Small Modular Reactors

What is the fuss about and does it matter?

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All nuclear reactors are not born equal. Two distinct families have emerged: large reactors, such as Hinkley Point C and Wylfa in North Wales, then a younger family with about thirty-year-old parents called the SMRs, small modular reactors. The SMRs are claimed to be more agile, quicker to reproduce via factory techniques and, most importantly, inherently safe.[1] The SMR family is emerging with extraordinary genetic diversity ranging from scaled-down, traditional, pressurised, light-water reactors to fundamentally different advanced modular reactors with different inner workings suitable for wider application in industry, domestic heating, electricity and transport. Since the 2014 publication of my earlier Civitas paper, 'Use It or Lose it: A business case for an alternative way to rejuvenate the UK nuclear industry',[2] SMRs have shot up the political agenda. The UK Government has separated the SMRs into two separate groups – light water reactors and the advanced modular reactors, which are all high temperature reactors – and will decide which makes it to market first. Why does this matter? This paper explains the crucial differences and why only high temperature advanced modular reactors could produce the national scale of carbon-free heat, hydrogen and electricity needed to transform our fossil-fuelled energy infrastructure. The argument now is about ensuring policy decision makers take a strategic, symbiotic approach to whole energy systems. Choosing the wrong sort of SMR for the UK could derail any attempt to meet carbon targets, vastly increase the cost of energy bills and leave a legacy of environmental, social and balance of trade issues.

To understand the argument requires a brief understanding of the energy difficulty the country is in. If the UK is to prosper post-Brexit, UK trade, industry and services must demonstrate strong and sustainable growth. However such growth is delivered, all sectors of business and society depend on one common denominator: access to affordable, 100% reliable energy. Energy is more than electricity, it includes heating our homes, fuelling our transport, industrial processes and much more. If the UK intends to comply with existing and subsequent energy and environmental

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[1] https://www.thechemicalengineer.com/features/cewctw-trevor-kletz-a-lifetime-spent-saving-lives/

[2] http://www.civitas.org.uk/content/files/IEGissue11.pdf

EU Directives that will doubtless remain in force as part of any bilateral EU trade negotiations, that energy must be low carbon; not coal or gas or oil. In addition, the UK has legally adopted the Climate Change Act of 2008 that demands greenhouse gas emissions, mainly carbon dioxide, are reduced by 80% by 2050. This means no coal or natural gas to drive industry, for fertilizer manufacture or for central heating. Decarbonising just electricity is the easier part of the story. As the CEO at Shell stated: 'If the whole power sector went zero carbon tomorrow, then that would only decarbonise some 20% of end-users' energy needs. Fossil fuels still dominate the other 80%. This is the reality. Change will come, but not at the flick of a switch.'[3]

UK interest in SMRs is in the context of our Clean Growth Strategy because they address both the 'Clean' and 'Growth' aspects due to the UK's combination of home market and unique selling points. The UK is a competitor in a global endeavour to bring SMRs to large-scale commercial reality. The United States 'has long recognized the transformational value that advanced SMRs can provide to the Nation's economic, energy security, and environmental outlook'.[4] Support started in the shape of a $452m[5] pot of funding to support new SMR technology through its arduous licensing process, first with mini versions of the traditional pressurised water reactors (PWRs), like Hinkley C and Sizewell B. Now they are investing several hundred million dollars in advanced modular reactors, despite having the luxury of large-scale fracking to keep their lights on and their industries energised. This autumn, following extensive consultation, the Canadian government is publishing a Roadmap to develop and deliver SMRs. It has extended an invitation for technology vendors to apply to site an SMR demonstration unit at a Canadian Nuclear Laboratories-managed site. Direct Canadian government investment in private companies[6] to develop an advanced modular reactor, has already resulted in the first successful completion of Phase One of the Pre-Licensing Vendor Design Review with the Canadian Nuclear Safety Commission, applying safety principles similar to those we use in the UK.

Small high temperature gas-cooled reactors, HTRs, have been built and reliably run in China and Japan since the turn of the millennium. In China, two 100 MWe HTR reactors are expected to be commercially operational in the next six to eight months. Japan too has spent many decades developing and successfully testing its HTR gas-cooled research reactor, which first ran in 1998 and has proven its inherently safe properties. HTRs are advanced modular reactors using technologies developed in the UK, Germany, USA, South Africa, China and Japan. The original development took place in the UK in the 1950s to 1970s, which led to the fleet of

[3] Speech given by Ben van Beurden, Chief Executive Officer at Shell, for the Aurora Spring Forum in Oxford, UK, on March 22 2017

[4] https://www.energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors

[5] https://www.energy.gov/articles/obama-administration-announces-450-million-design-and-commercialize-us-small-modular

[6] https://www.terrestrialenergy.com/2016/09/terrestrial-energy-surpasses-cad-20-million-financing-milestone-imsr-development/

Magnox and then the advanced gas-cooled reactors upon which about 20% of UK's electricity continues to depend. The international market eagerly awaits as countries such as Jordan, Saudi Arabia, Indonesia and Poland see SMRs as an affordable route to local, decentralised energy independence away from fossil fuels with their unwanted carbon content and price volatility.

The UK has not missed the advanced modular reactor opportunity, with world-class fundamental research taking place in our universities, but development from it has been rather slower than elsewhere. The UK Government recommenced investing in SMR application in 2013, in terms of viability for UK deployment. Following an open competition process the Department of Business, Energy and Industrial Strategy (BEIS) is currently supporting selected national and international technology vendors, having differentiated SMRs into PWRs and advanced modular reactors. All eight of the selected advanced modular reactors are HTRs. These produce heat at high enough temperatures for industrial processes, for hydrogen production from water and for domestic heat. The PWR group of SMRs is not able to operate at the high temperatures needed by industry. These high temperatures are produced using far less pressure than is necessary with a PWR. Higher temperatures also greatly improve efficiency. The Japanese gas-cooled HTR, for example, can produce heat at an efficiency of 80%, compared with only a 33% efficiency for PWRs. British engineers knew this in the 1960s when they chose to cool UK reactor designs with inert gas instead of volatile water. This perhaps conservative but wise decision resulted in the 14 gas-cooled reactors that have served the UK well and continue to do so. Most importantly, that design and operational experience is now highly prized as the HTR SMRs come to market.

Does this all matter to the UK? Whether high temperature advanced reactors or small PWRs, surely competition is ultimately good for the customer in a buyer's market. In theory, yes, but we do need to be an intelligent customer. The UK has made the mistake before of building reactors out of step with the international market, thus excluding any possibility of exports. Selecting a technology out of step with the transitional direction of UK energy will have additional consequences to failing to establish an export market. Like the UK, the global community is having to come to terms with the massive challenge of carbon-free methods to heat homes, hospitals, offices, to drive transport and to decarbonise industrial processes such as hydrogen production. If we do not start investing in long-term sustainable solutions that can address not just carbon-free electricity but heat, hydrogen and transport the country will have to continue its reliance on oil and gas. In 2017 gas met nearly two thirds of total domestic energy demand.[7] While gas has half the carbon content of coal, continued use of gas at its current level or an elevated demand will defy all attempts to meet national and international carbon targets. Some advocate a short-term

[7] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/729395/Ch4.pdf

option of using carbon capture, utilisation and storage (CCUS). However, CCUS technology is not proven on a commercial scale, plus Government-commissioned reports have repeatedly identified that the operation of CCUS, and its associated distribution and storage infrastructure, are extraordinarily expensive. In addition, the UK's indigenous supply of gas is reducing, forcing increased imports at volatile prices.

Nuclear was always seen in terms of just electricity generation and indeed large nuclear will continue to play a vital role in providing zero carbon electricity with the gigawatt new build programme to replace some of the existing fleet of 15 reactors around the UK (all gas-cooled HTRs except the PWR at Sizewell B), as they come up for well-earned retirement. Wind, solar and biomass combustion have made impressive progress over recent decades, with many also approaching well-earned retirement. It is 27 years since the first wind farm started operating and now renewables supply up to a quarter of the UK's electricity, although at significant cost to consumers. Considerable long-term subsidies paid for by the consumer on their bills, plus guaranteed priority access to the grid, have been drivers of development. By 2020, subsidies are expected to be in the region of £7bn a year. This level may start to test the ability and willingness of the consumer to pay in the face of other draws upon discretionary expenditure, especially if cheaper ways of achieving the same environmental result emerge from the vibrant pool of development and deployment options. The Committee on Climate Change believe that the costs of decarbonisation are already estimated at 20% of typical electricity bills. Dieter Helm's recent energy review for the Government, points out that the legacy costs of the existing contracts for renewable projects will amount to over £100 billion by 2020.[8] This is for just the renewables part of the electricity component, which itself is only 20% of the UK's energy demand.

This does not leave much capacity to tackle the hardest sectors to decarbonise that make up the other 80% of the UK's energy use; heating, transport and industrial processes. Industrial processes require high grade heat, over 500ºC, which neither renewables nor large or small PWRs can physically achieve. Happily, small HTRs could meet the UK's pressing need to provide this with zero emissions at the points of heat and power use and production.

Industrial processes require the kind of heat made in industrial gas and coal boilers whose flame furnaces operate in the red heat zone around 900ºC. PWR-style SMRs cannot supply such heat as explained above. Wind, solar and biomass burning could be expanded further to fill the heating gap, such as heat pumps. That would need massive investment in energy transmission systems as has been presented by National Grid in

[8] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/654902/Cost_of_Energy_Review.pdf

its Future Energy Scenarios.[9] There are, however, fundamental physical limits for renewables' contribution as quantified by the Government's late Chief Scientific Adviser David MacKay in his ground-breaking book *Sustainable Energy – Without the Hot Air*.[10] HTR types of SMR can provide this type of heat with zero emissions at both the points of decentralised heat and power use and their points of decentralised production which also elegantly addresses the transmission problem for this difficult heat part of the energy picture. Heat is 40% of UK's energy overall consumption, electricity is 20%, which could also be decentralised SMR, so that leaves 40% to consider; transport.

Transport in particular is responsible for a cocktail of emissions. Encouraging motorists to invest in diesel vehicles, on the understanding they produced lower carbon emissions, has led to unacceptable air pollution in many of our cities. Myopic focus on carbon dioxide blinded politicians to scientific data available at the time on the dangers of nitrogen oxide and particulates emitted by diesel cars. When in 1848-49 15,000 people died from cholera the first Clean Water Act (Metropolis Water Act 1852) was implemented. In 1952 air pollution from the Great Smog in London killed 4,000, thus in 1956 the Government brought out the Clean Air Act. Today the British Lung Foundation attribute 40,000 early deaths a year to air pollution. London is at times over World Health Organization limits. This is no territory for knee-jerk reactions. Energy and public health are multi-billions of pounds per annum business in UK alone and globally are among the largest organs of true public good. Balancing society's holistic needs with evolving technology is not new but the options and implications are wider than ever. Never has the need for the interdisciplinary systems engineering thought processes been more acute, uninterrupted by simplistic single-issue pressure groups and vested interests.

The Government is making a concerted effort to switch to electric vehicles (EVs), with a new strategy setting out its ambition for at least 50%, and as many as 70%, of new car sales to be ultra-low emission by 2030, alongside up to 40% of new vans.[11] A plethora of supportive initiatives have been rolled out including the 'Faraday Battery Challenge' to develop and manufacture batteries for the electrification of vehicles, worth £246 million over four years.[12] It is part of the Department for Transport's Road to Zero strategy, a £1.5bn programme for low and zero emission vehicle research, development and infrastructure, including charging point infrastructure and hydrogen fuel cells.[13] Pressurised hydrogen is stored on the vehicle and then used via a fuel cell to generate electricity, which provides electric traction.

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9 http://fes.nationalgrid.com
10 https://www.withouthotair.com/download.html
11 https://www.gov.uk/government/news/government-launches-road-to-zero-strategy-to-lead-the-world-in-zero-emission-vehicle-technology
12 https://faraday.ac.uk/the-faraday-institution-announces-42-million-for-energy-storage-research/
13 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/739460/road-to-zero.pdf

Carbon emissions, however, are not going to be eliminated unless cars, vans, lorries and trains are charged with electricity or hydrogen produced by low or zero carbon methods. If all transport, including difficult modes such as aircraft, ships, farm equipment and construction plant are run by electricity then the power demand and transmission capacity will approximately double from the present. Substituting transport's 40% in addition to heat's 40% is a challenge not to be underestimated. This point is reassuringly covered by the new Road to Zero strategy, albeit at point 39, confirming that a Taskforce is being created to tackle the future energy demand for transport question.

Hydrogen is increasingly likely to play a major role in fuelling heavy goods vehicles and long-distance driving. In the chemical industry, hydrogen is used to make ammonia for agricultural fertiliser (the Haber process) and intermediates in the production of plastics and pharmaceuticals. It is also used to remove sulphur from fuels during the oil-refining process. Large quantities of hydrogen are used to hydrogenate oils to form fats, for example to make margarine. In the glass industry hydrogen is used as a protective atmosphere for making flat glass sheets. In the electronics industry it is used as a flushing gas during the manufacture of silicon chips.[14] Worldwide and in the UK, hydrogen is produced by stripping carbon atoms from natural gas to leave just hydrogen and then releasing the carbon as carbon dioxide into the atmosphere. Thus, finding a low-carbon production of hydrogen is essential, even without new, additional, large-scale applications such as transport.

Hydrogen is found in the greatest quantities as water. It is present as a gas in the atmosphere only in tiny amounts, less than one part per million by volume. Unlike CO_2, any hydrogen that does enter the atmosphere quickly escapes the Earth's gravity into outer space. Because of their high operating temperatures, the SMR HTR reactors can convert water or steam directly to hydrogen, without the need for electrolysis,[15] by direct thermal decomposition of the water molecule into hydrogen and oxygen. Lower temperature PWRs cannot do this. Worldwide, direct production of hydrogen at high temperatures is under very active development, most notably in Japan where a strategy for a hydrogen economy will be highlighted at the Tokyo Olympic Games in the summer of 2020.

Thus, in summary HTRs are remarkably well suited to the local production of hydrogen-fuelled feedstock for transport and industrial manufacturing, for the local production of industrial and domestic heat, and for the decentralised efficient production of zero-carbon electricity, all close to the points of consumption. Being decentralised they can respond locally at the point of need to seasonal and daily heat and power load patterns, without the additional capital cost and inefficiencies of secondary energy storage.

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[14] http://www.rsc.org/periodic-table/element/1/hydrogen

[15] Electrolysis is the splitting of water into its constituent parts, hydrogen and oxygen, by passing an electric current through it.

HTRs are financeable off the public balance sheet. A 100MWe power plant costs approximately £500m; about the same as an A380 Airbus. Cost per MWh of electricity for a UK manufactured HTR SMR should be in the region of £65/MWh or lower when their associated heat and hydrogen sales are included. Many factors converge to lower the capital costs of these smaller technologies; less upfront capital required, factory-built and offsite quality-controlled manufacturing, reduced onsite delays, standardisation and economies of mass production in place of economies of scale. The standardisation of units should bring build time down to 36-48 months, compared with 10 years for large plants such as Hinkley C. However, the small size has an even greater advantage. All developers of SMRs, whether the PWR family or HTR family, appreciate that to be deployed in large numbers close to industry, their technologies must be unquestionably safe. In practice, this is the main reason why they are small. It is a universal truth of geometry that the surface area of a vessel increases, relative to its volume, as it becomes smaller. The result is that the surfaces of most small reactors can naturally dissipate their residual heat to their surroundings without human intervention or sophisticated controls before they reach a temperature which damages their internals. This kind of inherent safety based upon fundamentals, not probabilities or electromechanical systems, is a guiding principle for all SMRs.

The question arises whether there is an HTR SMR commercially ready in which the UK can participate. There are no home-grown UK PWRs or HTRs yet, although both are under research and development with several designs being encouraged and supported by BEIS and have long-term potential. However, the National Nuclear Laboratory (NNL) concluded that one option would be to partner with an international HTR vendor.[16] Several countries have years of experience and invested billions on research, development and prototypes. They are open for a collaboration to the benefit of the UK in terms of speed to market, thus achieving carbon targets, accelerating the EV agenda, while securing opportunities for the UK, particularly utilising the intellectual property that resides in the UK's universities, the NNL, advanced manufacturing centres and sustaining the UK's wider supply chain. If the objective is to achieve decarbonisation of heat, industrial processes and transport at the most reasonable cost to UK businesses and consumers, it does beg the question: why should the UK taxpayer duplicate the expense of developing its own SMR when a strategic opportunity exists to partner with a mature international technology and gain value from UK intellectual property by actively partnering in final development and advanced manufacturing techniques?

The decarbonisation challenge is immense, requiring all the tools in the box; renewables, energy efficiency, nuclear large and small, transitional use of gas and well-informed, willing, public engagement as well as

[16] http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf

investment. Small HTRs contribute synergistically with all envisaged combinations of renewables, large nuclear and transitional gas, providing zero carbon heat, transport and electricity. It is this holistic and symbiotic approach to whole energy systems that must drive timely policy decisions, without forgetting that, in the race for carbon reduction, satisfying the UK's energy demand remains paramount. National security depends on it.

The Author

Candida Whitmill is an energy professional with an entrepreneurial business background. She believes strongly in ensuring the UK remains globally competitive through access to affordable, reliable energy for all businesses, industry and society. Her interests include extracting economic and social benefits from decarbonisation, rather than allowing it to become simply another financial burden for consumers.

Candida has been an energy advisor to three secretaries of state for energy and has had many papers and articles published on various energy sectors including gas, renewables and nuclear. She has lectured at universities across the UK and in Europe and has media experience on both radio and TV. Formerly the Chairman of the UK Tidal Forum, she worked extensively with her team on a feasibility study for the £20bn Severn Barrage, also investigating a contiguous set of barrages around the UK.

Candida is a Member of the Worshipful Company of Fuellers.

Candida is Managing Director of Penultimate Power UK Limited, which is dedicated to enabling the best affordable and sustainable solution to the UK's national energy security, incorporating economic and societal benefits to the UK with the provision of emission-free energy at both the points of use and of production.

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