide useful load following capability for the UK grid?
- Will SMRs offer performance or economic improvements over large reactors?

Both renewable and nuclear low-carbon energy are capital intensive. They require certainty of revenue to recover their high fixed costs, which is achieved through Contracts for Difference (CfD). CfD prices assume that nuclear operates at high availability whenever it is available – 85% to 90% of the year. Therefore, continuous operation is currently the key to nuclear economics.[36]

If nuclear reactors operate below full power for grid power matching reasons within the current electricity market, there will be a loss of revenue. If nuclear is technically able to load follow, it will only become viable for power utilities with more flexible power contracts that provide additional value for flexible operation.

In the current context, the technical challenges and

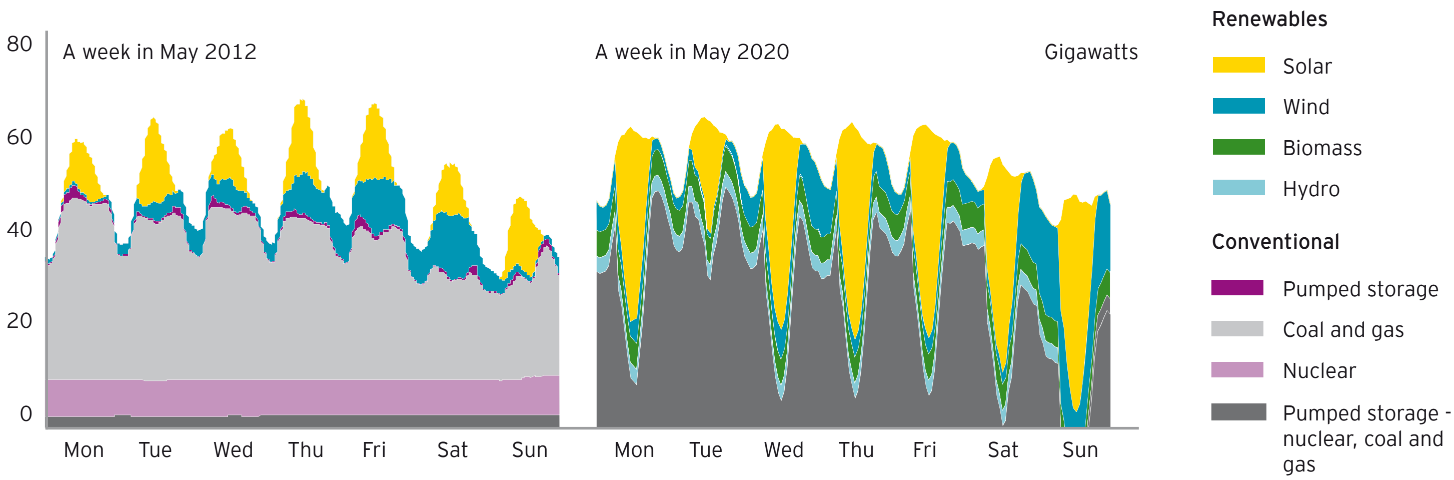


Figure 17 – Modelled power demand over a week in 2012 and 2020, Germany

loss of revenue for utilities from load following makes it unattractive. Given the structure of existing support mechanisms for new nuclear, utilities have a strong incentive to operate their plant in base-load mode, even where the power price falls below the plant running cost. The economic issues are similar for both SMRs and large reactors.

Load following is employed:

- In the short term for grid frequency control with small power ranges: primary (+/-2% power) or secondary (+/-10% power)
- In the longer term for power matching with large power variation (eg, 100% to 50%)

The European Utility Requirements[37] mandate that all new reactors, such as EPR and AP1000, must be able to load follow between 50% and 100% power, with ramp rates of ~5% per minute over this range of 50% to 100% power and up to 200 cycles per year.

Further flexibility is offered by an Extended Reduced Power Operation (ERPO) in which reactors can operate at powers as low as 30% of nominal power for periods of time ranging from several days to several months.[38] ERPO is technically more challenging for large reactors.

Most SMRs should be at least as capable as large reactors, and potentially may be able to operate over wider power ranges. Also, because of the smaller unit size, SMR power can be scheduled by the grid in smaller unit quantities.

What is load following?

Load following is varying the output of a generating unit as the system demand changes over the long and short term. A nuclear power plant is able to load follow through:

- Bypassing the steam turbine for rapid responses to change in demand (this could be used for district heating)
- Adjusting reactor power through reactor control rods or boron control
- Taking one or more modules offline

33. Energy Technologies Institute, *'Nuclear: The Role for Nuclear within a Low Carbon Energy System'* (2015).
34. World Nuclear Association, *'France Country Profile'*, ww.world-nuclear.org, accessed Jan 2016.
35. Lokhov, A. *'Technical and Economic Aspects of Load Following with Nuclear Power Plants'*, Nuclear Development Division, OECD NEA (2011).
36. Locatelli G., Boarin S., Pellegrino F., *'Load following with SMRs: A Real Options Analysis'*, – Energy – Vol. 80 1, February (2015):41-54.
37. European Utility Requirements, 2013.
38. Bessiron, et al. *'AREVA's PCI Methodologies for PWR Enhanced Plant Manoeuvrability. Proceedings of 2014 Water Reactor Fuel Performance Meeting/ Top Fuel / LWR Fuel Performance Meeting'*, WRFPM (2014): 784.

SMR vendor claims on load following[1]:

- Designs can accept 10% step changes in demand and are able to handle physically up to 10% per minute design transients.
- Daily load follow can be performed from 100% to as low as 20% power, at a linear power ramp rate of 5% per min
- Reactor coolant system and main steam supply system components will be affected by load following and may be subject to more frequent replacement.
- Increasing the power without notice at a rapid rate will induce temperature changes, which will impact the service life of the heat exchangers.
- Natural circulation systems will automatically return to equilibrium conditions after load following.

Load following characteristics

The ability of nuclear reactors to load follow improves with low core power densities and shorter cores. Most PWR-based SMRs[J] exhibit these characteristics. They can therefore be considered to offer the potential for an improved load following ability in comparison with large PWRs. Figure 18 compares the load following characteristics of large and small PWRs.

There are a number of areas where SMRs offer advantages over, or offer the same characteristics as, large reactors:

- Ramp rates during power operation are at least as high (5% per minute), with vendor claims of the potential for 10% per min.
- Local core power conditions may be less of an issue for SMRs, allowing load following over a wider power range and for the whole fuel lifetime.
- Start-up ramp rates are unlikely to differ in absolute terms, and start-up times from complete shutdown would be several days.
- There is not expected to be a difference in the effects of xenon poisoning, at least for a design with soluble boric acid.
- Low-cycle fatigue of reactor components and fuel is not considered to be more of a problem for SMRs, with a low potential impact (1-2%[39,40]) on long-term power availability.
- Refuelling periods for SMRs are expected to be the same as for large reactors.
- Small output multi-modular SMRs also offer greater flexibility through taking one or more modules offline while keeping the rest in operation, although long start-up times would impede this flexibility

However, there are some potential issues or uncertainties:

- Load following for both SMRs and large reactors could be limited due to the key issue of fuel pellet cladding interaction (PCI) at high power ramp rates (>5% per min). The risk of PCI is reduced if power density is low (as in SMRs), and both power ramp rates and the duration of low power operations are limited.
- Passive SMRs (natural circulation) may have limited ability to load follow:
  - Power stability concerns, because of the linkage between cooling flow and core power
  - Potential materials problems, as lower inlet temperatures (below ~220˚C) may lead to fuel rod failure associated with hydrogen embrittlement
- There are varying opinions around the impact of load following, maintenance and availability, but the general consensus is that the effects would be small.[41] Specific analysis is required for each reactor type, and further data will be needed from the SMR vendors to do this.

Fuel utilisation is a function of both the power density and the time the fuel resides in the reactor. The lower power density of SMRs means that they can operate for longer periods between refuelling.

Two fuel schemes are broadly being proposed. Both appear feasible, within current fuel enrichment (% of uranium 235) and fuel lifetime limits:

- Three-batch operation in which one-third of the core is replaced every two years
- Single-batch refuelling every five years

Preliminary calculations[41] do not show any significant fuel cost penalty from the use of multi-batch core designs without soluble poison, but there may be additional manufacturing costs for the more complex fixed poison elements. Single-batch core design and fuelling schemes are likely to reduce the average fuel burn up and, therefore, its utilisation. This would have a negative effect on operating costs – both for fuel and waste.

J. Indicative calculations performed using a series of assumptions, such as fuel design and clad type, which will differ between designs.

Load following characteristics[4]	Large reactors	Pumped SMRs	Non-pumped SMRs
Reactivity control	Control rods and soluble boric acid poison	Control rods: some utilise soluble boric acid	Control rods: some utilise soluble boric acid
Xenon-135 transients	Override xenon poison transient after shutdown	With soluble boric acid, same as large reactors case	With soluble boric acid, same as large reactors case
Xenon-135 axial oscillations	Susceptible to axial xenon oscillations	Stable against axial xenon oscillations for core heights <~2.5 m	Stable against axial xenon oscillations for core heights <~2.5 m
Start-up ramp rate	3% per hour	>3% per hour	>3% per hour
Ramp rate during power operation	1% to 5% per minute	≥5% per minute	Potentially susceptible to hydrogen embrittlement, which may limit ramp rate
Power range	Normally 100% to 50% (or 30% if cleared for ERPO)	100% to 20%	Currently unclear because of potential instability of core power and flow due feedback effects
Refuelling periods	Four to five weeks	Four to five weeks	Four to five weeks
ERPO	12- to 15-month fuel cycle possible	Full 24-month fuel cycle due to lower power density	Full 24-month fuel cycle due to lower power density

Figure 18 – Load following characteristics of PWRs[41]

Further load following analysis is required on specific designs to expand the SMR load following capability compared with large reactors; if required to achieve faster ramp rates, an SMR's capability will have to be confirmed through more analysis and testing, covering fuel and controls.

Furthermore, while large components have not been observed to experience fatigue failure due to load following within current limits, if the rate and magnitude of power changes were to increase or the number of cycles was to increase, there is the risk that large components may require more frequent replacement.

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39. Lokhov, A. *'Technical and Economic Aspects of Load Following with Nuclear Power Plants'*, Nuclear Development Division, OECD NEA (2011).
40. Bruynooghe et al., *'Load-following Operating Mode at Nuclear Power Plants (NPPs) and O&M costs'*, JCR Scientific and Technical Reports, SPNR/POS/10 03 004 Rev. 05 (2010).
41. National Nuclear Laboratory, *'Load Following Capabilities of Small Modular Reactors'*, 13771 Issue 2 (2016).

6 Operations: efficiencies could offset higher costs of SMRs

- The first SMRs, at least, are expected to have higher operating costs than large reactors due to much of the reactor staffing costs being fixed, regardless of power output.
- This can partially be offset by economies of volume, design standardisation and common management, which improve operational performance.
- SMRs offer a better opportunity for learning than large reactors; optimal operations can be reached with less capacity installed for SMRs.

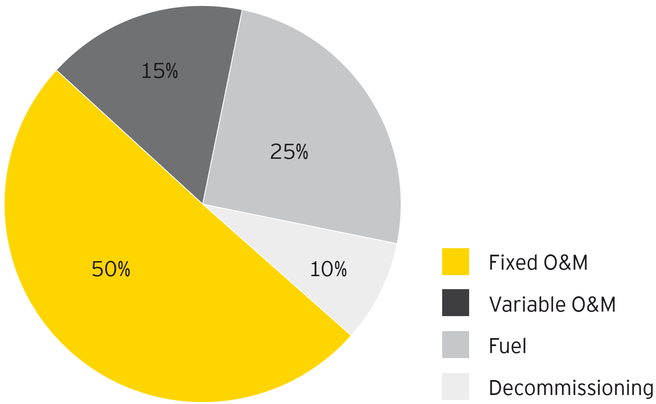


Figure 19 - Breakdown of operating expenditure for large reactors[4]

Both keeping the cost of operations in check and achieving high capacity factors are fundamental to the economic operations of nuclear reactors and hence to the affordability of nuclear power.

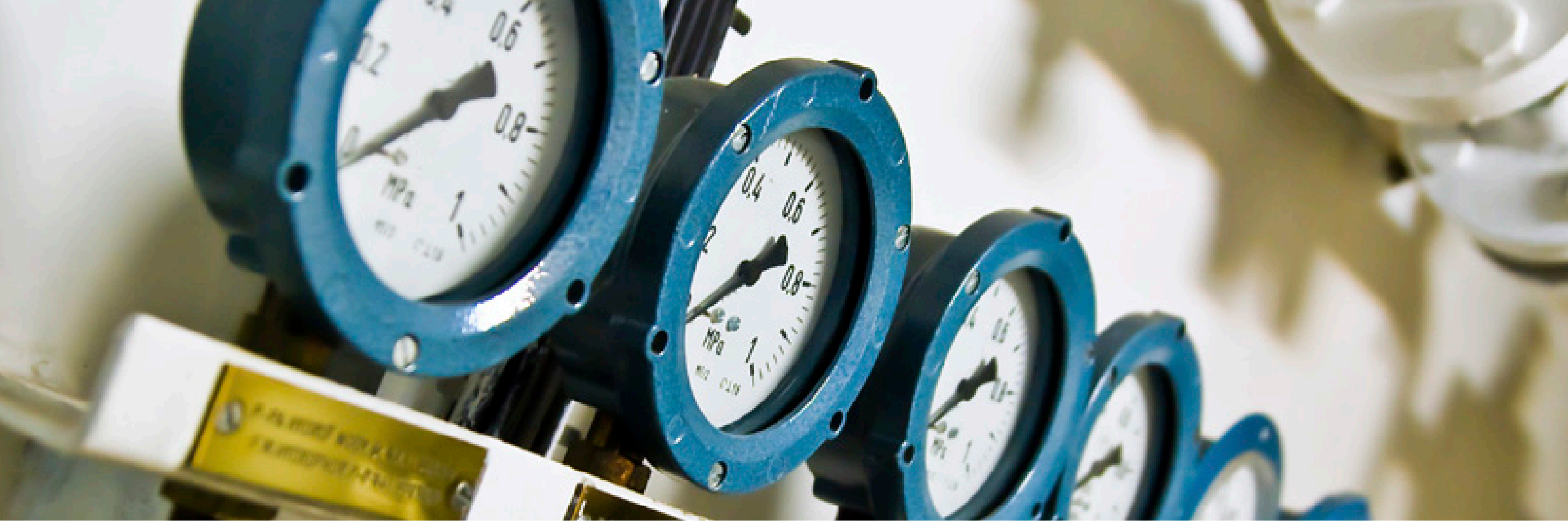
Cost

Operating costs are the smaller part of the cost of generation, circa 25% of LCOE.[42] They are made up of fixed and variable operation and maintenance (O&M), fuel and decommissioning costs (see Figure 19), as well as insurance and connection charges.

Operating costs can vary significantly depending on manning and efficiency of operations. By and large, fuel and decommissioning are independent of operational strategies.[43,44] Fuel costs may be a little higher for SMRs, particularly if a single-batch fuel strategy is adopted. But if they use three-batch refuelling at two-year intervals the burn-up penalty, and hence the fuel cost penalty, will be small. While large in cash terms, decommissioning costs only account for a small proportion of the life cycle cost[45] (though these costs are expected to be higher for SMRs on a per megawatt basis). Fixed and variable operations and maintenance elements of the operating costs are the key addressable areas.

Personnel accounts for approximately 50% of fixed operating costs. It is the most significant component of operations and maintenance expenditure for SMRs. Improving the efficiency of operational strategies and staff utilisation is therefore essential.

Manpower costs for large reactors are relatively low (6% of LCOE). Manpower costs per unit of output rise as reactor size decreases, due to some manpower costs being fixed and loss of economies of scale. For example, for the same number of reactors operating, the same number of technical and security staff may be required for a 600 MWe as a 1000 MWe unit. In a similar way, SMRs are expected to have higher specific manning costs, with premiums particularly pronounced for very small or multi-module designs. For example, the premium for a 50MWe reactor can be as high as 190%[46] compared with the fixed operating cost of a large (1000 MWe) reactor.



Experience from across the nuclear industry, particularly in South Korea (refer to case study B), has indicated that there are a number of conditions that can help optimise plant performance and utilisation of staff. These help to foster an environment that promotes safe, reliable and affordable nuclear power while balancing regulatory, financial and resource constraints.

Progressive and one-off operating cost reductions can be achieved through operational learning, co-siting and shared controls.[43,47] There may be potential for the operating costs of SMRs to become more comparable with large reactors, but only if the diseconomies of scale experienced by small reactors are able to be offset by capitalising on these operational benefits.

Capacity factor

A reactor's capacity factor is important because it relates directly to the revenue that is generated by the plant. It can be affected by lost time during refuelling, unplanned shutdowns because of faults or inadvertent operation of the automatic shutdown systems, or for planned maintenance. Capacity factor is also affected by load following.

Refuelling is usually done every 18 to 24 months and takes a number of weeks. Unplanned shutdown is reduced by improved operating procedures and practices, many of which are derived from operating experience. Planned maintenance and inspection of critical components is often scheduled at the same time as refuelling.

Opportunity	Impact	Value	Large reactor	SMR
Operational learning	Increase in revenue due to improvements in plant availability	5% to 10% increase in plant availability	√	√ √
	Reduce variable O&M costs	0.3% to 0.5% of opex	√	√ √
Co-siting of multiple reactors	Reduce total O&M costs	7% to 14% of opex	√	√ √ √
Shared control	Further reduce O&M costs		√*	√ √*

**Subject to regulatory approvals.*

Figure 20 - Potential cost reduction opportunities for large reactors and SMRs

42. DECC, '*Cost of Electric Generation Data*', provided by DECC, Nov 2015.
43. International Atomic Energy Agency, '*Staffing Requirements for Future Small and Medium Reactors (SMRs) Based on Operating Experience and Projections*' (2001).
44. Locatelli and Mancini, '*Small-Medium Sized nuclear Coal and Gas Power Plant: A Probabilistic Analysis of their Financial Performances and Influence of CO2 Cost*', Energy Policy, 38 (2010): 6360-6374.
45. OECD Nuclear Energy Agency, '*Decommissioning Nuclear Power Plants: Policies, Strategies and Costs*' (2003).
46. Barrios-Eufrasio F, '*Automation and Reduced Operational Manning Requirement in SMR*', University of Cambridge MPhil Dissertation (2014).
47. Carelli et al., '*Competitiveness of Small-Medium, New Generation Reactors: a Comparative Study on Capital and O&M costs*', Paper 48931, 16th International Conference on Nuclear Engineering, ICONE16, Florida, USA (2008).

PRIS data for capacity factors shows that it takes several years to optimise a reactor system, with capacity factor typically starting low (~60%) and subsequently improving to over >85%. The maximum achieved for large reactors is over 92% in the US and 86% in South Korea.[48] At Sizewell B, the capacity factor in 2014 was 84%, and 83% over the almost 20 years of operation.[48] Large utilities with many reactors achieve better reactor performance than small, less well-resourced utilities.

It is uncertain what capacity factor will be achieved for SMRs without further evidence to substantiate vendors' claims that SMRs can deliver 95% or more, though there is no reason to think they will be worse than other pressurised water reactors from which they are derived.

Some SMR designs have proposed five-year single-batch fuelling cycles. These would reduce the refuelling outage loss of availability at the cost of lower fuel utilisation. However, planned inspections and maintenance that are required more often than every five years would be impacted, either requiring dedicated shutdowns or extensions of sensitive inspections.

Case study: lessons learned from the nuclear programme of South Korea[49]

Experience from South Korea demonstrates the fundamentals of delivering reliable, economic electricity through nuclear. These include integration of key stakeholders, effective development of infrastructure, and efficient knowledge and personnel management. Operational benefits have come from consolidation of operator utilities, standardisation of reactor design and localisation of the supply chain.

Figure 21 shows reductions in unplanned outages, and a resulting increase in capacity factor, that have been achieved since the start of the nuclear programme. Consistency of reactor design and common management have been shown to facilitate learning, make the most of skilled resources, and incentivise focused research and development (R&D) spend.

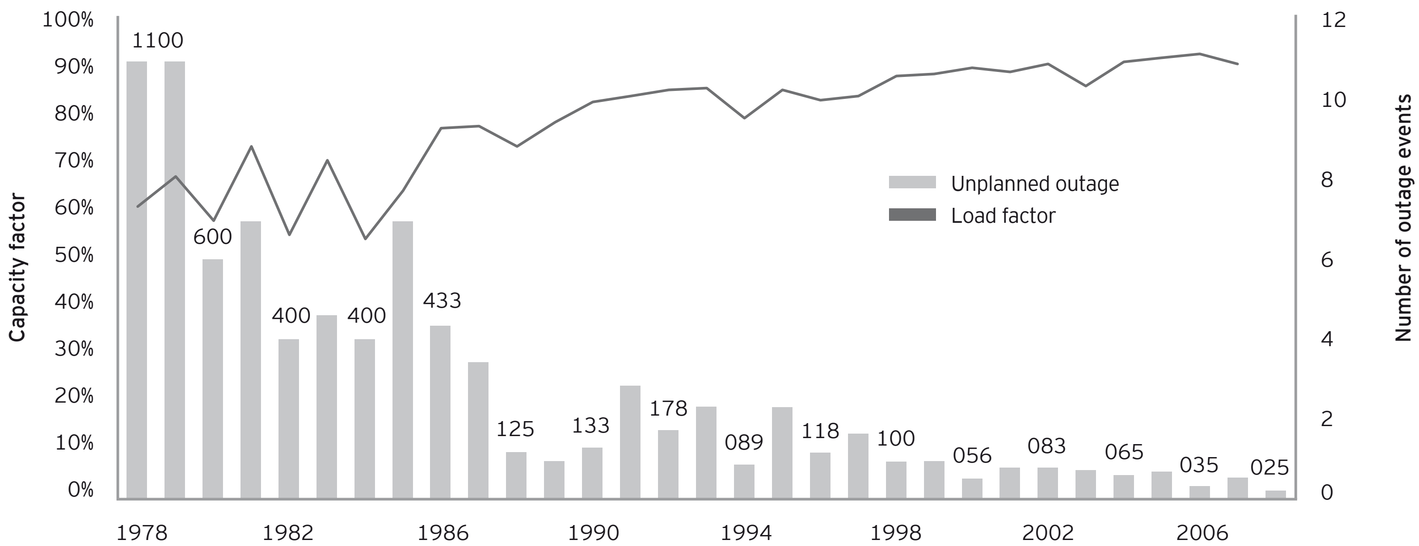


Figure 21 - The effect of learning on capacity factor[49]

48. IAEA, '*Power Reactor Information System (PRIS) Database: National Load Factors*' (2014).
49. Choi et al., '*Fourteen Lessons Learned from the Successful Nuclear Power Program of the Republic of Korea, Energy Policy*', 37 (2009): 5494-5508.
50. Carelli et al., '*Competitiveness of Small-Medium, New Generation Reactors: a Comparative Study on Capital and O&M costs*', Paper 48931, 16th International Conference on Nuclear Engineering, ICONE16, Florida, USA (2008).
51. Rosner & Goldberg, '*SMR Key to Future of Nuclear Generation in US*', University of Chicago, EPIC (2011).

Operational learning

- Operational learning can result in an improved capacity factor and reduced variable O&M costs through consistency of operations and familiarity with a design combined with better knowledge-sharing opportunities. Accumulated experience of running a number of reactors results in a steeper learning curve, reduces operational risk and in turn incentivises a higher level of investment. This is driven by standardisation of design, operations and the supply chain. Experience of operating large reactors in South Korea[49] has proven that minimising variation of designs allows for better leverage of specialist resources and reduces the need for R&D spend.
- SMRs are simpler than large reactors, with less components and often with passive safety systems. There is therefore less chance of component or system failures. Nonetheless, history suggests that it is unlikely that new reactor designs will perform better than average from the outset. As a result, a potential 5% to 10% increase is considered a conservative estimate for both large reactors and SMRs. Improvements in capacity factor can be accelerated for SMRs in comparison with large reactors, as operating time (or 'reactor years') is higher for SMRs for the equivalent power output.
- Operational learning has also been shown to deliver a reduction in variable O&M costs of 2% to 3%.[50] Scaling the benefits to the operating costs of nuclear reactors, there are potential savings of up to 0.5% of variable O&M.

Co-siting of multiple reactors

- Consolidation of resources and activities facilitates specialisation of operating engineering labour and capitalises on economies of scale in technical support tasks.
- Co-siting of SMRs could reduce fixed O&M expenditure by 10% to 20%, or 7% to 14% of total operating cost.[51]

Shared controls

- Having multiple reactors controlled by a single control room is important for multi-module reactors, for example, perhaps 12 are controlled using shared controls. With shared controls, staffing costs can be reduced.
- Consolidation of operating staff, feasible for multiple plants on a single location, is expected to bring additional cost savings. This would also help tackle shortages of highly skilled labour in the area.
- Further R&D activities are required to obtain regulatory approvals of shared controls. The ONR has indicated that the safety case could be difficult to prove (design features of EPR and AP1000 approved in the US and France have previously been questioned in the UK). To address the regulatory concerns, additional safety and control systems have been installed, making large reactors more complex and costly to build.
- The smaller size of SMRs, when compared with large reactors, provides an opportunity to deploy a greater number of units for a set output capacity. This added experience could accelerate learning, making SMRs better positioned to achieve the operational benefits.

The opportunity to achieve operational benefits should be assessed for a certain level of capacity. For example, in order to generate 2GWe, two 1GWe large reactors or 10 200MWe SMRs can be deployed. The size of the opportunity would be much larger in the latter case, simply due to greater accumulation of learning, achieved through the economies of volume, as shown in Figure 21. The smaller size of SMRs also provides a larger scope for co-siting, further increasing the potential to achieve optimal operations.

7 Industry: state of readiness

- Nuclear power plants have historically been delivered as site-based construction projects.
- Cost-effective delivery of SMRs will instead require a serial manufacturing approach and the management of an integrated supply chain.
- The UK could supply between 55% and 70% of the SMR supply chain requirements; to maximise this, investment and intervention is required from the UK Government and industry to turn nascent technical capability into competitive capacity.
- SMR vendors are at various levels of maturity in serial manufacturing and must take action in order to exploit fully the benefits of modularisation and advanced manufacturing.

Nuclear power plants have historically been delivered as major on-site construction projects with low volumes of large stick-build reactors of various designs. While the ABWR and AP1000 projects will introduce the idea of modularisation to UK nuclear, the size of the modules will mean that much of the fabrication and assembly work will be conducted close to site.

Deployment of SMRs introduces a major change in the delivery model for nuclear build. This is caused by a shift from site construction to factory manufacture. SMRs may be designed and supplied as modules such that many of the structures and installation equipment become factory assembly work, which can benefit from fixed tooling, better processes and automation rather than craft trades and the organisation of site labour. SMRs allow more of the plant to be manufactured off-site rather than through on-site construction (45% to 60% spend in factories for SMRs compared with 30% to 35% for large reactors).

Building SMRs effectively will require organisations to deliver as serial manufacturers (high rates of factory production). This is a completely new way of working for nuclear; designing for modularisation, manufacture and assembly to produce a large number of standardised reactors made from factory-manufactured components and modules. Modularisation, while being relatively new to nuclear, has been applied widely in UK oil and gas as well as shipbuilding, and is being used in rail and other construction sectors.

The smaller size and modular nature of SMR components may mean that the UK supply chain is better positioned to meet the capacity and capability requirements. This move from on-site construction to off-site manufacture will also necessitate a change in skillset, engineering standards, logistics set-up and the types of suppliers. This could present significant opportunities to existing suppliers and new entrants to the market.

The potential SMR market size is large, with scope for domestic production and global export. Based on the NNL *(SMR) Feasibility Study*[52], the size of the global SMR market is valued at a projected £250bn to £400bn by 2035. It has been estimated that there could be scope for 10GWe to 20GWe of small nuclear in the UK by 2050 if the technology can become cost-effective.[53] The UK export market also requires regulatory barriers to be overcome and international licensing harmonisation to be achieved.

The Nuclear AMRC has conducted a high-level assessment of the forecast capability and capacity in the UK. Its assessment for SMRs is more favourable than for current large reactors because large reactor vendors have existing sources for which the manufacturing process has been proven. SMR areas identified with high potential for development include the reactor pressure vessel, nuclear

52. Waddington, '*Small Modular Reactors (SMR) Feasibility Study*', NNL, Dec (2014).
53. Middleton, '*The Role for Nuclear within a Low Carbon Energy System*', Energy Technologies Institute, Oct (2015).
54. HM Government, '*Nuclear Supply Chain Action Plan*', Dec (2012).
55. Oxford Economics & Atkins, '*The Economic Benefit of Improving the UK's Nuclear Supply Chain Capabilities*', Mar (2013).

SMR integrated system	UK capability	UK capacity
Reactor pressure vessel	Able to meet requirements	Able to meet requirements
Nuclear Steam Supply System (NSSS) including steam generators and pressuriser	Able to meet requirements	Investment needed to meet requirements
Reactor vessel internals	Able to meet requirements	Investment needed to meet requirements
Reactor core and fuel components	Able to meet requirements	Investment needed to meet requirements
Integrated head, Control Rod Drive Mechanism (CRDM) or equivalent	Able to meet requirements	Investment needed to meet requirements
Reactor control instrumentation	Able to meet requirements	Able to meet requirements
Steam turbine sets	Investment needed to meet requirements	Investment needed to meet requirements
Diesel, waste and auxiliary buildings (typical balance of plant)	Able to meet requirements	Able to meet requirements
Integrated manufacturing and assembly (factory)	Able to meet requirements	Investment needed to meet requirements
Civil infrastructure	Able to meet requirements	Able to meet requirements
Cranage	Able to meet requirements	Investment needed to meet requirements

Able to meet requirements

Investment needed to meet requirements

Figure 22 - Nuclear AMRC forecast capability and capacity for SMRs in the UK – initial assessment (May 2015)

steam supply system and civil modules manufacture (Figure 22). The focus for developing the UK SMR supply chain should be on expanding the UK's capability and capacity for high-value components, and the potential design and assembly of modules.

SMR vendors

Although the UK does not currently have a supply chain in place to manufacture and assemble SMRs, reactor vendors have a positive view of UK capability and capacity, and have indicated a willingness to source from the UK. The design of SMRs is at an early stage, and sources have not yet been chosen. This will be dependent on the commercial competitiveness of the products, as well as investment from suppliers to meet vendor technical requirements.

The supply chain action plan[54] for large reactors needs to be adapted and updated for SMRs in order to direct investment, encourage supply chain participants and remove the relevant barriers. This is key to increasing the value of the SMR supply chain that can be captured by the UK, up from the current estimate of 55% of capex to 70%, including both conventional site and construction activities. This compares with 44% of the current large nuclear supply chain value captured by the UK, as illustrated in Figure 23.

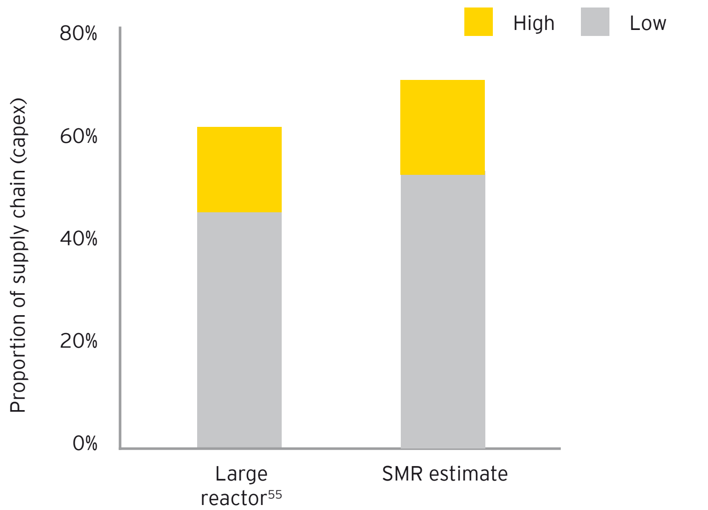


Figure 23 - UK nuclear supply chain capability

A key supply chain consideration is vendor readiness. The SMR vendors are at various levels of maturity in their serial manufacturing approach, and modularisation and advanced manufacturing thinking. There is some recognition that manufacturing in volume will allow learning, and as a result will improve quality and schedule, whilst lowering costs.

Vendors acknowledge the importance of applying advanced manufacturing techniques but have not demonstrated that they have developed this to maturity. Getting existing nuclear suppliers ready will require a fundamental change in thinking from the current construction engineering approach to a manufacturing mind-set, along with an organisation that is built around managing a supply chain and assembly for multiple reactor projects at one time.

Getting existing nuclear suppliers ready will require a fundamental change in thinking from the current construction engineering approach to a manufacturing mindset, along with an organisation that is built around managing a supply chain and assembly for multiple reactor projects at one time.

To build a supply chain that can deliver an SMR programme, nuclear vendors and suppliers should:

- **Design for manufacture and assembly.** Advanced techniques and processes should be applied at the early stages of design in order to achieve the highest cost reductions. As technology readiness levels increase, the technical and economic feasibility of applying advanced techniques and processes decrease substantially.
- **Design for NOAK delivery.** Supply chain, manufacturing facilities and processes should be optimised from the FOAK design to support SMR manufacture of the same design at high production rates to realise benefits from learning effectively.
- **Optimise business model for delivery.** Establish an effective underlying business model that is able to:
  - Schedule and manage an integrated supply chain and multiple projects
  - Deliver using a consistent workforce, streamlined business processes, and rigorous tools and technology
  - Underpin NOAK delivery at a competitive cost and schedule, ensuring an iterative and joined-up programme

A strategic delivery path for vendors should also focus on:

- **Tactical innovation.** Innovation in the nuclear industry is often seen as a cost driver rather than as a means of cost reduction. A shift in culture is required where vendors proactively pursue innovation that balances investment with benefits delivery.
- **Early engagement with the ONR.** Cost escalations in nuclear projects can be in part associated with design changes required to meet regulatory requirements. Early engagement with ONR the can provide a level of mitigation as design amendments could be made earlier in the maturity curve.

8 Delivery: realising the benefits

- If SMRs are to become more cost-effective, the approach will need to be very different from that typically taken for large reactors.
- A robust programme will be required with a single reactor design delivered in high volumes through a standard supply chain.
- It is expected to take over 10 years to develop the first SMR; developing the supply chain requires a FOAK unit to be proven to operate in the UK power market.

If SMRs are to become cost-effective, the following conditions need to be met:

Factory learning

- Select a single design based on sound and proven technology
- Achieve a production rate of 10 reactors per annum
- Design for modularisation and factory build, maximising application where viable
- Minimise design changes
- Establish and use a consistent supply chain
- Incentivise supply chain to deliver these improvements and pass on the benefits
- Exploit the global market
- Review regulatory process to consider:
  - Licensing of a design to a vendor
  - Simultaneous licensing of a design in multiple countries
- Invest in relevant skills and manufacturing infrastructure

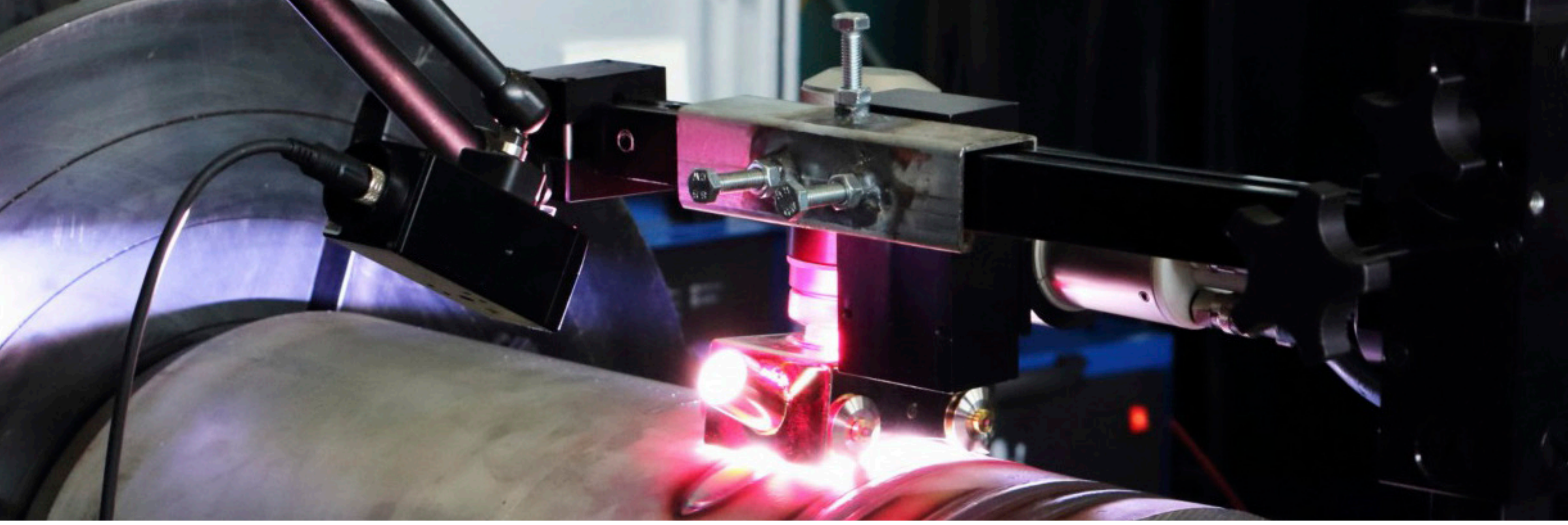
Schedule benefits

- Select a single design based on sound and proven technology
- Achieve a production rate of 10 reactors per annum
- Design for modularisation and factory build, maximising application where viable
- Minimise design changes
- Establish and use a consistent supply chain
- Apply advanced construction methods
- Invest in relevant skills and manufacturing infrastructure

SMR programme stages

For SMRs to be successful, a robust delivery programme will be required, ensuring an integrated, holistic life cycle approach from design through to NOAK deployment. A number of considerations should be taken into account:

Pre-GDA	GDA
Define the business case, programme and competition for SMRs, including design requirements, and review the regulatory requirements	Obtain design acceptance certificate for a selected design, complete site planning for FOAK, and set up production capacity and supply chain



One-off capex savings

- Fully implement BIM from early design
- Ensure the use of a common BIM platform across the delivery chain
- Design for modularisation, advanced manufacture and advanced construction methods, maximising application where viable
- Invest in the development of advanced manufacturing techniques
- Maximise co-siting of multiple reactors on the same site
- Invest in relevant skills and manufacturing infrastructure

Load following

- Establish the UK's future load following requirements
- If applicable, determine the optimum means of incentivising operators to load follow
- Assess specific designs for their ability to load follow

Operations

- Select a single design with low technical risk
- Employ a single utility to operate multiple reactors
- Adopt consistent operating practice across multiple SMRs
- Maximise co-siting of multiple reactors on the same site
- Conduct analysis of operational costs for specific designs and modes of operation
- Invest in the safety case for shared control

FOAK

Build and operate FOAK with a view to confirming production characteristics and cost profile for NOAK

NOAK

Series deployment of SMRs to meet the UK Government's programme objectives

Glossary

Advanced Boiling Water Reactor (ABWR)	A large (LNRM) Generation III boiling water reactor that is already licensed in Japan and the USA; four units have been built in Japan, and two are currently under construction in Japan.
Advanced Manufacturing Research Centre (AMRC)	Located at the University of Sheffield, it is dedicated to advanced materials and machining research.
AP1000	A large passive pressurised water reactor with modularisation; an LNRM.
Base-load	Base-load power sources can consistently generate the power needed to satisfy minimum demand.
Capacity factor	Refers to the ratio of the actual power produced by a plant to the potential power that could be produced by that plant over a specific time frame; also known as load factor.
Capital expenditure (capex)	The cost of bringing an asset to a point of operation following the final investment decision; this cost consists of the main plant and equipment package, typically called the engineering, procurement and construction (EPC) price as well as the infrastructure and connection costs.
Civil construction	The process associated with the design and build of bridges, dams, roads and large structures.
Co-siting	The building of multiple reactors on one site.
Critical path	The sequence of activities that determines the overall length of a project; this series of operations outlines the shortest possible completion.
Development expenditure (devex)	The cost of bringing a project to the point of final investment decision, including permitting and advisory services. In the case of the FOAK plant, this also includes the cost of bringing the technology through a GDA process.
European Pressurised Reactor (EPR)	A large pressurised water reactor; an LNR.
Economies of scale (change)	A term used to represent the increased cost efficiency that can be realised when a product is made at a larger physical size, when the cost per unit volume of material is typically less than its smaller counterparts.
Factory build	The fabrication of a component through the application of manufacturing techniques in a dedicated factory.
Finance costs	The interest and funding cost for repayment of the capex over the lifetime of the plant; the approach taken in this report is to apply a single cost of capital to all cash flows, including the schedule of capexs.
First of a kind (FOAK)	A term often used in economics where the costs associated with production of the first generation of a component are typically higher than later iterations.
Generic Design Assessment (GDA)	Used by UK regulators to assess the safety, security and environmental implications of new nuclear reactor designs separately from applications to build them at specific sites.
Gigawatt electrical (GWe)	A unit of power equivalent to 10^9 watts.
In-process savings	The savings that are achievable through the improvement of a current process, including labour, material and tooling costs.
International Atomic Energy Agency (IAEA)	An international organisation that serves as an intergovernmental forum for scientific and technical cooperation in the peaceful use of nuclear technology and nuclear power worldwide.
Large nuclear reactor (LNR)	A reactor system with an output in excess of 700MWe.
Large nuclear reactor with modularisation (LNRM)	Any nuclear reactor with output >700MWe that is designed for modularisation and contains large parts made of multiple components which are prefabricated off-site.
Large reactor	For the sake of this study, this is defined as an Large reactor with or without modularisation (LNR or LNRM).
Learning rate	The rate at which an individual or organisation gains skill or efficiency from their experiences and applies it to future applications in order to reduce cost or time of production.

Levelised Cost of Electricity (LCOE)	This represents the unit cost (per kilowatt hour) in real value of building and operating a power plant over an assumed financial and operational life cycle
Load following	A term reflecting the ability of a power supply to adjust its power output, depending on the current electricity demand.
Manufacturing Capability Readiness Level (MCRL)	A method used to assess the maturity of a technology, component or system with respect to manufacturing. MCRL is based on a scale from one to nine, with nine being the most mature.
Megawatt electrical (MWe)	A unit of power equivalent to 10^6 watts
Metrology	A scientific method of measurement to qualify novel parts and processes to ensure they meet specification standards.
Modularisation	A technique and philosophy which is used to design complex structures using individually designed sub-assemblies and components.
Module	Individually designed sub-assembly or package of components with interfaces for assembly.
Nth of a kind (NOAK)	A term used in engineering economics to identify the nth item or generation of items following on from the FOAK.
Office for Nuclear Regulation (ONR)	The regulatory authority responsible for governing the civil nuclear industry in the UK. This includes the operating of the GDA process to assess reactor designs.
Operating expenditure (opex)	The cost of maintaining a plant, including both the cost of keeping the plant available to generate (fixed opex) and the incremental cost of generation (variable Opex). Variable costs of operation include fuel, output related repair and maintenance, residue disposal and the incurring of charges that will fund the decommissioning costs after the operating life of the asset.
Operations and maintenance (O&M)	All actions which have the objective of retaining or restoring an item in or to a state in which it can perform its required function these include the combination of all technical and corresponding administrative, managerial and supervision actions.
Nuclear power plant	A thermal power station in which the heat source is a nuclear reactor.
Power density	A term that captures the amount of power per unit volume.
Power Reactor Information System (PRIS) database	A comprehensive database focusing on nuclear power plants worldwide, containing information on power reactors in operation, under construction or being decommissioned.
Pressurised water reactor (PWR)	A type of light water reactor (LWR). In a PWR, the primary coolant (water) is pumped under high pressure and prevents boiling to the reactor core, where it is heated by nuclear fission reactions. The heated water then flows to a steam generator, where it transfers its thermal energy to a secondary system that generates steam before flowing to the turbines which, in turn, spin an electric generator.
Ramp rate	The ramp rate of a power source refers to the overall change whether an increase or decrease, of output of a power source per unit time. It is usually presented as % per min.
Reactor	For the purposes of this study this refers to a single SMR or large-scale nuclear reactor unit
Research and development (R&D)	Any activities in connection with innovation or the development of new products or procedures.
Small modular reactor (SMR)	An advanced reactor that produces electric power of up to 300 MWe, designed to be built with modular components in factories and transported to site for installation; there is no distinction regarding technology, safety systems or reactor generation.
Standardisation	The process associated with developing standards with a view to enhance the repeatability, quality and consistency of a process.

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EY and collaboration authors






Chris Lewis
EY

Ray MacSweeney
EY

Miranda Kirschel
EY

Will Josten
EY

Tony Roulstone
Bracchium

Giorgio Locatelli
University of Leeds

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