Doing more with nuclear

Rushton, Michael; Evitts, Lee J.

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ADVANCED REACTORS

Doing more with nuclear

Why stop at power generation? Here, *Michael JD Rushton* and *William E Lee* suggest that small modular and other advanced reactors could also be employed to generate heat for use in homes and industry, as well as to create clean hydrogen. Experience of both exists in Europe and Russia.

The nuclear reactors under construction at Hinkley Point are all about big numbers: after an expected construction time of eight years, they will generate 3.2 GW of electricity for at least 60 years. Their price is also huge, with a projected cost of over £20bn. Once operational, the performance of such stations is impressive but in recent years actually getting large nuclear projects built has proven difficult – schemes of similar magnitude have failed at Moorside (3.4 GW), Wylfa (2.7 GW) and Oldbury (2.7 GW).

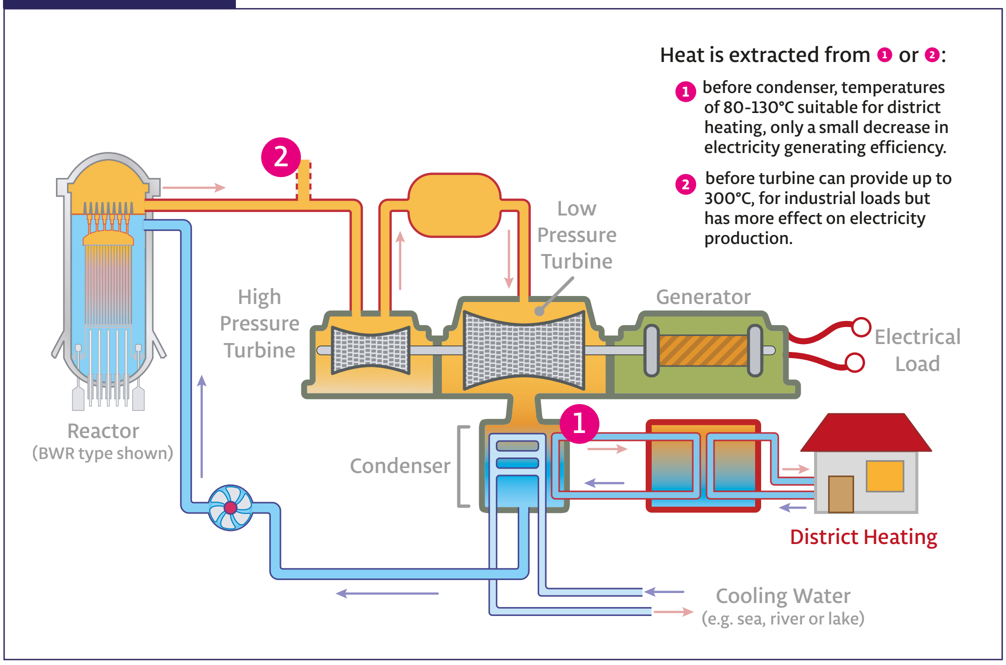
The large up-front cost and long pay-back period of big nuclear has made attracting private investors difficult. Even with the promise of government support such schemes have failed more often than they have succeeded. Could it be that thinking big is not nuclear's answer and that small is beautiful?

The 'small' in SMR primarily refers to their electrical output, which is typically below 500 MW. At the centre of their philosophy is the idea that the thermal output of a small reactor is easier to manage than in gigawatt reactors, allowing them to be simpler in design and therefore cheaper to build. Secondly, series factory production, including the adoption of advanced manufacturing methods and assembly line techniques, aims to reduce reactor cost and the need for on-site fabrication.

Instead, modules will be delivered to the build site then bolted together quickly – reducing construction time. SMRs aim to have a smaller physical footprint and lower cooling requirements, allowing more flexibility in their siting.

The SMR concept addresses the major issues with current nuclear projects – namely the high upfront cost and long build times. If build times can be brought down to around four years and cost savings of around 40-50% per kW can be achieved in comparison to current nuclear plants, SMRs could be cost competitive with gas in the future. GE-Hitachi have stated this is their aim with their BWR-X 300 SMR (see below) and have set themselves a cost target of $2,250/kW.

Figure 1. Diagram of an SMR system and methods for heat extraction
Source: authors



Three SMR designs

The leading designs for SMR deployment in the UK are the GE-Hitachi BWR-X 300, Rolls-Royce UK SMR and NuScale designs. All three are water-cooled reactors with the first two being relatively conventional in design. GE's BWR-X 300 is a 300 MW boiling water reactor (BWR) and the Rolls-Royce UK SMR a pressurised water reactor (PWR). In both cases they are modern designs optimised to take advantage of their smaller size through simplification, modularisation and factory construction.

Despite this, in terms of their overall layout and system architecture, they are recognisable as scaled down versions of BWR and PWR plants.

The NuScale reactor is a little different. Rather than generating its power from a single reactor, it will house several smaller reactors, known as power modules, each generating 77 MW. Using configurations with four, six and twelve power modules, total outputs of 308 MW, 462 MW and 924 MW are being proposed.

All three vendors are aiming for their first reactor to be built by the end of the decade. NuScale is slightly ahead, having received standard design approval from the US Nuclear Regulatory Commission in September 2020.

Due to the lower output of each reactor, a fleet of SMRs would be required to achieve the same capacity as a smaller number of big reactors, which could put pressure on site availability. In a densely populated country such as the UK, this may inevitably lead to sites nearer centres of population. However, this isn't without precedent, as the existing AGR stations at Hartlepool and Heysham were built in semi-urban areas, indicating that the UK regulatory system is robust and flexible enough to support such locations – although this is still a time-consuming process.

Nuclear district heating?

Decarbonising domestic heating poses a significant challenge in achieving the 2050 net zero goal – 72% of domestic energy in the UK is consumed as natural gas, oil or as solid fuels – the majority of which are used for heating. By comparison, only 22% of domestic consumption is electricity, with only 8% of homes using electric heating. However, nuclear district heating schemes are as old as the nuclear industry itself with examples in Canada, Russia, Sweden, Hungary, Bulgaria, Slovakia, Romania, Switzerland and China – and could help address this challenge.

These schemes use input temperatures of 80–130°C, which is easily generated from the 280–300°C steam from water cooled SMRs. High losses mean that heat is a poor long distance energy carrier, so consumers are normally within 50 km of the reactor, though longer distances are possible – the longest Russian distribution line is 72 km. The siting flexibility of SMRs should make them well suited to district heating as they can be sited closer to consumers to reduce heat transmission losses.

Heat extraction occurs between the SMR's low pressure turbine and condenser leading to a slight reduction in electricity generating efficiency – see **Figure 1**. This is compensated by a large increase in overall system efficiency: achieved by using heat that would otherwise be rejected to the environment and giving efficiency values up to 70–80% compared to the 33% obtained during electricity generation.

The Beznau district heating system in Switzerland is a good example of what may be achieved using an SMR installation. Its two 1960s era Westinghouse PWRs are similar in capacity to a SMR, each producing 365 MW. The plant delivers 150 GWh per year of heat to supply 2,432 connected homes. The loss of electrical power due to district heating is 18 GWh per year (around 0.3 %). Here district heating only uses 0.75% of the reactor's total heat production.

Other schemes extract far more – for example the Bohunice plant in Slovakia supplies 240 MW heat, which is 10% of the heat produced by its two VVER-440 PWRs.

Does district heating make sense in a UK context? Perhaps not, as there is no great tradition of district heating in the UK (with only 2% of the population being served by it), meaning infrastructure would need to be built from scratch and existing houses converted to use it, which could be prohibitively expensive. However, for major new housing schemes where such provision could be designed in from the start, it may remain as a viable option.

Alternatively, as 85% of households are connected to the natural gas network, nuclear generated hydrogen (see below) blended into the gas supply may be a more pragmatic route to decarbonisation of domestic heating.

High temperature heat for industry

Industrial loads may be a better use for nuclear process heat. Factories tend to be sited on industrial estates away from city centres and these clusters of businesses could be serviced by localised heat distribution networks with heat from a small reactor.

Although SMRs are able to supply temperatures up to 300°C, some applications require temperatures well beyond this, see **Figure 2**, including difficult to decarbonise processes like steel smelting (900–1300°C). With this in mind, a recent competition organised by the Department for Business Energy and Industrial Strategy (BEIS) aims to promote the development of what it terms advanced modular reactors (AMRs).

AMRs adopt the SMR philosophy but emphasise the production of high-grade process heat. Achieving higher temperatures than available from SMRs requires different reactor designs. Three designs have progressed to the second round of this competition each receiving a share of £40mn funding – Tokamak Energy's small fusion reactor, the Westinghouse lead-cooled fast reactor and Urenco's high temperature gas cooled U-Battery.

UKAEA's small fusion reactor the Spherical Tokamak for Energy Production (STEP) has recently received £250mn UK government funding. AMRs still require considerable development and the mid-2030s are being targeted for first deployment.

There is already a degree of operational experience with the metal (Westinghouse) and gas cooled (Urenco) fission reactors included in the AMR competition. The UK ran sodium metal-cooled reactors operating with a fast neutron flux until the 1990s at Dounreay with the prototype fast reactor delivering up to 250 MW to the National Grid. Meanwhile, Russia's BN-800 820 MW reactor demonstrates the maturity of the technology with a capacity factor of 68% rivalling the fleet average for the UK's AGR fleet since opening in 2015 (the earlier BN-600 is better still at 74%).

The Russian BREST-300, now under construction, has a lead-

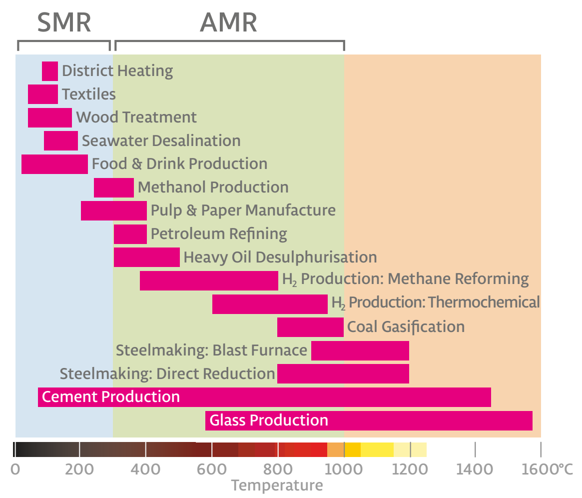


Figure 2. Temperature requirements for various industrial processes and range of applicability for SMRs and AMRs *Source: authors*

Government backs nuclear for green hydrogen production

Nuclear power could produce one-third of the UK's clean hydrogen needs by 2050, according to the Hydrogen Roadmap agreed by the Nuclear Industry Council (NIC) in February. The NIC, co-chaired by the Minister for Business, Energy and Clean Growth and the Chairman of the Nuclear Industry Association (NIAUK), sets strategic priorities for government-industry collaboration to promote nuclear power in the UK.

The roadmap outlines how large-scale and small modular reactors (SMRs) can produce both the power and the heat necessary to produce emissions-free hydrogen. Nuclear stations also provide a constant, reliable supply of power that allows electrolysers to operate more efficiently, cutting production costs.

Existing large-scale reactors could produce green hydrogen at scale through electrolysis, as could the next generation of gigawatt-scale reactors. SMRs, the first unit of which could be deployed within the next ten years, would unlock further possibilities for green hydrogen production near industrial clusters.

Advanced modular reactors (AMRs) under development offer one of the most promising innovations for green hydrogen production, since they will create temperatures high enough to split water without diverting electricity. The ability to generate both power and hydrogen would cut costs further, add flexibility, and allow co-location of reactors with industry to aid further decarbonisation, says the NIAUK. The UK government has targeted an AMR demonstrator by the early 2030s.

The roadmap estimates that 12–13 GW of nuclear reactors of all types could use electrolysis, steam electrolysis using waste heat and thermochemical water splitting to produce 75 TWh of green hydrogen by 2050.

Since the main obstacle to green hydrogen production is cost, the report identifies immediate steps to encourage nuclear-hydrogen development, including funding for electrolyser research and grants to zero carbon generators of all kinds, including nuclear, to install electrolysers.

cooled open pool design similar to the Westinghouse AMR, with both having outlet temperatures of around 500°C. It is due for completion in 2026.

The U-Battery is gas-cooled and is described as a micro-reactor due to its low 4 MW output. It would produce process heat at 710°C. Following a significant research effort in the 1970s the development of high temperature gas reactors has been frustratingly slow, given their clear promise for very high temperature operation.

A good example of the current state of the art is the 30 MW Japanese, High Temperature Engineering Test Reactor (HTTR) commissioned in 1998. This demonstrated continuous operation at an outlet temperature of 950°C for 50 days in 2010. This is significant as it is high enough to allow steel production via direct reduction without emitting carbon dioxide. It also enables thermochemical routes to hydrogen production (see below).

Clean hydrogen production

Production of hydrogen without any carbon dioxide emissions is another environmentally-friendly application for SMR and AMR technology. While nuclear electricity could power low-temperature water electrolysis, in the way proposed for renewables (eg using proton exchange membranes), it would really come into its own when also using heat to greatly improve the efficiency of hydrogen production.

In steam electrolysis, temperatures of 700–800°C are used alongside electricity to split steam with a solid oxide cell to give a thermal-to-hydrogen efficiency of 50%, double the overall efficiency of low-temperature electrolysis. The US Department of Energy has estimated that a high temperature gas reactor with a thermal capacity of 600 MW could produce hydrogen at a rate of 2.5 kg/s using this method, comparable to the large steam methane reforming plants operating today but without their carbon dioxide emissions.

There is still a significant increase in efficiency at the lower temperatures produced by other AMR concepts meaning they could all be useful for hydrogen production.

Reactors operating at even higher temperatures are able to produce hydrogen with even better efficiencies using thermochemical routes. The 950°C produced in Japan's HTTR (see above) has demonstrated the sulphur-iodine cycle where heat, sulphur and iodine compounds are used to split steam into hydrogen and oxygen. In 2019 this operated continuously for 150 hours to generate hydrogen at a rate of 30 litres/hour.

At the centre of the philosophy of SMRs is the idea that the thermal output of a small reactor is easier to manage than in gigawatt reactors, allowing them to be simpler in design and therefore cheaper to build

Some important industries require temperatures above 1,000°C, such as cement (1,450°C) and glass (1,575°C) manufacture. None of the reactors described can reach these temperatures. Hydrogen produced using AMRs may be able to help, as burning it in oxyhydrogen mixes allows temperature up to 2,800°C which would enable these processes.

We believe, and hope this article has demonstrated, that a mix of renewable and nuclear technology is a viable route to the UK achieving net zero by 2050 while retaining a successful economy and society. ●

Michael JD Rushton and William E Lee are both with the Nuclear Futures Institute at Bangor University.