PROSPECTS FOR NUCLEAR ENERGY IN THE UK

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The Global Warming Policy Foundation
Report 57

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About the author

Kathryn Porter is an independent energy consultant, with broad experience of the energy and finance sectors in both leadership and technical roles. She has specific expertise in the utilities, oil and gas sectors, with finance experience spanning equities and equity derivatives, debt capital markets, M&A, loans, and risk management.

Currently running her own consulting business, Watt-Logic, Kathryn advises clients across the energy value chain on the opportunities and risks arising from the energy transition. This includes analysis of investment opportunities in generation and storage, devising procurement and risk management strategies for buyers of gas and electricity, advising on commercial contracts, such as offtake and power purchase agreements, and helping clients to understand the impact of regulatory and market change on their businesses. Kathryn has also acted as an expert on a matter relating to cross-border energy trading.

Before starting her business, Kathryn held various energy structuring and hedging roles at Centrica, Société Générale, EDF Trading, and at Barclays Capital, where she moved into commodities after starting in a fixed income role. Prior to this she worked in the Capital Markets & Advisory division at Commerzbank and in the financial services audit practice at Deloitte.

Kathryn holds a Master's degree in physics from the University of Exeter and an MBA from London Business School. She is a Chartered Fellow of the Chartered Institute for Securities and Investments and is a member of the Institute of Directors. She is an associate member of the Executive Council for the All-Party Parliamentary Group for Energy Studies.

Kathryn is also a Trustee of The Kids' Cookery School, a London-based charity focused on teaching cooking and nutrition skills to children, and a Trustee of the Royal Choral Society.

Executive summary

The UK Government's commitment to nuclear power has strengthened significantly in recent years as concerns over energy security have risen, due to the uncertainty created by the Russian invasion of Ukraine, and a growing realisation of the risks posed by a reliance on renewable generation. Nuclear power has no carbon dioxide emissions in operation and, unlike wind and solar power, is not intermittent.

However, while this is superficially positive, the Government is still too tentative in its ambitions. It intends to see one new large-scale nuclear power station reach its Final Investment Decision by the end of this Parliament (likely to be in 2024), but the only contender is Sizewell C, a reactor of a type that its developer, EDF, has struggled to deliver elsewhere. At the same time, most of the existing fleet of nuclear reactors is scheduled to close by March 2028, leaving only Sizewell B running until the opening of the reactor at Hinkley Point C, now expected in September 2028.

The Government has shown an interest in small modular reactors (SMRs) and advanced modular reactors, with a particular focus in recent years on high-temperature gas-cooled reactors, which could be suitable for a range of industrial applications, including the production of hydrogen. However, none is expected to enter service before the next decade and – so far – only one SMR design, from Rolls Royce, has begun the process to license its design in the UK.

Nuclear power is capable of being developed at scale, delivering very large energy outputs from small sites. SMRs and smaller micro-reactors could power remote, decentralised sites and energy-intensive industries with minimal on-site operational requirements, while fast neutron reactors offer the prospect of greater fuel security and reduced waste. However, the capital costs of conventional large-scale nuclear projects are very high, and largely outside the reach of the private sector, absent significant state support. Decades of underinvestment have seen a major skills exodus across Western nuclear nations, and a slowing in the development of advanced nuclear technologies, a field in which China, Russia and India have now taken the lead.

The Government has indicated a desire to leverage the work of well-regarded regulators in friendly nations, to avoid duplication of work. Currently each new technology must be separately licenced in each jurisdiction, a process which is distinct from site-specific certification. It should build on this commitment to accelerate the approvals process for new reactor designs. And it should accelerate research into advanced technologies, particularly in the sphere of alternative nuclear fuels, to address concerns over uranium supplies.

The economic opportunities for nuclear power in Great Britain are mixed. The Government hopes that the new Regulated Asset Base model will attract investor interest by increasing income certainty and transferring some risks to consumers. However, Ofgem has been designated as the economic regulator in this area, and its track record in setting consistent and effective price controls for gas and electricity network operators has been mixed. It is now under significant pressure to contain energy company profits, which may make nuclear developers nervous about the model and how it may operate in practice.

Arguably, the Government should not shy away from direct investments in new nuclear projects, filling gaps where the private sector seems reluctant to invest. Private investors are not expected to fund physical security – the military or the police – this is done by the state. Perhaps the state should directly fund at least some portion of energy security as well.

In order to correct course, the Government should consider the following actions:

- *Maximise the contribution of the legacy fleet*: Based on current plans (which are under review) most existing nuclear reactors will close by the end of March 2028, in part due to concerns over cracking of graphite control rods. This issue should be reviewed to ensure that an excessively conservative regulatory approach is not risking energy security – if the reactors can be shut down using only a quarter of the control rods, it is difficult to justify a requirement by the nuclear regulator that all of them must be capable of being deployed during earthquakes of a magnitude never seen in the UK.
- *Accelerate the deployment of new large-scale reactors*: The Government needs to rapidly secure the delivery of additional nuclear capacity. The fastest and most efficient way of doing this would be to directly commission five or six, financing them with public money. A tender should be issued to developers with a proven track record of delivery, leveraging existing supply chains. The most credible technologies for such a tender are the APR-1400 and EPR pressurised water reactors, and the Advanced Boiling Water Reactor (ABWR). However, ABWR supply chains are arguably stale, while the EPR is as yet unproven in Europe, with only one unit having been commissioned, and then only very recently.
- *Create a streamlined regulatory framework for new technology certification, incorporating international co-operation*: The certification processes in Western countries present a major barrier to the delivery of new nuclear technologies, both in terms of cost and time taken. The Government should engage with trusted countries and their nuclear regulators to develop shared certification processes, minimising duplication across nations. Where a technology has been certified by a credible regulator in a trusted nation, the UK should be prepared to place reliance on that work, without repeating large parts of it. Establishing shared frameworks would build confidence in the robustness and reliability of the agreed processes.
- *Develop a credible pipeline of projects to deliver new technologies in the medium term*: Nuclear policy should explicitly distinguish between short-, medium-, long- and very long-term objectives. For the medium term – i.e. the end of this

decade and the early 2030s – plans for the delivery of new nuclear technologies, such as small and advanced reactors, should be put in place. The current patchwork of initiatives should be rationalised, with a small number of technologies consistently prioritised. The historic stop-start approach to small modular reactors has been particularly unhelpful, as has the plethora of other initiatives in the modular reactor space over the past decade. New large-scale reactors should also be ordered during this period, whether by continuing the public funding approach outlined above or by moving to private finance, if the market will support such a move. More speculative approaches, including nuclear fusion, should continue to receive innovation support, but should not attract undue focus.

- *Develop and maintain efficient supply chains and workforce skills*: It is widely accepted that the long hiatus in building new reactors has created significant challenges across the Western world, with both Europe and the US struggling to recreate supply chains and re-build workforce skills. Many (but not all) of the problems encountered with both the EPR and AP-1000 can be attributed to this issue. Partnerships are needed between Government, industry and the education sector to support the development of the nuclear workforce, underpinned by a commitment to building and maintaining nuclear reactors for many decades to come. A credible pipeline of new nuclear projects is a prerequisite to rebuilding both nuclear supply chain and workforce skills. Lessons should also be learned from the current experience to ensure that it is not repeated in the future – supply chains and workforce skills should not be allowed to ebb away again.

Britain should be an attractive market for nuclear power, which has the potential to make a significant contribution to the delivery of net zero ambitions, but in its determination both to avoid adding costs to the public balance sheet, and any perception of delivering poor value for money, the Government has failed to create the necessary conditions for new projects to flourish. The approaching closure of most of the existing fleet and overarching climate ambitions make it vital that a more robust approach is taken to securing the next generation of nuclear reactors in Britain.

Note

This paper has been through GWPF's open peer review process. Reviewer comments can be seen at the paper's page in the closed peer reviews section on the GWPF website.

1. Policy context

2022 was a year of upheaval in British politics, with three different prime ministers holding office, and several changes in the ministers responsible for energy. The current prime minister, Rishi Sunak, took office on 25 October 2022. On 7 February 2023 he undertook a departmental reshuffle, dividing the responsibilities of the former Department for Business, Energy and Industrial Strategy (BEIS)[1] between other ministries, including the newly formed Department for Energy Security and Net Zero (DESNZ).[2]

During this time, energy has been a political priority as a result of high energy prices, caused in part by an asymmetric response to the COVID-19 pandemic (gas demand recovering much more quickly than supply, leading prices to rise[3]) and the Russian invasion of Ukraine in February 2022, which reduced the amount of gas available to western buyers, due to Russia's use of energy as an economic weapon and Western sanctions. Arguably, since prices began to rise in September 2021, and more so since the subsequent invasion of Ukraine, affordability and security of supply have eclipsed decarbonisation as the main focus of short-to-medium-term energy policy.

Ten Point Plan, November 2020

After several years of policy drift, the Ten Point Plan[4] of November 2020 set a new direction, both for nuclear power in Great Britain and energy policy more broadly. Under Point 3 of the plan, the Government confirmed it was 'pursuing large-scale nuclear, whilst also looking to the future of nuclear power in Britain through further investment in small modular reactors and advanced modular reactors'. A commitment was made to the provision of development funding and up to £385 million for an Advanced Nuclear Fund, including up to £215 million for small modular reactors, and £170 million for advanced modular reactors (AMRs). The intention was to unlock up to £300 million of private-sector matched funding.

AMRs include technologies with high-temperature operation (650–750ºC), enabling production of high-grade heat. The Government believes this 'could unlock efficient production of hydrogen and synthetic fuels, complementing our investments in carbon capture, utilisation and storage (CCUS), hydrogen and offshore wind'. Industrial applications such as glassmaking require furnace temperatures of 1100–1400ºC – AMRs could be used to produce hydrogen, which could be burned to achieve

1 https://www.gov.uk/government/organisations/department-for-business-energy-and-industrial-strategy.

2 https://www.gov.uk/government/organisations/department-for-energy-security-and-net-zero.

3 https://www.reuters.com/business/energy/global-gas-prices-soar-industry-struggles-meet-resurgent-demand-kemp-2021-09-09/.

4 https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title.

these temperatures. The intention was to build a demonstrator by the early 2030s.

A further £40 million was committed for the development of regulatory frameworks and UK supply chains.

In total, the plan committed £525 million to nuclear power, compared with £2.8 billion for electric cars, £1 billion for energy 'efficiency',[5] £500 million for hydrogen, and a further £200 million for CCUS, bringing the total funding for that technology to £1 billion. Carbon capture is seen as a way to continue the use of fossil fuels, which are likely to play a role, albeit declining, both in the power sector and in industry, for decades to come. It is also necessary for the production of hydrogen by steam-methane reforming, which creates carbon dioxide as a by-product.

Despite the hopes, carbon capture and storage (CCS) remains relatively unproven – the few large-scale projects in operation rely on hydrocarbon fuel production (primarily enhanced oil recovery) or processing for their economics. The handful of power-CCS projects have cost more and captured less carbon dioxide than expected, and most have closed. Carbon utilisation is even less mature and remains largely speculative.

Energy White Paper, December 2020

The Ten Point Plan was followed by a new Energy White Paper,[6] published in December 2020, in which the Government said it aimed to bring at least one large-scale nuclear project to the point of its Final Investment Decision (FID) by the end of this Parliament, subject to it representing value for money and the relevant approvals being obtained. It said it would remain open to supporting further projects if the nuclear industry demonstrated it could reduce costs and deliver to time and budget, saying that it expected the sector to deliver the goal it set out in the 2018 Nuclear Sector Deal,[7] namely to reduce the cost of nuclear new-build projects by 30% by 2030.

The Nuclear Sector Deal suggested that these savings could be achieved through research into advanced construction, reduction of construction costs and supply chain development. However, it is evident that no such improvements have been achieved to date and, on the current trajectory, it seems unlikely this ambition will be achieved. It is worth taking note of research[8] by scientists at the Massachusetts Institute of Technology in 2020 which concluded that, contrary to expectations, building subse-

5 Government policy frequently uses the term 'efficiency' in relation to buildings. This is widely understood to mean efforts to improve insulation and reduce heat losses rather than improving the energy conversion rates of domestic appliances.

6 https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future.

7 https://www.gov.uk/government/publications/nuclear-sector-deal.

8 https://www.cell.com/joule/fulltext/S2542-4351(20)30458-X?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS25424351 2030458X%3Fshowall%3Dtrue.

quent plants based on an existing design actually costs more, not less, than building the initial plant, since site-specific considerations tended to dominate the cost of a new plant.

The White Paper re-iterated the commitments in the Ten Point Plan to AMRs and SMRs, and said the Generic Design Assessment (GDA) would open to SMR technologies in 2021, although in the event that did not happen until December 2022 (see below). The GDA is the regulatory process that ensures that new nuclear power stations built in Great Britain meet high standards of safety, security, environmental protection and waste management.

In September 2021, the Government consulted[9] on the use of high temperature gas-cooled reactors to enable an AMR demonstration by the early 2030s. The key objective for the AMR research, development and demonstration programme is to show that AMRs can produce high-temperature heat.

The White Paper also contained a plan to build a commercial fusion power plant by 2040, saying that 'the basic science and engineering involved in the production of fusion energy is now well advanced'. The Government had previously committed over £400 million towards new UK fusion programmes, the aim being to develop a concept design for the Spherical Tokamak for Energy Production (STEP) – expected to be the world's first compact fusion power plant, to be built by 2040 – and to invest in facilities and infrastructure to make the UK a global fusion industry hub. In December 2020, the STEP[10] programme published an open call for communities across the UK to apply to be the host site.

Net Zero Strategy, October 2021

In October 2021, the Government published its Net Zero Strategy,[11] of which new energy policies formed a part. An additional £120 million was committed for the development of nuclear projects through the Future Nuclear Enabling Fund,[12] which 'could support our path to decarbonising the UK's electricity system fifteen years earlier from 2050 to 2035'.

Regarding the large-scale nuclear project for which FID should be granted before the end of the current Parliament, the Net Zero Strategy says the Government had entered into negotiations with the developer of Sizewell C in December 2020. This project is slated to be a European Pressurised Water Reactor, developed by EDF. In January 2022, the Government invested[13] £100 million to support its continued development.

9 https://www.gov.uk/government/consultations/potential-of-high-temperature-gas-reactors-to-support-the-amr-rd-demonstration-programme-call-for-evidence.

10 https://step.ukaea.uk/.

11 https://www.gov.uk/government/publications/net-zero-strategy.

12 https://www.gov.uk/government/news/uks-path-to-net-zero-set-out-in-landmark-strategy.

13 https://www.gov.uk/government/news/government-readies-sizewell-c-nuclear-project-for-future-investment.

British Energy Security Strategy, April 2022

The British Energy Security Strategy,[14] published in April 2022, marked a significant uptick in support for nuclear power. The document acknowledged that the UK has fallen behind other countries in nuclear power, and that five of the six remaining plants (at the time) would be offline within the decade, with only one new project under construction.

The strategy called for a reversal in decades of under-investment in nuclear power, with the Government committing to 'kickstart a nuclear reaction to recover our global leadership in civil nuclear power and drive down costs by building at scale over the next thirty years'. This included a number of new nuclear ambitions:

- to increase plans for deployment of civil nuclear to up to 24 GW by 2050 – a threefold increase on existing capacity, representing up to 25% of projected GB electricity demand;
- to take one project to FID this Parliament and two projects in the next one, including SMRs;
- to deliver up to eight more reactors, the equivalent of one reactor a year, rather than one a decade;
- to set up and fund Great British Nuclear (GBN) in 2022, a new body tasked with developing a resilient pipeline of new builds, and helping projects through every stage of the development process, including securing funding;
- to work to explore the potential for streamlining the consenting and licensing process for new nuclear power stations, including possible harmonisation on international regulation (but without compromising safety, security and environmental protections);
- to collaborate with other countries on advanced nuclear technologies.

Energy Independence, November 2022

In November 2022, BEIS launched a new package to secure Britain's energy independence,[15] including 'continuing the revitalisation of the UK nuclear industry', by confirming the first state backing of a nuclear project in over 30 years, in the shape of a 50% stake in the Sizewell C project, buying out China General Nuclear at a cost of around £679 million. The Government said it would work to find third-party investment to help finance the project. It expects 70% of Sizewell C's construction and operational contracts to be placed with UK businesses.

Nuclear Fuel Fund, January 2023

14 https://www.gov.uk/government/publications/british-energy-security-strategy.

15 https://www.gov.uk/government/news/uk-government-takes-major-steps-forward-to-secure-britains-energy-independence.

In January 2023, the Government announced[16] £75 million in funding to support the development of alternatives to Russian nuclear fuel supply. This followed the June 2022 agreement by G7 leaders to begin concerted action to reduce reliance on civil nuclear and related goods from Moscow, which currently owns around 20% of global uranium conversion capacity and 40% of enrichment capacity.

The £75 million Nuclear Fuel Fund (NFF) will encourage investment in domestic fuel production capacity, including both freshly mined and reprocessed uranium. In December 2022, up to £13 million of the fund was awarded to Westinghouse,[17] which is already strategically important as the fabricator of fuel for the current advanced gas-cooled reactor (AGR) fleet.

The remaining £50 million fund, which opened for bids in January, is intended to stimulate a diverse and resilient nuclear fuel market, supporting specialist skills, and opening up export opportunities. It will also look to support projects producing new fuel types for AMRs. A Request For Information process,[18] carried out in summer 2022, identified several specific areas for the Fund to support:

- light water reactor fuel supply;
- high-assay low-enriched uranium supply;
- AMR fuel fabrication;
- UK fuel production.

All grant funding for NFF projects must be transferred to the recipient and spent by 31 March 2025.

Powering Up Britain, March 2023

Powering Up Britain,[19] published in March 2023, contained little that was genuinely new relating to nuclear, but there were updates to several previously announced initiatives. There was news on the appointment of the interim chair and CEO of Great British Nuclear, and an announcement that their first priority would be to launch a new competition to select the most promising SMR technologies for development. The Government will co-fund the selected technologies through their development phase, and work with successful bidders to ensure the right financing and site arrangements are in place.

The Government also launched the Future Nuclear Enabling Fund, offering up to £120 million to address barriers to entry to new nuclear technologies. A shortlist of applications to begin pre-grant award due diligence was announced in July 2023,[20]

16 https://www.gov.uk/government/news/ministers-bolster-uk-nuclear-fuel-capacity-to-squeeze-out-russian-influence.

17 https://www.gov.uk/government/news/102-million-government-backing-for-nuclear-and-hydrogen-innovation-in-the-uk.

18 https://www.gov.uk/government/publications/nuclear-fuel-fund-nff.

19 https://www.gov.uk/government/news/shapps-sets-out-plans-to-drive-multi-billion-pound-investment-in-energy-revolution.

20 https://www.gov.uk/government/publications/future-nuclear-enabling-

with three applicants selected for potential grants worth a total of £77 million.

The Government is also developing a new nuclear National Policy Statement (NPS; see below), which will cover the siting and policy framework for nuclear electricity generating infrastructure beyond 2025. As a first step, it will consult on the proposed approach to siting new nuclear projects, and it will aim to confirm the new NPS by early 2025.

Delivery of Phase A of the AMR Research Development and Demonstration (AMR RD&D) programme, which provided up to £2.5 million across six projects in 2022–23,[21] is concluding, and the Government is analysing the outputs. Phase B of the programme was launched in December 2022, providing up to £55 million across up to two projects, and as much as £5 million to support the UK's regulators. Successful bidders were announced in July 2023,[22] and received combined development funding of £37.5 million. This would enable them to undertake FEED+ (Front End Engineering Design and supporting activities) studies by March 2025, with the aim of delivering an AMR demonstration by the early 2030s.

A programme is being developed under the Advanced Nuclear Fund for further development of coated particle fuel (CPF),[23] which is used in high-temperature gas-cooled reactors (HTGRs). This differs from the NFF, which considers only commercial CPF projects (i.e. multi-tonne/year plants).[24] Along with the AMR R&D Phase 2 awards, £16 million was awarded as part of the UK Coated Particle Fuel Programme – Step 1, aiming to accelerate the development of CPF.

Energy Security Bill, 2023

The Energy Act 2023[25,26] has recently received Royal Assent. It legislates for many of the policy commitments made over the previous couple of years:

- facilitating the delivery of up to 24 GW of nuclear capacity

fund-shortlisted-applications/future-nuclear-enabling-fund-shortlisted-applications.

21 https://www.gov.uk/government/news/33-million-boost-for-next-generation-nuclear-technology.

22 https://www.gov.uk/government/publications/advanced-modular-reactor-amr-research-development-and-demonstration-programme-successful-organisations/amr-research-development-and-demonstration-phase-b-2023-2025-successful-organisations.

23 https://www.nnl.co.uk/wp-content/uploads/2022/04/Coated-Particle-Fuel-1.pdf.

24 https://www.gov.uk/government/publications/advanced-modular-reactor-amr-research-development-and-demonstration-programme-phase-b-competition/amr-rdd-programme-phase-b-applicant-questions-and-responses.

25 https://www.gov.uk/government/publications/energy-security-bill-factsheets/energy-security-bill-overarching-factsheet.

26 https://bills.parliament.uk/bills/3311.

by 2050;

- removing barriers to investment by enhancing the nuclear third-party liability regime;
- facilitating the safe and cost-effective clean-up of the UK's nuclear sites, clarifying that a geological disposal facility located deep below the seabed will be licensed;
- simplifying regulatory frameworks;
- bringing forward the final delicensing and re-use of nuclear sites to allow more proportionate clean-up of these sites;
- strengthening the powers of the Civil Nuclear Police;
- bringing Nuclear Decommissioning Authority (NDA) pensions into line with most of the rest of the public sector.

National Policy Statements

National Policy Statements (NPSs) establish the case for Nationally Significant Infrastructure Projects, as defined in the Planning Act 2008.

The current NPS for energy (designated EN-1) was updated in March 2023,[27] and influences new applications for nuclear electricity generation deployable after 2025. A new nuclear-specific NPS (EN-6) is currently being developed. The other four energy NPSs were all consulted on in 2021,[28] with updated versions being published in 2023 – the nuclear NPS was specifically excluded from that process.

The existing NPS (EN-6)[29] was published in 2011, and covers nuclear generation deployable up to 2025 , alongside the previous energy NPS, EN-1.[30] It lists eight sites as potentially suitable for the deployment of new nuclear power stations by the end of 2025: Hinkley, Sizewell, Heysham, Hartlepool, Bradwell, Wylfa, Oldbury and Moorside.

The nuclear NPS provides the primary basis for decisions taken by the Infrastructure Planning Commission (IPC; later replaced by the Planning Inspectorate) on applications it receives for nuclear power stations.

27 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147380/NPS_EN-1.pdf.

28 https://www.gov.uk/government/consultations/planning-for-new-energy-infrastructure-revisions-to-national-policy-statements.

29 https://www.gov.uk/government/consultations/national-policy-statement-for-new-nuclear-above-1gw-post-2025-siting-criteria-and-process.

30 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47854/1938-overarching-nps-for-energy-en1.pdf.

2. Decommissioning future nuclear power stations

Since the Energy Act 2008, developers of new nuclear power stations have been required to have fully funded decommissioning plans[31,32] in place to manage future liabilities. The Funded Decommissioning Programme (FDP) ensures that developers meet the costs of decommissioning and managing waste disposal, so the taxpayer does not have to bear the burden of these costs in future. The waste and decommissioning costs for Hinkley Point C are accounted for in the Contracts for Difference (CfD) strike price – the operator will pay a higher proportion of the strike price into their FDP fund if costs go up; but will benefit if they manage costs effectively.[33]

Under the Regulated Asset Base (RAB) funding model for future nuclear projects, it is envisaged that the FDP would apply from the point of nuclear operation for the remainder of the period in which a regulated allowed revenue was charged, with incentives placed on costs within the project company's control.

3. Current and potential future electricity generation mix

In 2022, the most recent year for which official data are available, nuclear was the third most important fuel in electricity generation[34] in the UK at just under 15% – behind gas at 38% and wind at 25% (Figure 1). In the late 1990s, nuclear generated almost 30% of UK electricity, but since then its importance has declined, although not linearly; as recently as 2015–17, it still contributed around 21%. However, in recent years, several nuclear reactors have closed: Dungeness in 2021, and Hinkley Point B and Hunterston B in 2022. These units together accounted for over 3 GW of capacity. There are now just five nuclear power stations operating in the UK, with a combined capacity of just under 6 GW.

In its *Future Energy Scenarios*,[35] National Grid ESO (NG ESO) expects nuclear to contribute 6.7–10.2% of electricity generation in 2030, and between 9.3% and 14.0% in 2050. In each of the scenarios, it expects nuclear output to be around 33 TWh in 2030, but there is significant variation between the four scenarios for 2050, with nuclear contributing 73 TWh in the lowest case and 95 TWh in the highest. Offshore wind is expected to be the dominant source of electricity in 2050, with onshore wind and solar

31 https://www.legislation.gov.uk/ukpga/2008/32/part/3/chapter/1/crossheading/funded-decommissioning-programmes/enacted.

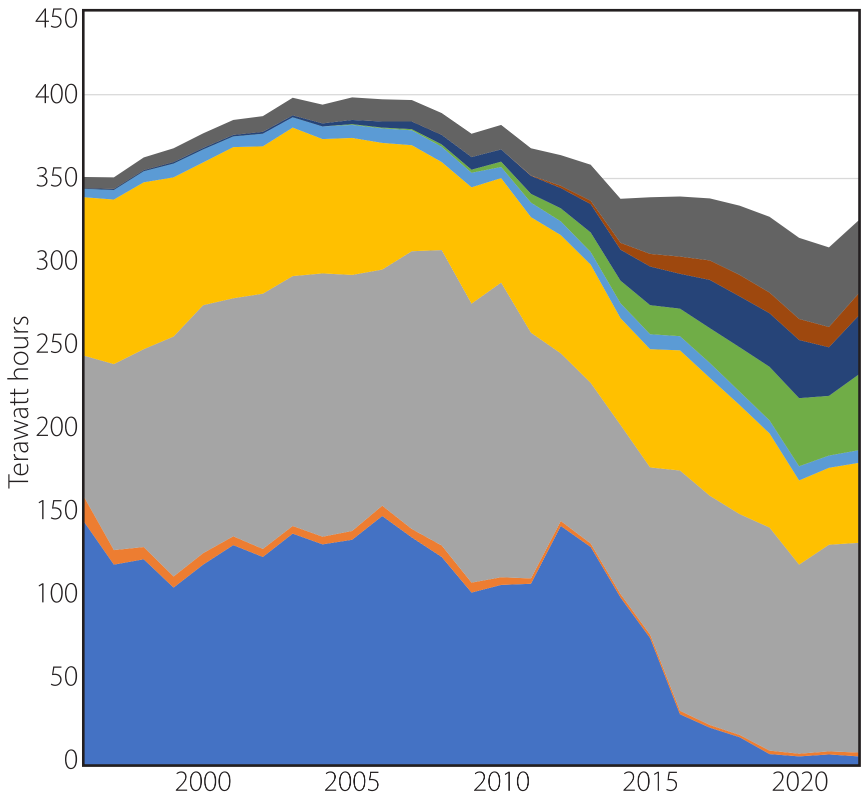
32 The Energy Act 2008: Funded Decommissioning Programme Guidance for New Nuclear Power Stations.

33 https://www.gov.uk/government/publications/hinkley-point-c-funded-decommissioning-programme.

34 https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes.

35 https://www.nationalgrideso.com/future-energy/future-energy-scenarios.

Figure 1: UK electricity generation by fuel type. 1996–2022
Source: DUKES, 2022.



varying in importance across the scenarios.

The Climate Change Committee[36] expects nuclear to be responsible for 10% of electricity sector carbon abatement in 2035, but cites delivery risks, highlighting the absence of an overarching delivery plan or any strategy for full decarbonisation of electricity generation by 2035, as required by current Government policy.

4. Nuclear technologies and their potential

For more details of these reactors, please see the appendix.

Large-scale reactors

The category of 'large-scale' reactors generally incorporates those over 700 MW in size, although modern ones tend to be over 1 GW. The 196 MW Calder Hall facility[37] was the first nuclear power station in the world to produce electricity for domestic use. Designed to last just two decades, it operated for 47 years, before closing in 2003. The station had four Magnox reactors of the gas-cooled graphite-moderated type. During its years of operation, it generated enough power to run a three-bar radiator for 2.85 million years.[38]

36 https://www.theccc.org.uk/publication/2022-progress-report-to-parliament/.

37 https://www.ice.org.uk/what-is-civil-engineering/what-do-civil-engineers-do/calder-hall-nuclear-power-station.

38 https://nda.blog.gov.uk/decommissioning-the-worlds-first-commercial-

Existing UK fleet

Nineteen nuclear power stations have since been built in the UK, with five still in operation, and one under construction. With the exception of Sizewell B, which is a pressurised water reactor (PWR), the other UK reactors are all AGRs (Table 1)

Table 1: UK nuclear reactors in operation or under construction

Plant	Capacity (MW)	Opening date	Expected closure	Comments
Hartlepool	1,185	1983	March 2026	Life extended by 2 years in 2023
Heysham 1	1,060	1983	March 2026	Life extended by 2 years in 2023
Heysham 2	1,240	1989	March 2028	Life shortened by 2 years in 2021
Sizewell B	1,194	1995	2035	EDF considering extension to 2055
Torness	1,200	1998	March 2028	Life shortened by 2 years in 2021
Hinkley Point C	3,260	Under construction	60-year life	Latest guidance for opening date is September 2028

Source: EDF Energy, Watt-Logic

Based on the current closure schedule, after Torness and Heysham 2 cease operation in March 2028, there will be only one reactor, Sizewell B, in operation in the UK until the completion of Hinkley Point C, which is currently expected in September 2028, although that date may still be subject to further slippage.

ONR approach to nuclear safety – graphite cracking risks

It is possible that Torness and Heysham 2 may have to close earlier than March 2028 – they have already exceeded the running hours of Hinkley Point B, which was forced to close due to issues with graphite cracking,[39] and the recent extensions announced for Hartlepool and Heysham 1 are subject to regular graphite inspections.[40]

Graphite bricks are used in the core of all of the UK's AGRs. Uranium fuel is inserted into the reactor through channels in the graphite core. Control rods are also inserted into the core through other channels to control the reaction and to shut it down if necessary. The graphite bricks act as a moderator, reducing the speed of the neutrons that allow a nuclear reaction to be sustained. They also perform an important safety function, providing the structure through which carbon dioxide flows, removing heat from the nuclear fuel.

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nuclear-power-station/.

39 https://www.onr.org.uk/pars/2021/hinkley-point-b-20-026.pdf.

40 https://www.edfenergy.com/media-centre/news-releases/edf-provides-update-uks-existing-nuclear-fleet.

Torness and Heysham 2 had previously been expected to run until 2030, but in 2021 their closure dates were brought forward by two years following the issues at Hinkley Point B and Hunterston B.[41] However, it can be argued that the ONR's approach to this issue is excessively conservative. It requires that *all* control rods be capable of being inserted into the reactor in the event of a 'California level' earthquake, judged to be roughly magnitude 7.2. Their concern is that an earthquake would shake some of the cracked graphite in the core loose, blocking the insertion of control rods into the reactor core. However, this is problematic for a number of reasons. Firstly, such earthquakes have never been experienced in the UK – the largest earthquake in recorded history in Britain was the 6.1 Dogger Bank earthquake of 1931,[42] which was ten times less severe than a California-level event such as that considered by the ONR, which is deemed to be a one in ten thousand year event.[43] Secondly, the AGRs can be shut down with fewer than a fifth of the rods (approximately 12 out of 80).[44] Thirdly, the AGRs have two further ways of being shut down should the control rods fail: secondary shutdown through boron injection, and tertiary shutdown through nitrogen injection.[45]

To require the permanent closure of a reactor if a single control rod is at risk of not being deployed, in a seismic event on a scale never previously experienced in the UK, and not expected to be experienced either, is arguably excessively risk-averse, particularly when the reactor will still shut down if 85% of the rods fail to deploy, and there are two further, independent means of shutting it down. It is important that the remaining AGRs are not closed prematurely, and the ONR should be encouraged to revisit its approach to reactor safety regarding this issue.

European Pressurised Water Reactor

The only large-scale nuclear technology currently being developed in Europe is the European Pressurised Water Reactor (EPR), developed by EDF and Areva. The EPR is a third-generation technology, and a development from previous PWRs, designed to be safer and more economic.[46] The design has several active and passive protection measures:

- four independent emergency cooling systems;
- leak-tight containment around the reactor;
- extra container and cooling area if a molten core manages to escape the reactor;
- a two-layer concrete wall, with a total thickness of 2.6 m,

41 https://www.edfenergy.com/media-centre/news-releases/agr-lifetime-reviews-carried-out.

42 http://www.earthquakes.bgs.ac.uk/earthquakes/UKhistoric/19310607002500.html#page=additional.

43 https://www.onr.org.uk/documents/2020/onr-rrr-059.pdf.

44 https://www.edfenergy.com/about/nuclear/graphite-core.

45 https://www.osti.gov/etdeweb/servlets/purl/448871.

46 https://web.archive.org/web/20071129121411/http://www.areva-np.com/common/liblocal/docs/Brochure/EPR_US_%20May%202005.pdf.

designed to withstand impact by aeroplanes and internal overpressure.

The technology has been plagued with problems. A recent report[47] by the French Parliament criticised the decision to approve the original EPR in 2004, before its design had been completed, saying that many of the subsequent problems stemmed from this decision. Further problems were attributed to the decade-long hiatus in new reactor projects, which saw a significant skills exodus from the industry.

Despite receiving approval in 2005, the first EPR in Europe, Olkiluoto 3 in Finland, only began commercial operations in April 2023,[48] 14 years late, 18 years after it broke ground, and €8 billion over budget. The final cost was €11 billion. The flagship EPR at Flamanville in France has been similarly plagued with problems, and is now on track to be 12 years late[49] and almost €10 billion over budget. The UK EPR project at Hinkley Point C has not escaped from the issues of delays and cost overruns. Its costs have ballooned from the initial estimate of £18 billion to £32 billion, and it may not open before September 2028.[50]

Although two EPRs were constructed at Taishan in China, a lack of transparency over these units means it is not possible to confirm the degree to which the design differs to those under construction in Europe. Taishan 1 was offline for a year while issues with its fuel assembly were corrected.[51] There is no information regarding Taishan-2, although it likely shared the same design flaw.

A further EPR is mooted for Sizewell C, but there are no guarantees the project will go ahead. EDF, now fully renationalised, is committed to the next-generation EPR2 technology, and against a backdrop of its wider financial difficulties and the loss of its Chinese partners (for political reasons), it is not clear that it has any appetite to proceed. In public, it remains committed to the project, but it should be noted that approval for Hinkley Point C was only narrowly granted by its board, with one member resigning in protest.[52] Until the board approves Sizewell C, doubts will remain as to its future. However, the UK EDF subsidiary, EDF Energy, remains supportive and expects to achieve significant delivery improvements compared with Hinkley Point C, based on the replication benefits in moving from unit 1 to unit 2, with

47 https://www.assemblee-nationale.fr/dyn/16/organes/autres-commissions/commissions-enquete/ce-independance-energetique.

48 https://www.globalconstructionreview.com/14-years-late-finlands-new-reactor-olkiluoto-3-starts-generating-power/.

49 https://web.archive.org/web/20141014020153/http://www.world-nuclear-news.org/newsarticle.aspx?id=14496.

50 https://www.edf.fr/sites/groupe/files/2023-04/2023-04-28-edf-book-q1-2023.pdf.

51 https://www.neimagazine.com/news/newschina-restarts-taishan-1-after-a-year-of-repairs-9937188.

52 https://www.ft.com/content/3209004a-54ca-11e6-befd-2fc0c26b3c60.

some tasks being completed 30% faster on the second unit.[53]

Westinghouse AP1000

In the US, the large-scale reactors being built use the Westinghouse AP1000 model. However, this, like the EPR, is suffering from major delays and huge cost overruns. The AP1000 was previously proposed for the Moorside site in Cumbria. The project had Design Acceptance Confirmation granted by the ONR in March 2017,[54] but collapsed[55] in November 2018 when Toshiba, its backer, exited its overseas nuclear business and was unable to sell it on.

First licenced[56] in the US in 2002, the AP1000[57] is a two-loop PWR, an evolution from the smaller AP600, one of the first new reactor designs certified by the US Nuclear Regulatory Commission. Simplification was a major design objective of the AP1000. Its core cooling system incorporates passive residual heat removal by convection, improved containment isolation, a passive containment cooling system to the atmosphere, and in-vessel retention of core damage (corium), with water cooling around it. No safety-related pumps or ventilation systems are needed. The structural design was significantly modified from 2008 to withstand aircraft impact.

AP1000s have been built in China at Sanmen and Haiyang, and another is under construction at Vogtle in the USA. The scheduled construction for the Chinese units was 57 months, but they actually took 110 months to deliver, in part due to a need to re-engineer the 91-tonne coolant pumps, of which each reactor has four.

Like EDF, Westinghouse had a long hiatus in building new reactors, and it experienced severe problems with the Vogtle project in Georgia and the VC Summer project in South Carolina. In a drive to lower the cost of new nuclear projects, it had planned a revolutionary modular approach to building the AP1000, with sections of the plant being pre-fabricated offsite. However, it miscalculated the time it would take, and the possible pitfalls led to an estimated US$13 billion in cost overruns. The company also misjudged the regulatory hurdles and used a construction company that lacked experience with nuclear work. In 2017, the VC Summer project was cancelled, with the reactors partly built, after Westinghouse filed for bankruptcy.[58] Several of the comp-

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53 https://www.edfenergy.com/sites/default/files/hpc_efficiencies_brochure_final.pdf.

54 https://www.onr.org.uk/civil-nuclear-reactors/moorside.htm.

55 https://www.neimagazine.com/news/newstoshiba-liquidates-uk-nugen-and-cancels-uk-moorside-project-6843979.

56 https://www.nrc.gov/reactors/new-reactors/large-lwr/design-cert/ap1000.html.

57 https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx.

58 https://www.nytimes.com/2017/03/29/business/westinghouse-toshiba-nuclear-bankruptcy.html.

ny's officials were later indicted[59] on charges of conspiracy, wire fraud, securities fraud, and causing a publicly-traded company to keep a false record. It was a similar story at the state utility, which was also forced into bankruptcy, and where officials were charged with offences in relation to the project. By the time of the cancellation, the costs of the scheme made up 20% of consumer electricity bills in the state of South Carolina.

The other two US AP1000 projects, Units 3 and 4 at Vogtle, continue to be developed. Construction of Unit 3 began in March 2013, and it finally started operations in summer 2023.[60] Work began on Unit 4 in November 2013, with completion due in the first quarter of 2024. The total cost of the two units is now projected to exceed US$30 billion, more than double the original estimate of US$14 billion.

In the UK, an AP1000 has been proposed for the Wylfa Newydd site on Anglesey, following the collapse of the planned Advanced Boiling Water Reactor project sponsored by Hitachi (see below), although as the site is still owned by Hitachi it is unclear how realistic this prospect is.[61]

KEPCO APR-1400

The APR-1400,[62] developed by the Korea Electric Power Company (KEPCO), is a Generation III reactor with a 1,400 MW capacity and an expected lifespan of 60 years.[63] There are commercial units in operation in South Korea, and also in the UAE, where it was selected for the country's nuclear programme on the basis of its competitive cost and its reliable building schedule.

The first APR-1400, Shin Kori unit 3,[64] was delivered in December 2016. This was three years later than planned, with delays experienced after it was discovered that safety-related control cabling with falsified documentation had been installed. There are now three APR-1400s in operation in South Korea and a further three in the UAE, with a fourth in the final stages of testing prior to starting commercial operations. Four further units are under construction in South Korea, one of which is expected to open in September 2023.

Aside from the fraud issue at Shin Kori 3, there have been no problems of note with the APR-1400 – delays at Barakah were attributed to staff shortages at the operating company. Construc-

59 https://thebulletin.org/2021/08/us-attorney-details-illegal-acts-at-construction-projects-sealing-the-fate-of-the-nuclear-renaissance/.

60 https://www.georgiapower.com/company/news-center/2023-articles/vogtle-unit-3-reaches-100-percent-energy-output.html.

61 https://publications.parliament.uk/pa/cm5803/cmselect/cmwelaf/240/report.html.

62 https://www.kepco-enc.com/eng/contents.do?key=1533.

63 https://www.neimagazine.com/news/newskoreas-apr-1400-certified-by-us-nrc-7394431.

64 https://www.world-nuclear-news.org/NN-First-Korean-APR-1400-enters-commercial-operation-2012164.html.

tion times for the more recent units have been around eight years. However, so far, none of the reactors has been delivered on budget, with the Barakah units so far being around US$4 billion over the US$20 billion estimate at the time of the bid award in 2009.[65]

KEPCO has also developed the EU-APR-1400 for the European market. The design, more recently referred to as the EU-APR, was approved in October 2017.

KEPCO subsidiary, Korea Hydro & Nuclear Power (KHNP) is also developing a more advanced 1,560-MW version of the APR-1400. Known as the APR+, it gained design approval in August 2014. It has modular construction, which is expected to give a 36-month construction time instead of the 52 months required for the APR-1400. It is also more highly reinforced against aircraft impact than any earlier designs.

In 2022, Westinghouse filed complaints[66] against KHNP and KEPCO in a US court to block exports of APR-1400 reactors to Poland, arguing the model was based on its original design and technology, and that the two South Korean companies should therefore pay licensing fees on any sales. Westinghouse had purchased the nuclear division of Combustion Engineering, on whose designs the reactor was based, in 2000. So far, no settlement has been reached and the dispute has been referred to the Korean Commercial Arbitration Board, which is unlikely to rule until 2025.[67] KHNP filed countersuits in the USA, calling for Westinghouse to withdraw the case, and in September 2023 a US court sided with the Korean company. However, Westinghouse intends to appeal.[68] Until the matter is settled, KEPCO's ability to export its APR-1400s will be in question.

Advanced boiling water reactors

While there is no current proposal for an advanced boiling water reactor (ABWR) in Britain, this technology was initially proposed for the Wylfa Newydd[69] site.

The ABWR was derived from a General Electric design in collaboration with Toshiba.[70] Four examples were built in Japan – two each by Hitachi and Toshiba – while two other units under construction in Taiwan were cancelled, largely for political reasons. The ABWR has been offered in slightly different versions by GE Hitachi, Hitachi-GE and Toshiba. The first four units were each built in 39–43 months on a single-shift basis.

65 https://www.inceptivemind.com/barakah-nuclear-plant-will-supply-25-uaes-electricity-needs/32477/.

66 https://energycentral.com/c/ec/westinghouse-khnp-seek-arbitration-over-ip-dispute.

67 https://www.kedglobal.com/energy/newsView/ked202308020008.

68 https://world-nuclear-news.org/Articles/US-court-dismisses-Westinghouse-case-against-Korea.

69 http://www.hitachi-hgne-uk-abwr.co.uk/reactor.html.

70 https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx.

In December 2017, the Office for Nuclear Regulation (ONR), the Environment Agency, and Natural Resources Wales granted the ABWR Design Acceptance Confirmation and a Statement of Design Acceptability.[71] However, the Wylfa project collapsed in early 2019 when Hitachi withdrew – despite the Government offering to take a one third stake in the project, it proved impossible to reach an acceptable funding agreement.[72]

Given an urgent need to deliver additional large-scale nuclear capacity to replace the UK's closing reactors, it would be sensible to focus on proven technologies, such as ABWRs, which were built on time (in under five years) and on budget[73] in Japan prior to the Fukushima disaster. Although they had limited operating time before the country-wide nuclear closures that followed the 2011 earthquake, a technology that can deliver construction times half those of EPRs deserves serious consideration.

Chinese HPR1000

There have been plans for EDF and China General Nuclear Power Group (CGN) to build two HPR1000 rectors at the Bradwell B[74] site in Essex. The UK Generic Design Assessment for the HPR1000 was successfully completed on 7 February 2022,[75] and by late 2022, the project had progressed to the feasibility study stage.[76] However, there are now significant question marks over its future; wider concerns over Chinese involvement in critical infrastructure projects within the UK have raised doubts about CGN's involvement at Bradwell. It is now unlikely that Bradwell B will be allowed to go ahead with Chinese involvement and using Chinese technology. (It also seems doubtful that EDF would develop an EPR there instead, although the site is currently officially designated as a potential site for new nuclear projects.)

Small and advanced modular reactors

Since the advent of nuclear power, reactors have grown in size to capture economies of scale. However, at the same time, very small-scale reactors have been developed for the marine propulsion sector. Work in this area began in the 1940s, with the first nuclear-powered submarine, *USS Nautilus*,[77] being launched in 1955. In the UK, Rolls-Royce PWR technology has powered nuclear submarines since 1966.[78] Nuclear power is also used for

71 https://www.onr.org.uk/new-reactors/uk-abwr/index.htm.

72 https://neutronbytes.com/2019/01/20/hitachi-freezes-plans-to-build-four-abwrs-in-the-uk/.

73 https://publications.parliament.uk/pa/cm201213/cmselect/cmenergy/117/11705.htm.

74 https://bradwellb.co.uk/.

75 https://www.gov.uk/government/publications/gda-decision-and-soda-uk-hpr1000-reactor.

76 https://www.geplus.co.uk/news/bradwell-b-progresses-to-feasibility-studies-29-09-2022/.

77 https://ussnautilus.org/history-of-uss-nautilus/.

78 https://fissilematerials.org/library/uk11.pdf.

surface-ship propulsion, for example in US aircraft carriers and Russian ice breakers.[79]

Small modular reactors are defined by the International Atomic Energy Authority as nuclear fission reactors with an output below 300 MW – the World Nuclear Association has expanded this definition to say that SMRs are also designed with modular technology to enable factory fabrication, pursuing economies of series production and short construction times.

Most SMRs are use one of four technologies:

- light water reactors (LWRs)
- fast neutron reactors (FNRs)
- graphite-moderated high-temperature gas-cooled reactors
- molten salt reactors (MSRs)

There is some overlap in the definitions with AMRs. Although other designs have also attracted interest, the main focus has been on advancing LWRs, which are viewed as having the lowest technological risk, being similar to conventional nuclear plant.

Licensing is potentially a challenge for SMRs, as design certification, construction and operation licence costs are not necessarily less than for large reactors.

There have been multiple initiatives in the UK exploring the potential of SMRs and AMRs – these are detailed in the appendix. The current state of play is described below.

Small modular reactors

The UK government believes that SMRs could play an important role alongside large nuclear as a low-carbon energy source. Projects range from micro-generation (see below) through to 600 MW reactors, with costs from £100 million to £2.5 billion.

In November 2019, the Government initiated the Low Cost Nuclear Challenge,[80,81] with a commitment to invest up to £18 million in the creation of SMRs. In a second phase,[82] announced in November 2021, a government grant of up to £210 million, matched by £258 million of private funding, was awarded to support Rolls-Royce in moving its SMR towards a final design concept, as well as completing the second stage of the Generic Design Assessment process with the UK nuclear regulators by 2025. The governments's interest in the projected is managed by UK Research & Innovation (UKRI[83]; a quango).

79 https://world-nuclear.org/information-library/non-power-nuclear-applications/transport/nuclear-powered-ships.aspx.

80 https://www.gov.uk/government/news/innovative-funding-models-and-technologies-to-drive-investment-in-new-wave-of-low-carbon-energy.

81 https://www.gov.uk/government/publications/beis-government-major-projects-portfolio-accounting-officer-assessments/small-modular-reactors-low-cost-nuclear-challenge-accounting-officer-assessment-2021-html.

82 https://www.gov.uk/government/news/uk-backs-new-small-nuclear-technology-with-210-million.

83 https://www.ukri.org/what-we-offer/browse-our-areas-of-investment-and-support/low-cost-nuclear/.

In November 2022, Rolls-Royce announced[84] that it had identified four sites for its SMRs: Trawsfynydd, Wylfa, Oldbury and Sellafield. All are on land owned by the UK Nuclear Decommissioning Authority (NDA), although in the case of Wylfa and Oldbury it is currently leased to third parties. In April 2023, the Rolls Royce SMR passed the first step of the GDA process[85] and proceeded to step two, which includes public engagement (there are three steps in total[86]). However, there have been reports[87] that the project may run out of money by the end of 2024.

The US company NuScale has also expressed an interest in deploying SMR technology in the UK. In 2017, it set out a five-point action plan[88] that would see its reactors in operation by the mid-2020s. The company's design, named VOYGR,[89] was the first SMR appoved by the US Nuclear Regulatory Commission.[90] Each VOYGR plant can accommodate up to 12 power modules – each one a 77 MWe PWR generating unit containing all the components for steam generation and heat exchange. Last year the company indicated[91] that it was interested in the Trawsfynydd site in Wales.

In July, GBN launched a tender[92] to select partners that would provide design, development, manufacturing, supply, installation and commissioning of the products, equipment or services required for SMRs– essentially close to a full turnkey solution. Each 'technology partner' will be responsible for delivery to site of a designed and tested solution, development of a complete set of interface specifications, and installation and commissioning of the solution. GBN intends to establish project development companies that will help the technology partners to connect and test interfacing equipment, complete integrated system testing and complete final commissioning and handover.

Subject to affordability, GBN could make up to four awards, with a total budget of £20 billion, and contract lengths of up to 186 months. It could make co-funding of up to 50% available to the selected technology partners to help with the development of their Generic Design Solution so that projects are ready to take

84 https://www.rolls-royce-smr.com/press/rolls-royce-smr-prioritises-four-nda-sites-for-15-gw-of-new-nuclear-power.

85 https://www.gov.uk/government/news/small-modular-reactor-design-completes-first-step-of-assessment.

86 https://environmentagency.blog.gov.uk/2023/04/03/taking-the-rolls-royce-small-modular-reactor-smr-to-the-next-step/.

87 https://www.neimagazine.com/news/newsrolls-royce-smr-faces-financial-problems-10648145.

88 https://www.nuscalepower.com/en/news/press-releases/2017/nuscale-launches-ambitious-action-plan-for-uk-smr-deployment.

89 https://www.nuscalepower.com/en/products/voygr-smr-plants.

90 https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/nuscale.html.

91 https://www.dailypost.co.uk/news/north-wales-news/energy-firm-talks-welsh-government-25842380.

92 https://www.find-tender.service.gov.uk/Notice/020640-2023.

their FID by 2029.

In addition, GBN intends to award a two-stage contract for technology partners for the provision of site-specific designs, the first stage being delivery of a design and the second stage being its supply. GBN will make funding available to cover certain site-specific design solution development costs. The supply phase (the period from FID to the commercial operation date) for a first-of-a-kind project in the UK will include the manufacture, supply, installation and commissioning of the supply works and provision of fuel assemblies and supporting maintenance services, up to and including first refuelling outage.

In October 2023, the first results of this process were announced.[93] Six companies – EDF, GE-Hitachi Nuclear Energy International LLC, Holtec Britain Limited, NuScale Power, Rolls Royce SMR and Westinghouse Electric Company UK Limited – were selected for the next stage of the programme, in which the shortlisted companies bid for contracts. This will be launched 'as soon as possible'. The ambition is to announce in spring 2024 which of the six companies will receive government support, with contracts awarded by summer 2024.

High-temperature Gas-cooled Reactors

The UK Government has also progressed a number of initiatives exploring the potential for high-temperature gas-cooled reactors (HTGRs) due to their potential for generating heat: for low-carbon hydrogen production, industrial and domestic processes, and cost-competitive electricity generation. In December 2022, it committed funding[94] of up to £60 million for the next phase of research into HTGRs, in the hope of delivering a demonstration of the engineering design by the end of the decade.

HTGRs (and Very High-temperature Reactors) are Generation IV reactors,[95] primarily dedicated to the cogeneration of electricity and hydrogen. Their high outlet temperatures also make them attractive for the chemical, oil and iron industries.

HTGRs[96] are similar in concept to the AGR, using uranium fuel, graphite as moderator, and gas cooled. Neither graphite nor the cooling gas – helium – react at high temperatures. A typical HTGR will operate at a pressure of 100 atm and at a temperature of 650–750°C, which enables better thermodynamics, leading to higher efficiency. The reactor is designed so that in the event of a coolant failure it will be able to withstand the rise in internal temperature without failing. Several attempts have been made to build HTGRs, but none has so far entered commercial service.

93 https://www.gov.uk/government/news/six-companies-through-to-next-stage-of-nuclear-technology-competition.

94 https://www.gov.uk/government/news/102-million-government-backing-for-nuclear-and-hydrogen-innovation-in-the-uk.

95 https://www.sciencedirect.com/book/9780080983301/power-generation-technologies.

96 https://www.world-nuclear-news.org/NN-Westinghouse-proposes-UK-deployment-of-small-modular-reactor-21101501.html.

HTGRs can be built in relatively small unit sizes, with generating capacities between 100 MW and 200 MW. In theory, the modular form should allow plant expansion through the addition of new modules.

Other advanced reactor technologies

The UK's AMR programme is now focusing on HTGRs, due to the wide industrial application of their high output temperatures. However, the UK remains part of the Generation IV International Forum, which is developing other reactor technologies:[97] gas-cooled fast reactors, lead-cooled fast reactors, molten salt reactors, supercritical water-cooled reactors, sodium-cooled fast neutron reactors (FNRs) and very high temperature reactors. Developers of several advanced reactors are in pre-application discussions with the US nuclear regulators.[98]

Both molten salt and FNRs are of interest because they reduce the need for uranium, the availability of which has become a concern given the dominance of Russia in the production and processing of conventional nuclear fuels. FNRs[99] operate without a moderator, such as water or graphite, to sustain the fission chain reaction and can extract up to 70 times more energy from fuel than conventional reactors. They can produce or 'breed' more fuel than they consume, and can burn some of the waste contained in used fuel, greatly reducing the problem of high-level waste. FNR systems enable a fully closed nuclear fuel cycle, in which irradiated fuel is reprocessed and reused.

Although FNR development had effectively ended in Europe and the US by the 1990s, it continued in Russia, China[100] and India, where there are now five FNRs[101] in operation and several more under development. Russia's BN-class reactors have already proved the commercial viability of sodium-cooled FNRs, while its lead-cooled Brest reactor and associated ODEK project are on track to demonstrate the feasibility of a completely closed fuel cycle in FNRs.

Interest in the technology is now reviving in Europe, prompted by the Sustainable Nuclear Energy Technology Platform project.[102] In the US, the Mechanisms Engineering Test Loop Facility[103] has been testing fast-neutron reactor components since 2018. In July 2022, the US Department of Energy announced plans to build a sodium-cooled FNR at the Idaho National Laboratory, which, if approved by Congress, would be the first such

97 https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems.

98 https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities.html.

99 https://www.neimagazine.com/features/featuretime-for-a-new-focus-on-fast-reactors-10380132/.

100 https://spectrum.ieee.org/china-breeder-reactor.

101 https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.

102 https://snetp.eu/esnii/.

103 https://www.anl.gov/nse/mechanisms-engineering-test-loop-facility.

reactor to operate in the USA in nearly three decades. Although Congress did not provide funding in 2022, a new request was made in 2023.

Nuclear fusion

There has been renewed interest of late in the prospects for nuclear fusion. In a fusion reaction, energy is released when two light atomic nuclei join to form one heavier atom. To achieve fusion, the fuel must be heated to extreme temperatures; the sun, which is powered by fusion, is estimated to be at 15 million degrees centrigrade.

In terrestrial fusion, the most efficient reaction is between two types of hydrogen – deuterium and tritium – which only fuse at temperatures over 100 million degrees. At these temperatures, the fuel becomes an electrically charged gas or 'plasma', a fragile material a million times less dense than air, which has to be carefully contained.

There are currently two distinct approaches: in Europe, STEP[104] in the UK and ITER[105] in France are developing magnetic confinement, while in the US, a laser driven inertial confinement approach is being developed (see the Appendix).

5. Economics of electricity generation

In the GB market, electricity generators can benefit from several income streams – indeed it is now rare for generators to only receive one source of income, and, in most cases, more than one is required for the plant to remain economic. The so-called 'revenue stack' for electricity generation includes the following elements, although some are mutually exclusive:

- Wholesale market;
- Balancing Mechanism;
- Imbalance or cashout market;
- Ancillary Services (also known as Balancing Services) markets;
- Local flexibility markets;
- Capacity Market;
- Subsidies (CfD, Feed-in-Tariff, Renewables Obligation etc).

Almost all generators sell their electricity into the wholesale markets on a forward basis (which means anything from one day to two years in the future). Any volumes that are not sold, or generation shortfalls where the generator fails to produce enough electricity in any settlement period to meet its contracted obligations, are settled in the imbalance or cashout market. Some generators choose to use this as their main source of income, for example if they are small and trading charges make forward trading difficult and/or expensive.

104 https://step.ukaea.uk/.

105 https://www.iter.org/.

The Balancing Mechanism[106] is the primary tool used by the transmission system operator, NG ESO, to balance the grid in real time. Generators submit bids and offers representing the prices at which they are willing to increase or reduce output in order to help balance the grid. For flexible gas plant, this can be a very significant source of income, but it is less suited to baseload operators, such as nuclear units.

All transmission-connected generators participate to some degree in the provision of balancing/ancillary services,[107] such as reactive power, but many of the services require a degree of operating flexibility, which nuclear reactors lack. There are, however, growing opportunities for nuclear to earn income from the provision of inertia, as the replacement of conventional thermal generation with inverter-based resources such as wind and solar reduces grid strength and stability.

Local flexibility markets[108] are emerging for the provision of ancillary services at the distribution level. These are unlikely to be of interest to nuclear generators, although it is possible that small or micro reactors might participate in the future. These markets are highly localised and currently in their infancy.

Another potential source of income for existing nuclear is the Capacity Market,[109] where participants receive payments in exchange for being available to operate at times of system stress. Prices are set through auctions that take place four years before delivery, with a smaller top-up auction one year before delivery.

Finally, generators may receive subsidies, to support the financing of capital costs. Hinkley Point C has a CfD, but future nuclear projects will be funded under the RAB model (see below).

In July 2022, the Government consulted on potential changes to the electricity markets, including the subsidy regimes and the basis of price formation, in the Review of Electricity Market Arrangements (REMA).[110] One of the motivations for the review was concerns that GB electricity prices are based on the cost of generating electricity using gas, since this is almost always the marginal source of generation (i.e. the last unit that needs to be used in order to meet demand tends to be a gas plant). This means that consumers are not able to benefit from the near-zero marginal costs of generation associated with renewable technologies, and particularly exposes them to high electricity prices at times when gas prices are high, as they were throughout 2022.

However, changes to market price formation cannot be implemented quickly, and most respondents to the consulta-

106 https://www.nationalgrideso.com/what-we-do/electricity-national-control-centre/what-balancing-mechanism.

107 https://www.nationalgrideso.com/industry-information/balancing-services.

108 https://smartgrid.ukpowernetworks.co.uk/flexibility-hub/.

109 https://www.gov.uk/government/collections/electricity-market-reform-capacity-market.

110 https://www.gov.uk/government/consultations/review-of-electricity-market-arrangements.

tion expressed concerns about the difficulties in developing an alternative market design, and the time it would take to implement. The Government has decided not to take forward 'pay-as-bid' pricing into the next phase of assessment, on the basis that it does not meet the criteria of least cost and investor confidence. Other options for decoupling gas and electricity prices for some generators will still be considered: a green power pool and moving more generation on to CfDs. A second consultation, expected later in 2023, will consider next steps.

In the meantime, concerns that renewable generators have made excess profits by receiving income based on high gas prices have been addressed through a windfall tax – the Electricity Generator Levy – announced in the 2022 Autumn Statement.[111] The levy also applies to nuclear generators. This tax is structured as a temporary 45% levy on 'extraordinary profits', defined as electricity sold above £75/MWh. Combined with corporation tax, this brings the cumulative rate on earnings over £75/MWh to 70%. The levy will apply from 1 January 2023 until 31 March 2028.

Impact of renewables on GB market economics

There is currently uncertainty as to how the economics of the electricity market will develop as the penetration of intermittent renewable generation – and in particular wind power – increases. There is currently dissatisfaction from policymakers, among others, that renewable generators receive a wholesale electricity price linked to the short-run marginal cost (SRMC) of generation of electricity produced using gas, which is currently expensive. There is an assumption that since the SRMC of renewable generation is close to zero, consumers should be able to benefit from these low prices. As a result, there has been talk of splitting the market between renewable and non-renewable sources of generation.

Setting aside the difficulty of designing and implementing such a change, it is necessary to consider the logic that is driving it. While the SRMC of renewable generation is indeed close to zero, were renewable generators to only receive an electricity price close to this, they would never earn enough money from selling electricity to recover their capital costs, which are significant, particularly in the case of offshore wind. This means that developers would require some other form of income – which would ultimately be paid for by consumers, either directly through higher bills, or indirectly through higher taxes. In any case, the requirement for this additional income undermines the logic of splitting the market – yes, the wholesale price of electricity might be different for renewable generators, but not necessarily the price paid by consumers, which includes a wide range of additional costs, some of which do not exist or are lower in a conventional electricity system without large amounts of

111 https://www.gov.uk/government/publications/autumn-statement-2022-energy-taxes-factsheet/energy-taxes-factsheet.

intermittent generation.

Splitting the market might make differences between the SRMCs of renewables and other forms of generation more explicit, but it would, particularly in the case of renewables, widen the gap between wholesale prices and the price paid by consumers. It would also potentially be a temporary solution, which would lose importance as and when renewable penetration reached a scale that would allow it to set wholesale prices outright. There are also questions as to how costs that arise as a result of the addition of those renewable resources are recovered. Currently, those costs are recovered from consumers without being first allocated to any particular generation technology. If they were to be so allocated, the cost of renewables versus conventional generation would change, and could potentially be higher.

For example, if a new transmission line is required to connect offshore wind generation to demand centres, that cost could be explicitly attributed to the cost of renewable generation. Similarly, the costs of back-up generation could also be allocated to renewables, something Professor Dieter Helm recommended in his 2017 *Cost of Energy Review*[112] – his 'equivalent firm power' auctions would have required renewable generators to take responsibility for the system effects of mitigating the intermittency they introduced. Currently these costs are recovered through green levies (capacity market costs) and network-use charges (balancing and grid reinforcement costs).

Any market framework that addresses these challenges will have an impact on the economics of nuclear generation. If the status quo is maintained, gas prices will continue to drive wholesale electricity prices, supporting margins for nuclear generators. The more wholesale prices are reduced by the impact of renewables, the lower those margins will be. However, in a market with high renewables penetration and a lower wholesale price, the distortions arising from the inability of the wholesale price to capture the full costs of renewable generation will increase.

The existing approach to determining the merit order is already failing to properly reflect the marginal cost *to consumers* of different forms of generation. This is because renewables do not bear the higher balancing costs associated with their intermittency: even when renewable generation is available, its true cost impact varies with weather conditions. In a conventional electricity system, variability in the supply/demand balance is driven from the demand side, but in the presence of intermittent renewable generation, it is also driven by the supply side, causing balancing costs to rise. These effects are not captured by the current means through which the market establishes the merit order, which determines the wholesale electricity price.

Helm's equivalent firm power model would incentivise renewable generators to co-locate or contract with storage, but

112 https://www.gov.uk/government/publications/cost-of-energy-independent-review.

the costs of building and operating that storage capacity would need to be factored in – under this model, it would likely be captured in the price at which the generator would be willing to sell its electricity, moving it away from the current near-zero expected level. Clearly this would impact the expected margins for renewable generators, and possibly their position in the merit order. It could also affect the level of the wholesale price, which would in turn impact the margins of nuclear generators. In this sense, it is not just the future generation mix that impacts the economics of nuclear generation, but the extent to which market frameworks and the approach to wholesale price formation is changed by policymakers.

Many renewable generators have benefitted from both generous subsidies and high wholesale electricity prices. This has happened as a result of the poor structuring of the Renewables Obligation subsidy framework. However, this issue has at least been partially addressed through the imposition of the Electricity Generator Levy,[113] and the introduction of CfDs for new capacity.

The other implication of a wholesale electricity price for renewable generation being at or close to zero is that the electricity they sell would be essentially worthless. This reduces the rationale for avoiding its curtailment since developers would in any case be relying on alternative sources of income to recover their capital and ongoing operational (primarily maintenance) costs. And these other costs, rather than the wholesale price of electricity, would drive the price paid by consumers. While the Government has made some progress towards recognising some of these conflicts within the REMA process, it is unclear whether it has appreciated the full implications of near-zero wholesale prices, particularly when it comes to its impact on the merit order: if the bulk of the cost paid by consumers is something other than the wholesale price of electricity, the merit order, which determines that price, reduces in significance.

Of course, it will still be desirable to minimise the wholesale price of electricity, but only where doing so does not increase other costs to which consumers are exposed. It is not unreasonable to suppose that the most efficient forms of generation from a whole-system-cost perspective will be those with the highest utilisation rates. The interaction between nuclear energy and intermittent renewable energy – the two low-carbon energy sources favoured in current UK energy policy – is not immediately obvious. Nuclear power has higher capital and SRMC than wind or solar (it requires fuel where they do not), but:

- it has much higher utilisation rates because output does not depend on weather;
- it tends not to impose extra network infrastructure costs;
- because there are enough available sites with existing grid connections to meet current needs;

113 https://www.gov.uk/government/publications/electricity-generator-levy.

- because there is no requirement to site new reactors in places without existing connections, such as offshore, or in places that are remote from demand, such as the north of Scotland, (although the Scottish Government opposes nuclear power anyway);
- it does not create additional balancing costs because it is not intermittent;
- it does not require backup generation or energy storage for the same reason.

Determining the optimal generation mix of nuclear and renewable energy when taking the full costs to consumers into account is challenging. These questions are further complicated when decommissioning costs are factored in – nuclear decommissioning is certainly expensive, although reactors have long operating lives, possibly as long as 60 years, which is roughly equivalent to four generations of wind turbines (although some early offshore windfarms have recently extended their accounting lives to 30 years). All forms of generation have decommissioning challenges and costs, but only nuclear power is forced to deal with them up front.

There are also legitimate questions around the extent to which the government should seek to determine and impose the optimal generation mix on the market or whether the market should make this determination for itself. At the moment, the Government has set targets for different technologies, and put in place incentives it hopes will help them to be met. In doing so, it has significantly distorted the wholesale market by providing price hedges for generation.

The work of Helm is interesting here.[114] He argues that the privatisation model, which was originally designed to take electricity and gas out of a social context and to treat like any other commodity business, has been undermined by the Electricity Market Reform (EMR), which was designed to stimulate decarbonisation. Under the original model of privatisation, consumers could switch suppliers, and suppliers could choose among the generators for their supply. Pricing was based on short-term spot markets.

However, under EMR, the government, rather than consumers, effectively became the buyer of electricity – in other words, the state now buys almost all electricity generation. The increasing penetration of near-zero marginal cost generation has undermined the wholesale price (which in the retail market leads to lower incentives to switch supplier, since suppliers are increasingly all exposed to the same costs). The supply model has devolved to a point at which suppliers are little more than bill collectors, collecting the costs of CfDs, network costs, and various social and environmental policy costs. The interventions following the price shock of autumn 2021 saw a return to the

114 https://dieterhelm.co.uk/energy-climate/energy/how-to-pay-for-energy/.

pre-privatisation model, in which the Government decided how much citizens should pay for electricity. Helm goes on to say:

> Admit it or not, the electricity industry is returning towards a monopoly – monopoly of generation contracting (the electricity system operator, ESO), monopoly of transmission, monopoly of supply, plus in effect an oligopoly of similar suppliers passing on these costs. In the process, the energy system looks much more like the CEGB again (starting with EMR), and it is the state directing and, in the case of nuclear, investing in generation. The CEGB did not build power stations. It let contracts to do so – as the state does now via the auctions it backs.

It is not the purpose of this paper to argue one way or another for or against nationalisation of the electricity market, but it is worth considering the extent to which the competitive forces envisaged at the time of privatisation have been neutered by subsequent policy decisions designed to deliver decarbonisation, and the impact this is having on the wholesale electricity market. These considerations are particularly relevant in the context of the approach to funding nuclear power.

Funding models for nuclear power

Nuclear power is difficult to finance in the private sector due to its combination of very high capital costs and a high regulatory burden, with significant risks of regulatory change both during construction and subsequent operations, which add further costs. As a result, the Government has been forced to offer subsidies, but has a strong desire to keep the costs involved off its balance sheet.

In its first recent attempt at nuclear subsidies, the Government offered CfDs, for example to the Hinkley Point C project. This deal was evaluated by the National Audit Office,[115] which found it was unlikely to represent value for money for consumers. Under the CfD model, developers bear all the project delivery risk and only receive a guaranteed minimum electricity price (the 'strike price' which secures the price received for the electricity generated by the plant) once the plant begins to operate. However, while the CfD scheme has secured many gigawatts of renewable generation projects, investors were reluctant to commit to new nuclear projects without a high strike price – which raised concerns about costs for consumers and value for money – and even then, investors continued to be deterred by the construction and development risks. The Wylfa Newydd project, in particular, failed due to attempts by the Government to push down the strike price.

Despite these problems, the Government remains committed to the delivery of new nuclear, which led it to revise the funding model in the hope of making it more appealing to investors. The

115 https://www.nao.org.uk/reports/hinkley-point-c/.

Nuclear Energy (Financing) Act 2022[116] (NEFA 2022) came into force in May 2022, and sets out the new Regulated Asset Base[117] (RAB) funding model. This differs from CfDs in that it provides for risk sharing between investors and consumers, with consumers contributing indirectly towards construction costs through a small charge on their bills.

Under the model, a company receives a licence from an economic regulator (in this case, Ofgem) to charge a regulated price to consumers in exchange for providing the infrastructure in question (a new nuclear power station). The sharing of construction and operating risks between investors and consumers should lower the cost of capital for projects and provide greater certainty for investors, delivering some level of return in the early stages of the project. The regulator determines the charge paid by suppliers, which is passed on to consumers.

This charge (the allowed revenue for the developer) can be adjusted throughout the life of the licence to ensure that project costs are recovered, and a permitted profit margin is maintained. The calculation is based on the cost of capital, depreciation, operating costs, grid costs, decommissioning costs, and tax, with incentives and penalties applied by the regulator to ensure expenditure is in the interests of consumers.

The model also has financial implications for the Government, because the cost of construction is likely to appear on its balance sheet.[118] A similar funding model has been used to finance the construction of the £4 billion Thames Tideway Tunnel[119] and the £4 billion Heathrow Terminal 5,[120] although it should be noted that new nuclear projects are significantly larger and more complex.

To be eligible to benefit from the RAB funding model, a company has to be a 'nuclear company', meaning it must hold an electricity generation licence in respect of a nuclear project, and be officially designated to deliver that project. There are two criteria that need to have been met: the Secretary of State must believe the development of the project is sufficiently advanced to justify the designation (the 'maturity' test); and, must also be of the opinion that designating the company is likely to result in value for money (the 'value for money' test). In April 2022, the Government published the *Statement on Procedure and Criteria for Designation*,[121] which explains how to meet the criteria.

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116 https://www.legislation.gov.uk/ukpga/2022/15/contents/enacted.

117 https://www.gov.uk/government/news/future-funding-for-nuclear-plants.

118 https://publications.parliament.uk/pa/bills/lbill/58-02/089/5802089en08.htm.

119 https://www.constructionnews.co.uk/civils/new-tideway-delay-cost-increase-25-08-2020/.

120 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/439677/cost-and-commercial-viability-literature-review-update.pdf.

121 https://www.gov.uk/government/publications/nuclear-regulated-asset-

The maturity test assessment will focus on evaluating whether there is a credible strategy and plan for the design, construction, operation and ultimate decommissioning of the project. The value for money assessment will be carried out in line with the Green Book, which sets out the Government's general approach to appraisal and evaluation. A key test will be to assess the difference between the costs of the electricity system if a project goes ahead and if alternative projects with different generation technologies were built.

In addition to applying the two designation tests, the Government must also consult on the proposed designation of a nuclear project with a broad list of statutory consultees, including Ofgem, the ONR and the relevant environmental regulators. It is also possible that future designations will include a condition allowing the Secretary of State to take a 'special share' in the company where national security interests are involved, and to ensure that significant stakes cannot be sold without the Government's knowledge or consent.

Although the designation process is intended to occur early in the development of a new nuclear plant, a significant amount of upfront investment and effort will be involved. Designation is time limited and will expire, typically after five years, although the Secretary of State may specify a different date following consultation. The Secretary of State also has the power to revoke a designation in certain circumstances.

Following designation, the generation licence held by the nuclear company will be modified to ensure certain conditions are met. The list of potential modifications is detailed in NEFA 2022, and includes:

- provisions relating to the revenue the nuclear company may receive and how it is calculated;
- details on how the construction risk and associated development costs will be shared;
- permitted and prohibited activities, and how the former shall be carried out;
- requirements for the provision of information to Ofgem;
- the circumstances in which a licence may be revoked; and
- the process for appealing a licence modification decision to the Competition and Markets Authority.

In respect of the project economics, nuclear generating licences will contain details of the 'base cost forecast', which estimates the total expenditure required to complete the project. With the exception of certain specified items, all expenditure up to the base cost forecast will be added to the RAB, on which investors will be able to earn a return. The licences will also include a 'financing cap': cost overruns between the base cost forecast and the financing cap will be assessed by Ofgem: if they are accepted, they will be considered to fall within the RAB, but

base-rab-model-statement-on-procedure-and-criteria-for-designation.

above the cap, they are expected to be covered through a state support package, which is expected to be negotiated on a case-by-case basis. The intention is for the financing cap to be set at a level that is unlikely to be reached, so as to provide protection against remote but high impact events. Investors must finance the construction of the project up to the financing cap.

In June 2022, the Government consulted on the revenue mechanics[122] of the RAB model, and determined that the revenue collection counterparty (the Low Carbon Contracts Company Ltd) will collect payments from suppliers and pass them to the nuclear company, in a process that largely follows that in place for the CfD scheme.

A particular benefit of the RAB model compared with the CfD and other approaches is that it avoids the compounding of finance interest during construction, which otherwise has a significant impact on the costs to consumers. This was a specific design choice of the funding model, and is of particular benefit in the current high interest rate environment.

However, the entire approach in the nuclear context is as yet unproven: no new nuclear projects have yet reached their Final Investment Decision on the basis of the RAB model. Sizewell C is expected to be the first, but there is no pipeline beyond that deal. It may be that the structure still does not go far enough to secure investor interest, and without doubt, the complexities of the scheme do nothing to speed the progress of potential projects.

An alternative would be to abandon the idea of incentives altogether and return to direct public funding of nuclear projects. The Government is already toying with this idea through the co-funding models being developed by GBN, but, in the interests of expediting much needed new large-scale projects, it may need to go further. Simply issuing a tender for a handful of reactors, to be paid for by the state but built and operated by private companies, is likely to deliver faster results, potentially at a lower cost to consumers given the relatively low cost of finance available to the Government compared with the private sector. As the experiences with the Private Finance Initiatives[123] of the 1990s show, private sector funding does not guarantee a lower cost to consumers, and the delays inherent in securing investor interest in high-cost, high-risk projects could be avoided through public funding, creating further benefits (or at least avoiding detriments) to consumers.

6. Regulatory framework

Nuclear regulatory frameworks, by their nature, tend to be cumbersome and conservative, not least to satisfy the public that

122 https://www.gov.uk/government/consultations/revenue-stream-for-the-nuclear-regulated-asset-base-rab-model.

123 https://committees.parliament.uk/committee/158/treasury-committee/news/177569/pfi-report/.

nuclear power is safe, and remains so. However, there is a degree to which regulation has been shaped by a desire to provide a comfort blanket in response to various nuclear incidents, notably Three Mile Island, Chernobyl and Fukushima. However, it is important to note that of these, there were only fatalities at Chernobyl, and that incident was a result of egregious human error of the type that is easy to avoid if the most basic risk frameworks are enforced.

Despite these high-profile incidents, nuclear power is extremely safe[124] – there have only been around 30 documented fatalities associated with nuclear accidents (although long-term data relating to Chernobyl are not readily available), and the number of incidents is actually very low: Chernobyl was the most serious, followed by Fukushima, and then Three Mile Island, where there was no radiation leak outside the plant.

The use of the term 'disaster' to describe the events at Fukushima is only appropriate in the context of the impact the event had on the industry, rather than in and of itself. The only fatalities at the plant arose directly as a result of the earthquake and tsunami (people being struck by falling debris), and not as a result of radiation. There were no deaths during the nuclear accident itself and, so far, instances of illness and death in people that may have experienced radiation exposure do not appear to be statistically different from the wider population. By comparison, 19,500 people were killed by the tsunami. The reality is that all heavy industries bring physical safety risks; extractive industries, including oil and gas production and mining, are particularly hazardous.

However, in the wake of Fukushima, and to a certain extent the events of 11 September 2001, nuclear regulation has become significantly stricter, and arguably presents a major barrier to new projects. For example, none of the existing in-service French reactors would achieve a safety certification if they were being commissioned today, despite decades of trouble-free operation. To give an idea of the scale of the regulatory challenge, SMR developer NuScale has described the process by which it secured NRC approval, saying the process ran from 2008 to 2020, cost half a billion dollars and generated around two million pages of documentation.[125] Elsewhere in this paper, the ONR's approach to graphite cracking provides further evidence of the difficulties of the current regulatory approach.

While it is essential for public confidence in nuclear power that regulators hold developers and operators to high standards, it is also important that these standards are proportionate. While suggesting nuclear power should be made 'less safe' might sound irresponsible, it is far from responsible to mandate the closure of

124 https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx.

125 https://www.technologyreview.com/2023/02/08/1067992/smaller-nuclear-reactors/#:~:text=NuScale%20started%20working%20toward%20regulatory,to%20the%20NRC%20in%202016.

perfectly safe reactors at a time when security of supply is at risk. There are two fundamental problems: regulatory approaches have become excessively and unreasonably conservative, and processes so involved that they represent a material deterrent to the delivery of new nuclear technologies.

A two-fold problem requires a two-fold solution: regulations need to be adjusted to be more proportionate to the risks, and processes need to be streamlined. The UK Government has expressed a desire to collaborate with overseas regulators, but it could and should go further, instigating a shared framework for regulation and certification with nuclear regulators in trusted nations. This would speed the adoption of new technologies and, in particular, of SMRs and AMRs, which are widely seen as important for the delivery of the energy transition.

7. Supply chain and workforce

One consequence of the long hiatus in the construction of new nuclear power stations and the progressive closure of the legacy fleet has been a dismantling of nuclear supply chains and a gradual erosion of workforce skills, as experienced nuclear engineers retire and are not replaced. Many (but by no means all) of the challenges faced by EDF and Westinghouse in developing new reactors are a result of these factors – both companies have been forced to rebuild supply chains and develop workforce skills from the ground up. These are not insignificant challenges.

Earlier this year a French Parliament report[126] into the country's energy market pointed to a failure to consider life extensions of the nuclear fleet early enough, resulting in a loss of key skills and a degradation of supply chains. Correcting this situation was identified as a key energy policy for the future.

Nuclear supply chains

Nuclear supply chains encompass a wide range of activities, from uranium extraction and enrichment, to plant construction, operation, decommissioning, and waste management. Within plant construction, which is the main area of immediate concern in the UK, hundreds of contractors can be involved. Supply chain considerations relate to all aspects of procurement, from sourcing materials, the construction, assembly and installation of components, testing and so on. At each stage, and for each contractor, there are questions of cost, delivery times, quality control and safety. There are significant opportunities to deliver economic benefit as more of these activities are captured within the UK rather than imported from elsewhere. Any nuclear supply chain plan should seek to maximise the domestic supply chain, in an economically efficient manner.

In 2012, the Government produced a Nuclear Supply Chain

126 https://www.assemblee-nationale.fr/dyn/16/organes/autres-commissions/commissions-enquete/ce-independance-energetique.

Action Plan,[127] which aimed to maximise economic activity, jobs and growth in the nuclear sector at both the national and local level, ensuring that potential skills shortages did not act as a barrier to the development of the nuclear industry. A successful domestic civil nuclear industry was to serve as a basis to access export opportunities. A 2013 study[128] suggested the potential value of a 16.5 GW programme of new nuclear reactors could be £37.3 billion of gross value added to the UK economy and 587,000 job years. The number one recommendation for achieving this was: 'confidence and certainty in the new build programme'. Clearly this has not been delivered – then, as now, the only new nuclear project firmly in the pipeline was Hinkley Point C.

The Government has been broadly silent on the question of nuclear supply chains since the 2012 Action Plan, although in April 2023, the UK and Republic of Korea signed a co-operation statement[129] which included reference to nuclear power:

- accelerating plans for civil nuclear;
- collaborating to promote the highest standards of safety, regulation, security, safeguards and non-proliferation;
- confirmation of plans to build robust and resilient nuclear supply chains;
- sharing knowledge about the development of new nuclear technologies, including SMRs.

Nuclear workforce skills

The National Skills Academy for Nuclear (NSAN),[130] created in 2008, is the lead strategic skills body for the nuclear industry in the UK. It is an employer-led and -funded membership organisation, established to ensure that the nuclear industry and its supply chain has the skilled workforce it needs. NSAN received almost £1 million of funding as part of the 2012 Nuclear Supply Chain Action Plan, anticipating the creation of 6–7,000 jobs at each of Hinckley Point C, Wylfa and Oldbury. Of course, of these, only the first materialised.

In 2013, the Nuclear Industrial Strategy[131] established a new Nuclear Industry Council (NIC)[132] to bring together all the key players across the supply chain. The strategy also included a long-term plan to ensure the industry would have the necessary skills for the future. However, the most recent meeting minutes on the NIC website are dated 2019, and are more concerned with

127 https://www.gov.uk/government/publications/nuclear-supply-chain-action-plan.

128 https://www.gov.uk/government/publications/economic-benefit-of-improving-the-uks-nuclear-supply-chain-capabilities.

129 https://www.gov.uk/government/news/shapps-uk-to-partner-with-korea-on-energy-transition-and-stand-united-against-putins-aggression.

130 https://www.nsan.co.uk/page/AboutNSAN.

131 https://www.gov.uk/government/publications/nuclear-industrial-strategy-the-uks-nuclear-future.

132 https://www.gov.uk/government/groups/nuclear-industry-council.

diversity in the workforce than skills.

In 2015, the Nuclear Sector Skills Strategy[133] noted that the challenges of building the UK's nuclear skills base were significant and that existing expertise lay primarily in the operation and decommissioning of reactors rather than construction. At this time, the intention was to 'ensure the [UK's] nuclear workforce's expertise is unsurpassed globally'.

The following year saw the launch of the National Nuclear Skills Strategic Plan.[134] The Nuclear Skills Strategy Group[135] (NSSG) was established in 2016, and is an employer-led skills body. Its members include a variety of organisations involved in the sector: major employers, government departments and trade unions. The NSSG has recently[136] identified and prioritised 11 of the most critical skills in demand, and is collaborating across the sector to mitigate the most significant skills risks. In 2018, the National College for Nuclear[137] was founded,[138] as a partnership between industry employers, regulators, skills bodies and training providers.

More recently, the Government announced a new Nuclear Skills Taskforce[139] to 'turbo charge skills activity in [the] nuclear sector.'

The frequency with which nuclear skills strategies are released suggests a lack of follow-up in relation to their actions. There appears to be minimal relationship between successive strategies, each of which recognises the magnitude of the challenge, but either fails to identify credible solutions, or else lacks appropriate frameworks for their delivery. There has been a worrying drift towards concerns over workforce diversity, potentially overshadowing the basic skills requirements. While diversity is desirable, it should not be unduly prioritised. The Government needs to move on from planning and the 'busywork' of all these skills strategies, and knuckle down to following through.

Success is unlikely in the absence of a credible pipeline of new nuclear projects. The disappointing lack of progress in this respect represents a major barrier to the creation of a skilled workforce. Not only are the projects on which skills can be built lacking, but the absence of a pipeline makes the sector significantly less attractive to potential nuclear workers.

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133 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/415427/Sustaining._Our_Nuclear_Skills_FINAL.PDF.

134 https://www.gov.uk/government/news/launch-of-national-nuclear-skills-strategic-plan-unites-sector-on-skills-as-it-embarks-upon-renaissance.

135 https://www.nssguk.com/about-nssg/overview/.

136 https://www.niauk.org/developing-uk-nuclear-skills-a-national-imperative-nssg/.

137 https://www.ncfn.ac.uk/.

138 https://www.gov.uk/government/news/new-national-college-for-the-nuclear-industry-launches.

139 https://www.gov.uk/government/news/new-taskforce-to-build-uk-nuclear-skills.

8. Conclusions

The past few years have seen significant progress in some detailed areas of policy relating to nuclear energy, which is positive. However, at a high level, a stronger commitment is needed. The near-term milestones remain modest, and may well be missed.

In terms of large-scale nuclear projects, the Government needs to urgently deal with the issue of AGR retirements. While lifetime extensions are to be welcomed, they are not guaranteed, and there continue to be risks that any of the existing reactors, with the exception of Sizewell B, could see their closure dates brought forward, while Hinkley Point C could be subject to further delays. As concerns over energy security heighten, the urgency of the task of replacing closing AGRs grows. With new EPRs (or the AP1000) taking at least a decade to build, the Government should look again at technologies with a history of faster delivery, such as the APR-1400 and the ABWR. Currently there are no signs of this happening.

Similarly, ambitions for SMRs have slipped, in part due to delivery issues: developers, whose initial plans were to have projects running by the mid-2020s, have now delayed to the end of the decade. The Government could help by streamlining the approvals processes. It has spoken of leveraging the work of credible regulators elsewhere, and should ensure that this happens in practice, so that UK regulators do not duplicate the work of US, Canadian, French, Japanese and South Korean regulators in particular.

AMRs are not expected to enter service this decade, but the Government should continue to facilitate research and development to secure their contribution to electricity generation in the 2030s. Provision of innovation funding for fusion has merit, but not at the expense of projects with closer and more credible delivery prospects.

The policy directed towards newbuild projects should clearly differentiate between short-, medium-, long- and very long-term horizons. A credible pipeline of projects is a prerequisite to building efficient nuclear supply chains and a skilled nuclear workforce.

As with many countries, the UK has belatedly begun to focus on access to nuclear fuels. Some countries, such as India, have been ahead of the game, progressing with FNR projects to mitigate the risks inherent in uranium imports. Since the closure of the UK FNR programme in the 1990s, there have been no further domestic efforts to develop fast breeder reactors, although the UK is participating in the Generation IV International Forum, which is developing six technologies, including sodium-cooled fast breeder reactors, which use depleted uranium fuel.[140]

The economic opportunities for nuclear power in GB are mixed outside the RAB model. The ability to provide non-intermit-

140 https://www.gen-4.org/gif/jcms/c_42152/sodium-cooled-fast-reactor-sfr.

tent low-carbon generation is attractive, but even the relatively low operating costs of nuclear will struggle to compete against the near-zero marginal costs of operation of renewable generation, especially wind power, which the Government intends to build at very large scale. To support wholesale market revenues, nuclear reactors are also able to benefit from the Capacity Market, although reliance on such mechanisms for new projects would be risky since the Government is undertaking a wide-reaching review of the electricity market, and all market structures could change in the decade or so it would take for most large projects to be delivered. In this respect, technologies that can be developed faster would have an advantage.

The Government hopes that the RAB model will mitigate these risks. However, developers may be nervous about the role of Ofgem. Its track record as the economic regulator of gas and electricity networks is mixed, and it has faced significant pressure to reduce energy company profits. Its calculation of the cost of capital for network companies has attracted criticism,[141] as has its ability to set incentives and penalties. While Ofgem will not have the power to change the RAB model, as it does with the regulated income for network companies, it is likely to determine the income received by nuclear generators, through its discretion over calculation of the cost of capital and its ability to set incentives and penalties.

Electricity generation is not the only source of potential income for future nuclear projects. As decarbonisation continues and the use of natural gas is reduced, there will be a need for alternative sources of high-temperature heat, which cannot be provided by renewables. Nuclear reactors could therefore replace fossil fuels in a range of industrial applications.

The UK Government recognises many of these factors, but its progress in addressing them is too slow and too timid. Arguably, it should not shy away from direct investments in new nuclear projects, filling the gaps the private sector seems reluctant to fill itself – the private sector is not expected to fund physical security in terms of the military or the police. There could be a similar role for the Government to directly fund at least some portion of energy security as well, particularly given the strategic importance of nuclear power. Of course, this would bring nuclear power stations onto the government balance sheet, but the economic costs of energy shortages are significant, and a cost-benefit analysis of this option would be worthwhile.

Britain should be an attractive market for nuclear projects, but in its determination both to avoid adding costs to the state balance sheet, and any perception of delivering poor value for money, the Government has failed to create the necessary conditions for new projects to flourish. The approaching closure of the AGR fleet, and overarching climate ambitions make it vital that a

141 https://www.newpower.info/2017/04/opinion-energy-networks-are-making-too-much-profit/.

more robust approach is taken to securing the next generation of reactors in Britain.

9. Appendix: Small and advanced modular reactors

Small modular reactors are defined as fission reactors with an output below 300 MW using modular technology and factory fabrication. Their developers pursue economies through series production and short construction times. Most SMRs are being developed using one of four technologies:

- Light Water Reactors (LWRs)
- Fast Neutron Reactors (FNRs)
- Graphite-moderated High-temperature Gas-cooled Reactors (HTGRs)
- Molten-Salt Reactors (MSRs)

There is some overlap in definition with Advanced Modular Reactors.

Initial SMR studies in the UK

In 2014, the UK Government commissioned a report on SMR concepts, feasibility and potential.[142] It concluded that there is a 'very significant market' for SMRs where they fulfil a need that cannot necessarily be met by large nuclear plants. The size of the potential market was estimated at 65–85 GW by 2035, valued at £250–400 billion. The study also determined that there could be a UK market for SMRs of around 7 GW by 2035.

In November 2015, the Government announced that it would invest at least £250 million over five years in nuclear R&D, including SMRs.[143] In March 2016, the Department of Energy and Climate Change (DECC) called for expressions of interest in a competition to identify the best value SMR for the UK.[144] The first phase was an evidence-gathering exercise, with the goal of gauging market interest among technology developers, utilities, and potential investors. Expressions of interest were received from 33 eligible participants, with whom officials worked to understand the technological and commercial viability of new reactors in development. The competition closed in December 2017.

In December 2017, BEIS (the successor department to DECC) announced[145] it would invest up to £44 million to estab-

142 https://namrc.co.uk/wp-content/uploads/2015/01/smr-feasibility-study-december-2014.pdf.

143 https://www.gov.uk/government/publications/spending-review-and-autumn-statement-2015-documents/spending-review-and-autumn-statement-2015.

144 https://www.gov.uk/government/publications/small-modular-reactors-competition-phase-one.

145 https://apply-for-innovation-funding.service.gov.uk/competition/80/overview.

lish a feasibility and development programme for AMRs, which were defined as a broad group of advanced nuclear reactors that use pressurised or boiling water for primary cooling. Organisations could apply for a share of up to £4 million to develop feasibility projects. Twenty bids were received by the initial deadline, with eight organisations[146] awarded contracts. In July 2020, BEIS awarded[147] £10 million to each of:

- Westinghouse, for its 450 MWe LFR;
- U-Battery consortium for its 4 MWe HTGR; and
- Tokamak Energy for its compact fusion reactor project.

A further £5 million was made available for British companies to develop new ways of manufacturing advanced nuclear parts for modular reactor projects, and a further £5 million to strengthen the regulatory regime.

In 2017, the Government commissioned an independent techno-economic assessment[148] of SMRs, which explored the following technologies:

- Integral Pressurised Water Reactors (IPWRs);
- Pressurised Water Reactors (PWRs);
- High-temperature Gas-cooled Reactors (HTGRs);
- Molten Salt Reactors (MSRs);
- Sodium-cooled Fast Reactors (SFRs); and
- Lead-cooled Fast Reactors (LFRs).

It found that IPWR technology had the potential to be operable in the UK around 2030, having a high level of technical readiness. The other technologies would require significant investment in R&D before they could be commercially deployable, although could offer technical advantages and greater cost competitiveness than IPWRs, possibly through the development of intrinsically safe designs with less complex systems. With well-funded R&D programmes, HTGRs and SFRs could be ready for commercial deployment between 2035 and 2050. Other reactor technologies were considered less likely to be deployed in this timeframe.

As a follow-up to this report, in July 2020, the Government commissioned[149] the National Nuclear Laboratory and the Nuclear Advanced Manufacturing Research Centre to assess the strengths of the UK's supply chain and R&D capabilities in design, manufacture and deployment of the different AMR technologies.

146 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/738082/Advanced_Modular_Reactor_Competition_Phase_1_Feasibility_and_Development_Study_Abstracts_from_the_Vendor_s_Proposals.pdf.

147 https://www.gov.uk/government/publications/advanced-modular-reactor-amr-feasibility-and-development-project.

148 https://www.gov.uk/government/publications/small-modular-reactors-techno-economic-assessment.

149 https://www.gov.uk/government/publications/uk-rd-and-supply-chain-capability-for-advanced-modular-reactors.

They found that the UK R&D sector and the supply chain had a number of development needs, which would need to be met before the UK could deploy AMRs, and some of which applied across multiple AMRs and SMRs. Roadmaps produced for each AMR system showed they had similar R&D needs, but that the UK capability to meet these needs was questionable. Key barriers included a lack of verification and validation facilities (such as environmental test loops, zero-power research or materials test reactors), as well as a lack of suitably qualified and experienced personnel. On the supply-chain side, it found that key UK manufacturing needs existed across all AMRs – a maximum of 20% of the components assessed in the study could be manufactured in the UK at the time of the study. The UK manufacturing capability was higher for AMR systems, with which there was historic experience, for example, from the Fast Reactor Programme.

In December 2022, BEIS opened a process[150] for market participants to submit applications for Generic Design Assessment for advanced nuclear reactors, including applications for projects under the Future Nuclear Enabling Fund. This is an open process, although applications for the latter closed at the beginning of 2023.

UK Government interest in HTGRs

In July 2021, the Government published a research paper[151] from the Nuclear Innovation and Research Office, which assessed AMR technologies that might support the UK's net zero targets. The analysis indicated that HTGRs were the most promising technology with respect to the key objective of generating high-temperature heat for low-carbon hydrogen production, process heat for industrial and domestic use, and cost-competitive electricity generation.

In February 2021 BEIS undertook market engagement[152] in relation to a new AMR RD&D programme, indicating that it would likely take a three-phase approach:

- Phase A: Pre-FEED (Front-end engineering design) phase, to understand the potential size, type, cost, and delivery method for an HTGR demonstration;
- Phase B: FEED phase, the output of which would be the basis of detailed design and engineering work, including accurate assessments of the total investment and life-cycle costs, how the demonstration would be sited, and overall project delivery planning;
- Phase C: Permissioning, construction, detailed engineering and operation – this phase could see a successful

150 https://www.gov.uk/government/publications/entry-to-the-generic-design-assessment-for-advanced-nuclear-reactors.

151 https://www.gov.uk/government/publications/advanced-modular-reactors-amrs-technical-assessment.

152 https://www.gov.uk/government/publications/advanced-modular-reactor-amr-research-development-and-demonstration-programme.

proposal from Phase B undertake detailed site-specific design, planning permissions, environmental permitting, nuclear site licensing, construction, commissioning and initial operation of the HTGR demonstration.

The Phase A competition was launched in April 2022, seeking to identify and understand the feasibility of credible, cost-effective, innovative HTGR reactor and fuel solutions to be used to define the scope of future AMR RD&D programmes and to inform associated policy developments. In September 2022, BEIS announced[153] that five organisations had received funding across six projects that would test the feasibility of HTGR technology and coated particle fuel. Early evidence from these projects was due to be received by the end of the year.

Phase B was launched in December 2022,[154] and ran until the end of March 2023. It was a separate open competition – applications were not limited to successful Phase A projects, but had to be capable of delivery of a HTGR demonstration by the early 2030s. The results have yet to be announced.

Also in December 2022, the Government committed[155] funding worth up to £60 million to kickstart the next phase of research into HTGRs. The funding, from the Advanced Modular Reactor R&D programme, aims to get a demonstration project of the engineering design up and running by the end of the decade. This funding was supported with a further £4 million for the AMR Knowledge Capture Project, which aims to reduce the time, risk, and cost of the programme delivery.

Small modular reactors

The UK government believes that SMRs could play a significant role in Britain's energy mix, and has been exploring options for a number of years.

In 2015 Westinghouse presented an unsolicited proposal[156] for a 'shared design and development model', under which the company would contribute its SMR conceptual design and then partner with UK government and industry to complete, license and deploy it. The current Westinghouse SMR design, the AP300,[157] was launched in 2023. It is a 300 MW integral PWR utilising the AP1000 technology. Westinghouse believes it could deliver the first unit by the end of the decade.[158]

153 https://www.gov.uk/government/publications/advanced-modular-reactor-amr-research-development-and-demonstration-programme-successful-organisations.

154 https://www.gov.uk/government/publications/advanced-modular-reactor-amr-research-development-and-demonstration-programme-phase-b-competition.

155 https://www.gov.uk/government/news/102-million-government-backing-for-nuclear-and-hydrogen-innovation-in-the-uk.

156 https://www.world-nuclear-news.org/NN-Westinghouse-proposes-UK-deployment-of-small-modular-reactor-21101501.html.

157 https://www.westinghousenuclear.com/energy-systems/ap300-smr.

158 https://www.world-nuclear-news.org/Articles/Westinghouse-unveils-

In 2018, the UK Government convened a working group to advise on how SMR projects could raise investment in the UK. In its report,[159] the group concluded that the UK could be well placed to develop first-of-a-kind small reactors, with overnight costs of less than £2.5 billion, by 2030. It recommended a focus on technologies capable of being commercially deployed by 2030, reducing the cost of capital and sharing risks by assisting with their financing through a new infrastructure fund (seed funded by the Government) and/or direct equity and/or state guarantees; and also via the use of funding support mechanisms such as Contracts for Difference, power purchase agreements or the Regulated Asset Base model. For next-of-a-kind projects it expected the market to be self-sustaining.

Micro-reactors

In March 2019 BEIS released a 2016 report[160] on micro-reactors, which it described as a distinct class of small reactor systems, typically of under 30 MW electricity and 100 MW thermal output, which are expected to occupy distinct and different market niches to SMRs. The report projected a global market for micro-reactors of around 570 units by 2030, totalling 2850 MW.

Although some micro-reactors have evolved from LWR technology, they are typically HTGRs, liquid-metal-cooled fast reactors or molten salt reactors, using the more efficient Generation IV concepts, which are at a lower level of technology readiness. They use a compact reactor and heat exchange arrangement, frequently integrated in a single reactor vessel. Micro-reactors are designed to be factory manufactured, eliminating the need for complex on-site assembly. They are also designed to operate with minimal on-site supervision, and require no operator intervention in the case of emergency shutdown. Their small size means they can be removed from site and taken to a specialist facility for decommissioning.

Westinghouse is currently developing the 5 MW eVinci[161] micro-reactor, which is a good example of the type, designed for decentralised and remote locations. The reactor is intended to be transportable, fully factory built, fuelled and assembled, and able to run for at least eight years before re-fuelling, including on a load-following basis. The company is hoping that on-site installation can be completed in just 30 days. At the end of its life, the reactor, complete with any spent fuel, would be fully removed from the site, which would require minimal remediation. The company is currently engaging part in pre-application processes

AP300-small-modular-reactor.

159 https://www.gov.uk/government/publications/market-framework-for-financing-small-nuclear.

160 https://www.gov.uk/government/publications/market-and-technical-assessment-of-micro-nuclear-reactors.

161 https://www.westinghousenuclear.com/energy-systems/evinci-microreactor.

with the US nuclear regulator.[162]

Earlier this year, US company Last Energy announced[163] it had contracted to sell 24 of its 20 MW micro reactors directly to customers in the UK, bypassing all Government initiatives and without the need for any subsidies. The PWR-20[164] is a single-loop PWR, with a continuous output of 300°C, and is offered for both gridscale and behind-the-meter applications, where customers effectively lease the units without the need for upfront capital. The company commits to managing every stage of the plant's life, from design through to operations and maintenance. However, the design has yet to secure approval from UK regulators, and it is not clear that the process has even started, as there is no mention of it in the ONR pipeline.[165]

While the concept is compelling, its technological readiness is low compared with other technologies, and in the UK work on the area has been absorbed into the AMR programme.

Other advanced reactor technologies

Molten salt and fast reactors are of interest because they reduce the need for uranium, which has become of increased interest given the dominance of Russia in the production and processing of conventional nuclear fuels. The first ever nuclear reactor to generate electricity was an FNR, cooled by liquid sodium. The Experimental Breeder Reactor,[166] launched at the US Idaho National Laboratory in 1951, produced enough electricity to illuminate four 200 W light bulbs. The 60 MW Dounreay Fast Reactor[167] in the UK opened in 1962, and was the world's first FNR to provide electricity to the national grid. A second FNR, with a capacity of 250 MW,[168,169] was later built on the same site and operated until 1994. Both were sodium cooled.

Enthusiasm for FNRs grew in the 1960s and 1970s in the US and Europe, but as concerns about access to uranium began to decline, and public hostility grew following the Three Mile Island incident in 1979 and the Chernobyl disaster in 1986, interest began to wane. By the early 1990s, the US, the UK and Germany had all closed their FNR programmes, followed by France in 2019. Public opinion became particularly hostile after several failures with test projects, which suffered from corrosion and leaks in

162 https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/evinci.html.

163 https://www.telegraph.co.uk/business/2023/03/20/us-firm-agrees-sell-24-mini-nuclear-reactors-uk-customers/.

164 https://www.lastenergy.com/technology.

165 https://www.onr.org.uk/new-reactors/assessment.htm.

166 https://inl.gov/experimental-breeder-reactor-i/.

167 https://www.gov.uk/government/news/dounreays-oldest-reactor-to-be-demolished.

168 https://www.world-nuclear.org/reactor/default.aspx/DOUNREAY%20PFR.

169 https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/026/28026107.pdf.

their cooling systems.

Although FNR development effectively ended in Europe and the US by the 1990s, it continued in Russia, China[170] and India. India is developing a 500-MW prototype sodium-cooled fast breeder reactor at Kalpakkam, which is currently under construction and is expected to open in 2024.[171] However, the project has experienced delays[172] and cost overruns. But despite these issues, and historic challenges with fast breeder reactors, India is persevering, in part due to increasing difficulties in obtaining uranium. It is also developing thorium reactors.[173]

Nuclear fusion – tokamak

In a magnetic confinement system, fusion plasma is heated and confined in a ring-shaped bottle known as a tokamak, where it is controlled with strong magnetic fields. Here, deuterium and tritium fuse to produce helium and high-speed neutrons, releasing approximately 10,000,000 times more energy per kilogram of fuel than is released in burning fossil fuels. A commercial fusion power station would use the energy carried by the neutrons to generate electricity – the neutrons would be slowed by a blanket of denser material surrounding the machine, with the resultant heat converted into steam to drive turbines.

The UK is developing a fusion project known as the Spherical Tokamak for Energy Production, or STEP. The first phase, to produce a concept design, is due to be completed in 2024. In phase two, the design will be developed, and regulatory consents obtained. In phase three, a prototype will be constructed, with completion due around 2040. Five sites were shortlisted in 2021:[174] Ardeer (North Ayrshire), Goole (East Riding of Yorkshire), Moorside (Cumbria), Ratcliffe-on-Soar (Nottinghamshire), and Severn Edge (Gloucestershire). In October 2022, the Government confirmed that the West Burton site in Nottinghamshire had been selected as the location for the STEP prototype,[175] (having replaced Ratcliffe due to site availability issues[176]). In February 2023, the Government set up UK Industrial Fusion Solutions Ltd,[177] to deliver the STEP fusion prototype.

The UK is also a partner in the European ITER (and has

170 https://spectrum.ieee.org/china-breeder-reactor.

171 https://www.world-nuclear-news.org/Articles/India-gives-update-on-nuclear-construction-project.

172 https://www.nuclearasia.com/news/indias-prototype-fast-breeder-reactor-delayed-further-likely-to-be-commissioned-in-2024/4912/.

173 https://www.barc.gov.in/randd/tfc.html.

174 https://www.gov.uk/government/news/five-sites-shortlisted-for-uk-fusion-energy-plant.

175 https://www.gov.uk/government/news/west-burton-selected-as-home-of-step-fusion-plant.

176 https://www.business-live.co.uk/technology/ratcliffe-soar-dropped-shortlist-first-22829046.

177 https://www.gov.uk/government/news/uk-takes-major-step-towards-near-limitless-low-carbon-energy.

remained so despite Brexit[178]), which had been scheduled to start generating its first plasma in 2025 before starting high-power operation around 2035 – although there could be some delays due to the pandemic.[179] The project builds on the work of the Joint European Torus (JET) in Oxfordshire, which was the first device to produce controlled fusion power with deuterium and tritium, and holds the world record for fusion power.[180] ITER is designed to:

- achieve a deuterium-tritium plasma in which the fusion conditions are sustained mostly by internal heating;
- generate 500 MW of fusion power in its plasma from 50 MW of input heating power. ITER will not convert the heating power it produces to electricity;
- contribute to the demonstration of the integrated operation of technologies for a fusion power plant;
- test tritium breeding in the later stages of the project;
- demonstrate the safety characteristics of a fusion device.

It should be noted that the 50 MW 'input heating power', does not represent the total amount of energy required to run the plant – the site will have an electrical load of up to 620 MW, much of which will be required for plasma containment. The technology will need to be developed further, to yield even higher thermal gains (of at least another order of magnitude) and thus to offset this parasitic load.

Nuclear fusion – laser

The US approach[181] involves firing 192 high-energy lasers at a peppercorn-sized lump of hydrogen atoms. In December 2022, the National Ignition Facility at the Lawrence Livermore National Laboratory achieved 'ignition',[182] extracting more energy from the reaction than was put in for the first time – 3.15 MJ of fusion energy output was realised from 2.05 MJ of laser energy delivered to the target.

In an ignition experiment, a tiny capsule containing deuterium and tritium is suspended inside a cylindrical x-ray 'oven' called a hohlraum, which is heated by lasers to temperatures of more than 3 million degrees centigrade. The resulting x-rays heat and blow off ('ablate') the surface of the target capsule, causing a rocket-like implosion that compresses and heats the fuel to extreme temperatures and densities until the hydrogen atoms fuse, creating helium nuclei (alpha particles) and releasing high-energy neutrons and other forms of energy.

178 https://www.gov.uk/guidance/nuclear-research-from-1-january-2021.

179 https://ec.europa.eu/research-and-innovation/en/horizon-magazine/dream-unlimited-clean-nuclear-fusion-energy-within-reach.

180 https://ccfe.ukaea.uk/programmes/joint-european-torus/.

181 https://lasers.llnl.gov/about/how-nif-works.

182 https://www.energy.gov/articles/doe-national-laboratory-makes-history-achieving-fusion-ignition.

If the implosion is symmetrical, and compression and temperature in the 'hot spot' at the centre of the capsule are sufficient, the resulting alpha particles will spread through and heat the surrounding cold fuel, triggering a self-sustaining fusion reaction. However, as with the ITER project, while a thermal gain has been achieved, there is still a long way to go until total energy output exceeds total energy input.[183]

In any case, commercial fusion reactors are still sufficiently remote to be discounted from any meaningful discussions of the GB electricity mix out to 2050.

183 https://bigthink.com/the-future/fusion-power-nif-hype-lose-energy/.

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