Written evidence from Imperial College London (NCL0026)

Summary Statement

Nuclear energy will play a critical role if the UK is to achieve its target of Net-Zero by 2050 and support our future energy security.

The development of next generation nuclear fission plants and a successful nuclear industry in the UK is however dependent on ensuring progress across a number of technical, regulatory, skills and capability challenges. Without substantial support from the UK government, it is unlikely that a future successful nuclear industry in the UK will develop to the level required to meet our Net-Zero and energy security targets.

To help achieve its aims, the UK government should consider the following points:

- Greater government investment in the nuclear sector is required. The experience globally is consistent in that a successful nuclear fleet roll-out is correlated with size of the government investment.
- Develop the skills pipeline through the creation of dedicated national laboratories, ensure the continuity of funding for Centre's for Doctoral Training and expansion of undergraduate and masters' programmes with a nuclear component.
- Replicate the incentives for companies to base themselves at designated sites like Culham in order to create more sites of excellence in the UK.
- A decision be made as soon as possible for a minimum life extension of 10 years with the possibility of 20 years for Sizewell B.
- Greater funding for the long-term research and development programmes on closed fuel cycle technologies to help reduce the issue of waste.

What technical challenges do the next generation of nuclear fission power plants, including Small Modular Reactor and Advanced Modular Reactors, face?

Authors: Matt Eaton, Mark Wenman, Robin Grimes, Catrin Davies, Michael Bluck

It is important to distinguish between reactor types when discussing technical challenges:
- Large light water-cooled reactors (PWRs & BWRs) are very well understood with decades of design and operational experience and present few technical challenges.
- Small Modular Reactors (SMRs) can literally be smaller variants of current designs (e.g., Rolls Royce SMRs), or some perhaps have additional novelty such as using passive cooling with integrated cooling systems within the pressure vessel (e.g., NuScale).
- Advanced Modular Reactors (AMRs) which include some 'Generation IV' designs are technically more speculative but offer the potential for closed fuel cycles to greatly reduce waste concerns.

SMRs present several technical challenges with the most significant being fuel qualification (the regulatory approval of the fuel and clad performance). Fuel qualification is a significant technical and regulatory hurdle and can take a decade or more. However, the use of existing, already qualified fuel forms can reduce/eliminate this hurdle.

Advanced Modular Reactors (AMRs) are characterised by non-light water coolants. These can be gas-cooled, liquid metal-cooled and molten salt-cooled. A number of these will claim to be inherently safe and/or able to support a ‘closed’ fuel cycle. A closed fuel cycle results in much reduced waste (both in terms of volume and longevity).

Whilst there is some existing design and operating experience for the technologies underlying AMRs (uniquely, the UK has 60 years of gas-cooled reactor experience and some sodium-cooled experience), there is more to do for LWRs. Fuel development will be a significant technical challenge as all fuel forms will have to go through a full qualification process. In addition, closed fuel cycles will require the development of recycling processes and facilities.

Irrespective of design, the claimed benefit of factory-build modularity is key to the next generation concept. Currently, we have no experience of this (nor does anyone else). There are technical challenges in demonstrating this at scale with the appropriate sites, facilities and supply chains.

Beyond the reactor itself, cogeneration is becoming an important feature (both in terms of economics and environmental impact). Cogeneration technology can provide heat for domestic/commercial and industrial applications. There are technical challenges in doing this, depending on the application (low temperature steam is easy and well understood, high temperature less so). Future nuclear plants will need to become ‘load following’ and replace the role of the current gas plant’s flexible operation to accommodate renewables on the grid (i.e. increase/decrease supply in response to the availability of renewables) and to match the variability in demand.

Flexible operation leads to plant thermal gradients and hence stresses causing fatigue damage issues in plant component, as has been experienced on gas plants in recent decades. Hence, there is a need for new plant designs knowledge and experience to address the issue of fatigue (and the combined creep-fatigue behaviour of high temperature plant) behaviour of the materials employed.

However, issues with flexible operation can be accommodated for by co-generation, such that the power generated by the nuclear power plants doesn’t vary, but the output power is switched between electricity generation and e.g., energy for hydrogen supply.

Nuclear reactors are best suited to the generation of baseload electricity. In a renewables-dominated grid, there would be a need to adapt power generation in response to relatively short-time-constant changes – commonly called load following. Nuclear reactors can react to changes on such timescales, but it presents engineering challenges that may require more frequent maintenances and shorten the life of components.

Co-generation could help here; instead of load following, one could divert power to another application (e.g., hydrogen production) when demand reduces. In this way, the reactor operates optimally and provides an additional revenue stream.

For Very High Temperature Reactors (VHTR) that can support green hydrogen production, the UK would need a TRISO fuel factory to be built in short order to supply the fuel. Equally, while a demonstrator could be built with current high temperature creep and corrosion resistant steels, this may limit outlet temperatures to the lower end promised by BHTR closer to 750°C.

To reach the temperatures promised by VHTR of near 1000°C would require new steels to be developed. Any such programmes should be done in co-ordination with the fusion community as they have the same goals.

When will fusion power supply electricity to the grid?

Authors: Brian Appelbe, Michael Bluck, Matt Eaton

It is very difficult to provide a definitive answer as to when fusion power will supply electricity to the grid. The technical uncertainty around fusion is very large and stubbornly remains so. We would be surprised (pleasantly) if there is anything practical (by which we mean economic) before 2040, so fusion's role in net-zero by 2050 would be limited.

There have been some significant, headline-grabbing breakthroughs in the last few years (as considered below) but these are scientific breakthroughs (taking us closer to a "proof-of-concept" experiment for fusion energy) rather than commercial breakthroughs. A commercially viable fusion source is unlikely to be available before 2040.

There are a wide variety of approaches to fusion energy that are currently being investigated, each with their own specific challenges. The approaches differ both technically and in terms of level of resources and investment. Magnetic Confinement Fusion (devices such as JET, ITER, EAST, SPARC etc) is the most researched approach, has the largest number of people working on it and (in the case of ITER) involves a large international consortium working on a Megaproject.

Intertial Confinement Fusion (e.g., NIF at Lawrence Livermore National Laboratory) has been most actively supported by the US Department of Energy. Other approaches are mainly supported by private investors. The "Fusion Industry" supported by private investors has grown enormously in the last decade.

Fusion has been dominated by large designs and experiments (JET, ITER). However, we have seen a relatively recent change with a growing focus on smaller designs. Smaller designs are claimed (and there is some evidence) to offer scientific and technological benefits and benefits from development agility. There is a multitude of smaller design developers and they have made a range of claims regarding dates for when fusion may supply electricity to the grid from 2030 to 2050 and beyond.

The smaller design developers have attracted significant sums from private investors and clearly investors expect things to happen 'quickly'. They may be disappointed. The delays and costs experienced with large designs and experiments such as JET and ITER are one of the drivers towards smaller devices.

Recent headlines claiming breakthroughs (e.g., China's EAST reactor, Lawrence Livermore National Laboratory, JET in the UK) are all very impressive but there remain huge obstacles to commercialisation including getting beyond energy breakeven, the tritium fuel cycle, the effect of neutron damage on the materials and the mechanisms for extracting useful energy are key. An optimist would say that these will be overcome in time.

The principal advantages of fusion energy are:

- It does not produce greenhouse gases

- Fuel is, in principle, abundant. Deuterium can be obtained from water, tritium could be bred in a working fusion reaction
- Radioactive waste would be produced in relatively small quantities.
- Licencing should be less onerous, and the consequence of a worst-case accident would be limited compared to fission.

Currently, the main disadvantage is the scientific and technical challenge of developing a commercially viable fusion energy source (as outlined above). If this is achieved, then the main disadvantage is likely to be the costs of frequent maintenance to components exposed to intense radiation and neutron environments.

What could be done to ensure that the UK's electricity supply is not affected by the high proportion of reactors being decommissioned?

Authors: Matt Eaton, Mark Wenman, Daniele Dini

There are few real ways to mitigate at this stage. The current AGR fleet is scheduled for shutdown by 2028. It has recently been suggested that two of those due for shutdown in 2024, Hartlepool and Heysham 1, could be extended but this is likely to be shorter than previous life extensions.

Dungeness B, the first AGR power station, did not operate as much as others. Therefore, despite it being the first AGR, it had not actually reached the points (due to unresolvable safety concerns) where decommissioning was essential. EDF Energy took the decision to decommission it in 2021 based on an analysis of costs and technical challenges to get the plant back operational. It is now in defueling process. In today's energy market, and with Government support, it might still be possible to revisit that decision, although, given its prior low load factor, it would be a risky proposition. However, it could operate for 5-10 years, it was previously given life extension to 2028, whilst plants such as Hinkley Point C come online. Dungeness B could provide 1090 MWe if at full power.

A crucial way to ensure that the UK's electricity supply is not affected by decommissioning is to accelerate the SMR programme and ensure there are no delays in the Generic Design Assessment process (scheduled to finish around 2024). The process must be independent and led by the Office of Nuclear Regulation, but lessons can be taken from the speed at which vaccines were licensed during the COVID pandemic.

Further support to Rolls-Royce, as the only viable UK SMR supplier, would help build the UK supply chain for fission and fusion. Rolls-Royce are pressing ahead with the design and build of the first SMR factory which could be ready by 2024-5 with a first-of-a-kind SMR by 2030-32.

A second way to reduce electricity supply disruption is life extension to Sizewell B, which is essential. Sizewell B is due to be decommissioned in 2035 but a life extension decision is due in 2024. A decision should be made as soon as possible for a minimum extension of 10 years with the possibility of 20 years. Sizewell B is a reliable reactor that is capable of producing a significant portion of supply (1200Mwe or 3%) to the grid.

Interconnectors between the UK and Europe will also increasingly play an important role in stabilising the UK's future energy system. Many interconnectors have already been established but it is likely that more will be needed over time. However, interconnectors do have a limitation in that in times of intermittent generation of renewables across the continent, they may not be able to reliably supply energy to the grid, this may in turn lead to electricity prices being volatile at times as a result due to a lack of security of supply.

What needs to be done to improve the UK's approach to dealing with nuclear waste and to ensure that the Government can meet its aims of transferring waste to geological disposal facilities?

Authors: James Lawrence, Michael Bluck

The challenges of producing nuclear waste into a form suitable for long-term disposal are well understood and most is currently undertaken at Sellafield. There remains a clear-up activity for legacy waste, and plainly this must continue. There is a silver lining to this, as our experience of problematic waste handling will be of benefit for future nuclear waste.

For the long-term disposal of waste, the most critical need is to identify and agree a site. We have been near such decision in the past but have failed due to rejection by certain (but notably not all) public representative bodies. Nuclear Waste Services (NWS) has proposed 'Community Partnerships' at four sites (3 in west Cumbria, 1 in Lincolnshire).

A major difficulty to achieving this is that nuclear is a controversial topic and the anti-nuclear body is vocal and well-organised, particularly through local councils. In fact, the majority of people are much more amenable and accepting of nuclear but are understandably unwilling to openly challenge a vocal minority.

The anti-nuclear lobby need to be consistently and transparently challenged on specific misinformation. This is a difficult task but has been achieved in Finland.

In addition, closed fuel cycle technologies (fast neutron spectrum reactors) could greatly reduce the issues of long-term waste disposal and improve fuel utilisation. Though the UK has some history in this area, we would need to develop long-term research and development programmes in support of this.

How can the funding methods that support the development of nuclear technologies be improved?

Authors: Michael Bluck, Jonathan Tate, Mark Wenman.

The deployment of large nuclear reactors involves a very large upfront build cost, which is only made profitable by a subsequent long generation life. This is not a natural investment profile for the private sector and in most countries with a nuclear sector, it is the state that bares the risk. Recent UK funding of new nuclear technology has relied largely (if not exclusively) on private investment. Hinkley Point C used a contract-for-difference model (CfD), which placed the financial liability entirely on the private investor, in exchange for a fixed price.

For the proposed reactor development at Sizewell, the regulated asset base (RAB) model is being considered. The RAB model places some financial risk with the taxpayer/user in order to be more attractive to the investor than CfD. Either way, the private investor must secure considerable funds for the large build costs.

Experience has shown that these are not a particularly attractive models for large reactors. Government funding will always help with investor confidence, but that is entirely a matter of proportion. The experience globally is consistent in that a successful nuclear fleet roll-out is correlated with size of the government investment. Typically, governments can borrow much more cheaply than the private sector, so there is an element of a virtuous circle here.

There is a widely held view that small reactors (SMRs) offer the possibility of reduced capital investment, or at least the capital is invested more in manufacturing processes and less in the specific site build. This may make the investment profile more attractive and bring in private money.

Irrespective of reactor type, investors must be confident that the government will commit to nuclear for the lifetime of the reactor. If the government is reticent to back these technologies in terms of investment, it suggests to the private sector that this is not the case the case.

In short, to attract the necessary investment from the private sector, it needs confidence, and there is nothing quite like a substantive government investment to help provide private sector confidence.

Centres for Doctoral Training (CDTs) use a funding model that enables industry to leverage private investment against research council funds. Over the past decade CDTs have attracted substantial investment from industry partners across the UK nuclear sector. Provided that UKRI continues to support CDTs, there is every reason to suspect this stream of private investment will continue. Private investment in CDTs both supports research and development in clean energy technologies and trains the future subject matter experts that will help nuclear power contribute to net-zero.

Whilst investment in nuclear has been forthcoming from Government through BEIS, this has often been frustratingly slow. An example is the advanced fuel cycle programme, which has seen several phases. From an academic point of view, with skills in mind, any gaps in continuity of funding means losing skilled people, especially at post-doctoral level and those transitioning from PhD to post-doctoral positions. Ensuring there are no gaps in funding would improve this situation.

The UK has attracted significant private investment in small scale nuclear fusion projects but less so in nuclear fission. The Culham site now hosts many fusion projects alongside the JET reactor, and this is attractive to companies as the skills are all on-site. A similar method could be applied to fission private ventures making the UK the place to come to for skilled workers. Any incentives for companies to set-up in a designated site, like Culham, could help create sites of excellence in the UK.

What support will industry need to meet the Government's ambitions for delivery new nuclear power plants in the next decade?

Authors: Catrin Davies, Michael Bluck, Robin Grimes, Mark Wenman, Jonathan Tate.

Steps to support nuclear reactor technology development are dependent on the technology involved. UK designed large ‘conventional’ LWRs seem unlikely and are arguably not worth considering here.

Non-UK large ‘conventional’ LWRs (e.g., EPR, AP1000), as are currently under construction at Hinkley Point C and potentially at Sizewell, require long-term maintenance of the existing skills base and a migration of staff from the shrinking Advanced Gas-cooled Reactor (AGR) fleet to support these new reactors.

UK SMRs that are based on relatively mature technology (e.g., RR SMR) require a skills pipeline, but relatively modest R&D. Government support for manufacturing capability, either directly or by encouraging investment, to accelerate and aid the production of prototype NOAK reactors is vital.

Even small reactor deployment demands significant upfront capital, but the point of SMRs is the streamlining of production processes. Such a programme of deployment requires a significant expansion of appropriately trained scientists and engineers. This would likely need coordination of technical education from apprentice to subject matter expert levels.

More generally, SMR/AMR and Gen IV technologies are some way off deployment and require considerable R&D before they get to the build stage and can contribute to net-zero targets.

The UK has world leading expertise in operating high temperature reactors, which is invaluable for AMRs however we are at imminent risk of losing such expertise if the skills pipeline of people is not encouraged and the transfer of knowledge not ensured.

Irrespective of technology, some coordination of the skills needed to support supply chains is necessary. The National Skills Academy for Nuclear (NSAN) is already positioned to support skills development in the sector and expansion of its remit and ambition is needed to help meet the demands outlined above. The University Technical College (UTC) model is already established and should be aligned with any nuclear strategy.

At degree level, an expansion of undergraduate and masters’ programmes with a nuclear component should become more widespread; institutions with a nuclear engineering capability are relatively few. If we are to become reactor vendors, then an expansion of the research base is essential. This includes dedicated national laboratories, well beyond the scope of the existing NNL, and large university research programmes.

The skills challenge has been discussed constantly for well over two decades (e.g., Science and Technology Committee - Third Report Nuclear Research and Development Capabilities, 2011). The academic community appreciates that the task is too great for any one university or national laboratory to address alone.

Consequently, strongly collaborative programmes have developed with the UK currently having three CDTs in nuclear energy: GREEN at Manchester (including Liverpool, Lancaster, Sheffield and Leeds); Nuclear Energy Futures (NEF) at Imperial College (including Bangor, Bristol, Cambridge and Open) and Fusion at York (including Durham and Oxford).

CDTs do and can continue to supply PhD-level experts to the nuclear sector at a rate of about 60 per year. CDTs also attract students from overseas countries keen to develop an indigenous nuclear capability. Overall CDTs are also an extremely effective mechanism of attracting private investment into the development of nuclear technology.

Second, the National Nuclear User Facilities project, now completed, which has provided experimental facilities, including those capable to handling radioactive materials, to most Universities participating in civil nuclear research. Universities in receipt of equipment are required to share it broadly with others.

Third, research consortia, in which academics come together from different universities, with national laboratory and industry partners, to tackle a specific research challenge. All these have created an environment in which collaboration is fundamental and leadership roles are shared across institutions. Given that the structures have been developed bottom-up and are widely supported by the academic community, it is crucial that we take advantage.

We therefore strongly recommend continued funding for multiple CDTs in nuclear energy, which give universities access to efficient training of cohorts of young scientists, who also learn from each other and form life-long networks and develop new research consortia that are challenge focused.

September 2022