Prospects for nuclear generation in Great Britain

Kathryn Porter, Consultant, Watt-Logic

May 2023

Contents

Executive Summary....3

Policy context for nuclear power in GB....4

- Ten Point Plan, November 2020....4
- Energy White Paper, December 2020....4
- Net Zero Strategy, October 2021....5
- British Energy Security Strategy, April 2022....5
- Energy Independence, November 2022....6
- Nuclear Fuel Fund, January 2023....6
- Powering Up Britain, March 2023....7
- Energy Security Bill, 2023....7
- National Policy Statements....8
- Decommissioning future nuclear power stations....8

Current and potential future electricity generation mix in Great Britain....9

Nuclear technologies and their potential deployment in the GB electricity mix....10

- Large-scale reactors....10
- Small Modular Reactors and Advanced Modular Reactors....14

Economics of electricity generation in GB....23

Funding models for nuclear power....24

Conclusions....26

Executive Summary

The UK Government has renewed its commitment to nuclear power alongside an arguably stronger commitment to intermittent renewable generation, and in particular, wind power. Given the extreme variability of wind output from close to zero to potentially close to 100% of demand at any time, and the uncertainty created by the Russian invasion of Ukraine, the Government's commitment to nuclear power has strengthened significantly in recent years.

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 next year), but the only contender is Sizewell C, a European Pressurised Water ("EPR") reactor of a type its developer EDF has struggled to deliver elsewhere. At the same time, the existing fleet of Advanced Gas Cooled Reactors ("AGRs") is expected to close by March 2028, leaving only the Sizewell B Pressurised Water Reactor ("PWR") running until the new EPR at Hinkley Point C opens, now expected to be in September 2028.

The Government has shown an interest in Small Modular Reactors ("SMRs") and Advanced Modular Reactors ("AMRs") with a particular focus on High Temperature Gas Reactors ("HTGRs) whose high output temperatures could have a range of industrial applications including the production of hydrogen. 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 secure a Generic Design Assessment from the Office for Nuclear Regulation ("ONR").

Nuclear power is low carbon and not intermittent, and is capable of being developed at scale, delivering very large energy outputs from small sites. SMRs and smaller micro-reactors could power remote, de-centralised sites and power heavy industry with minimal on-site operational requirements, and Fast Neutron Reactors ("FNRs") offer the prospect of greater fuel security and reduced waste considerations. However, the capital costs of conventional large-scale nuclear projects are very high, and largely outside the range of the private sector, absent significant state support. Decades of under-investment have seen a major skills exodus across Western nuclear nations and a slowing in the development of advanced nuclear technologies, where China, Russia and India have taken the lead.

The Government has made moves to leverage the work of well-regarded regulators in friendly nations – 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 fuel models to address concerns over uranium supplies.

The economic opportunities for nuclear power in GB are mixed. The Government hopes that the new Regulated Asset Base ("RAB") model will attract investor interest by increasing income certainty and transferring some risks to consumers. However, Ofgem has been designated as the economic regulator and its track record in setting consistent and effective price controls for gas and electricity network operators has been mixed. The regulator is 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 the gaps the private sector seems reluctant to fill – private investors are not expected to fund physical security in terms of 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.

Britain should be an attractive market for nuclear projects, but in its determination both to avoid adding costs to the Government 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 advancing closure of the AGR fleet, and over-arching climate ambitions make it vital that a more robust approach is taken to securing the next generation of nuclear reactors in Britain.

Policy context for nuclear power in GB

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 was elected on 25 October 2022, and on 7 February 2023 he undertook a departmental re-shuffle, 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[3], and the Russian invasion of Ukraine in February 2022, which reduced the amount of Russian gas available to western buyers – partly due to Russia's use of energy as an economic weapon and partly due to Western sanctions. This led to a renewed focus on energy security. Arguably, since prices began to rise in September 2021, and more so since the invasion of Ukraine, affordability and security of supply have eclipsed de-carbonisation 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 GB 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 the UK 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 to enable investment of up to £215 million into Small Modular Reactors. The fund was intended to unlock up to £300 million of private sector match-funding.

The Government also committed up to £170 million for a research and development programme on Advanced Modular Reactors, whose high temperature operation (over 800°C) and production of high-grade heat "could unlock efficient production of hydrogen and synthetic fuels, complementing our investments in carbon capture, utilisation and storage ("CCUS"), hydrogen and offshore wind". 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.

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 to £1 billion.

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 value for money and relevant approvals. It said it would remain open to 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], to reduce the cost of nuclear new build projects by 30% by 2030.

---

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

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

The Nuclear Sector Deal suggested that these savings could be achieved through research into advanced construction, reduction of construction costs and supply chain development. 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 Massachusetts Institute of Technology in 2020, which concluded that, contrary to expectations, building subsequent 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 would open to SMR technologies in 2021 (this did not happen until December 2022, see below). This is the regulatory process through which developers obtain approval for their design approach.

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

The White Paper also contained a plan to build a commercially viable 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 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 in the UK 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 for STEP.

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, which "could support our path to decarbonising the UK's electricity system fifteen years earlier from 2050 to 2035".

In reference to the new 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 is slated to be a European Pressurised Water Reactor, developed by EDF. In January 2022, the Government invested[12] £100 million to support the continued development of the project.

British Energy Security Strategy, April 2022

The British Energy Security Strategy[13] 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.

8 https://www.cell.com/joule/fulltext/S2542-4351(20)30458-X?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS254243512030458X%3Fshowall%3Dtrue

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/government-readies-sizewell-c-nuclear-project-for-future-investment

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

The Strategy called for a reversal in decades of under-investment in nuclear power. The Government committed 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", with 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;
- An intention to take one project to FID this Parliament and two projects to FID in the next Parliament, including SMRs;
- Delivery of up to 8 more reactors across the next series of projects, the equivalent of one reactor a year, rather than one a decade;
- Setting up Great British Nuclear in 2022, tasked with helping projects through every stage of the development process and developing a resilient pipeline of new builds;
- Backing Great British Nuclear with funding to support projects to get investment ready and through the construction phase, with the selection process expected to start in 2023, and negotiations to enable a potential government award of support as soon as possible, including (but not limited to) the Wylfa site;
- Plans to work with regulators to explore the potential (without compromising safety, security and environmental protections) for streamlining or removing duplication from the consenting and licensing process for new nuclear power stations, including possible harmonisation on international regulation;
- Collaboration with other countries to accelerate work on advanced nuclear technologies, including SMRs and AMRs.

Energy Independence, November 2022

In November 2022, BEIS launched[14] a new package to secure Britain's energy independence, including "continuing the revitalisation of the UK nuclear industry" by confirming the first state backing of a nuclear project in over 30 years, with the state taking a 50% stake in the Sizewell C project, buying out China General Nuclear ("CGN") at a cost of around £679 million. The Government said it would work with the project company to seek third-party investment to help finance the project's construction and operation. It expects Sizewell C's supply chain strategy to ensure 70% of the construction and operational contracts being placed with UK businesses.

Nuclear Fuel Fund, January 2023

In January 2023, the Government announced[15] £75 million in government funding to support the development of alternatives to Russian nuclear fuel supply. This followed agreement by G7 leaders in June 2022 to begin concerted action to reduce reliance on civil nuclear and related goods from Russia. Russia currently owns around 20% of global uranium conversion capacity and 40% of enrichment capacity.

The £75 million Nuclear Fuel Fund will encourage investment into the development and commercialisation of domestic nuclear fuel production including advanced fuel technologies. This includes the development of new conversion capacity in the UK for both freshly mined and reprocessed uranium to help power existing plant and future advanced reactors. Up to £13 million of the fund was awarded[16] in December 2022 to Westinghouse in Preston, which has strategic importance to fabricating fuel for the current AGR fleet, to help develop primary conversion capability for reprocessed and freshly mined uranium.

The Government aims for the remaining £50 million fund, which opened for bids in January, to stimulate a diverse and resilient nuclear fuel market, supporting specialist skills, and opening up export opportunities. It will also look

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

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

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

to support projects producing new fuel types for AMRs. There are specific categories of fuel capabilities which were identified through the Request For Information process[17] carried out in summer 2022, for the Fund to support:

- Light Water Reactor Fuel Supply;
- High Assay Low Enriched Uranium Supply Chain;
- Advanced Modular Reactor Fuel Fabrication Capabilities;
- Enabling UK Fuel Production Capabilities.

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[18] 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 GBN, and that their first priority would be to launch a new competition to select the best SMR technologies for development by Autumn. The first phase – market engagement – was slated to begin in April, while the second phase – the down-selection process - will be launched in the summer. The Government will co-fund the selected technologies through their development, and work with successful bidders on ensuring the right financing and site arrangements are in place.

The Government has also launched the Future Nuclear Enabling Fund of up to £120 million to provide targeted support for new nuclear to address barriers to entry. A shortlist of applications to begin pre-grant award due-diligence was to be announced in the near future.

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 later in 2023, and aim to designate 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[19], is concluding and the Government is analysing the outputs. Phase B of the programme was launched in December 2022 (to run from 2023 to 2025) and will provide up to £55 million across up to two projects, and up to £5 million to support the UK's regulators. Successful bids will commence work in early summer 2023.

A programme is being developed under the Advanced Nuclear Fund, for further development of coated particle fuel ("CPF")[20] used in High Temperature Gas Cooled Reactors. This differs from funding for CPF which will be available under the Nuclear Fuel Fund which will focus on commercial deployment[21]. Further information on the eligibility of CPF projects under the Advanced Nuclear Fund is yet to be released.

Energy Security Bill, 2023

The Energy Security Bill[22,23] is currently going through Parliament. This Bill legislates for many of the policy commitments made over the previous couple of years:

[17] https://www.gov.uk/government/publications/nuclear-fuel-fund-nff

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

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

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

[21] 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

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

[23] https://bills.parliament.uk/bills/3311

- Facilitating the delivery of up to 24 GW nuclear power capacity 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 de-licensing and re-use of nuclear sites to allow more proportionate clean-up of these sites;
- Strengthening the Civil Nuclear Police's powers enabling the Civil Nuclear Constabulary to support the security of other critical infrastructure sites; and
- Bringing Nuclear Decommissioning Authority pensions into line with most of the rest of the public sector.

The Bill is currently in the Committee stage.

National Policy Statements

National Policy Statements ("NPS") 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[24] and has effect in relation to any new applications for nuclear electricity generation deployable after 2025. A new nuclear NPS (EN-6) is currently being developed (the other four energy NPSs were all consulted on in 2021[25] with updated versions being published in 2023 – the nuclear NPS was specifically excluded from that process).

The current NPS (EN-6)[26] covers nuclear generation deployable up to 2025 and was published in 2011, alongside the previous energy NPS, EN-1[27]. 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.

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[28,29] in place to manage future liabilities. The Funded Decommissioning Programme ("FDP") ensures that developers meet the costs of decommissioning and managing and its waste disposal, so the taxpayer does not to bear the burden of these costs in future. The waste and decommissioning costs for Hinkley Point C are accounted for in the 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[30].

Under the Regulated Asset Base 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.

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

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

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

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

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

[29] The Energy Act 2008: Funded Decommissioning Programme Guidance for New Nuclear Power Stations

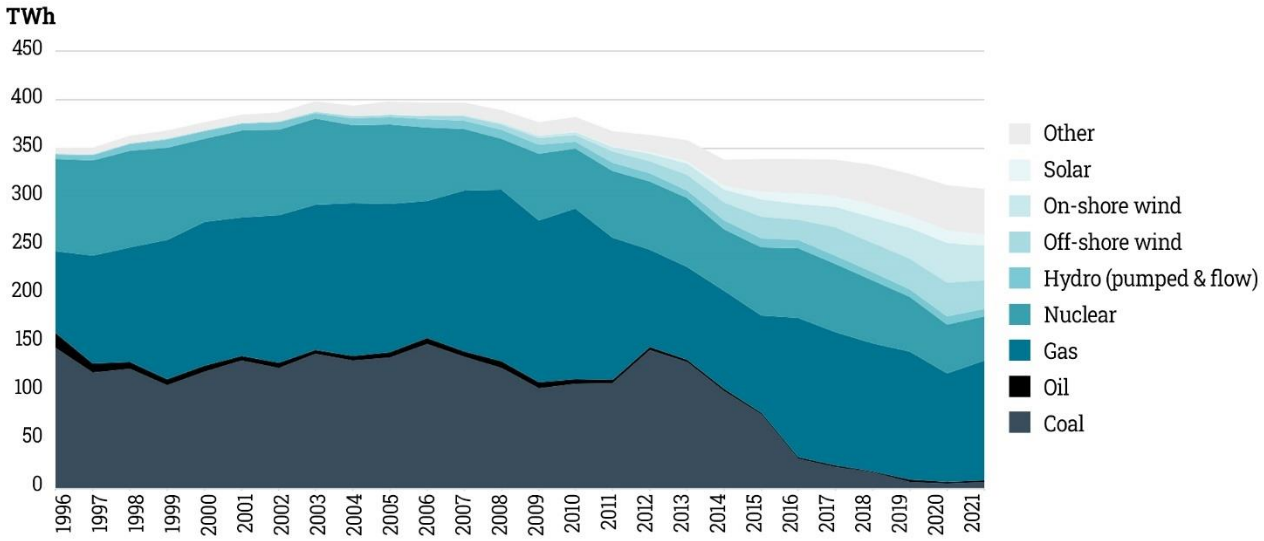
[30] https://www.gov.uk/government/publications/hinkley-point-c-funded-decommissioning-programme

Current and potential future electricity generation mix in Great Britain

In 2021, the most recent year for which official data are available, nuclear was the third most important fuel in electricity generation[31] in the UK at 15% - behind gas at 40% and wind at 21%. In the late 1990s, nuclear generated almost 30% of UK electricity, but since then its importance has declined, although not in a linear way, and even more recently in 2015-17 it contributed around 21%. However, in the past few years, several nuclear reactors have closed: Dungeness in 2021, and Hinkley Point B and Hunterston B in 2022, together accounting for over 3 GW capacity. There are now just five nuclear power stations operating in the UK with a combined capacity of just under 6 GW.

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

UK electricity generation by fuel type



Source: DUKES, 2022

Under National Grid ESO's Future Energy Scenarios[32], nuclear is expected to contribute between 9%- 10% in 2030 and between 8% and 15% in 2050. In each of the scenarios, NG ESO expects nuclear output to be around 31-33 TWh in 2030, however out to 2050 there is significant variation between the four scenarios, with nuclear contributing 58 TWh in the lowest case and 92 TWh in the highest case. Offshore wind is expected to be the dominant source of electricity in 2050, with onshore wind and solar varying in importance across the scenarios.

The Climate Change Committee[33] expects nuclear to be responsible for 10% of 2035 electricity sector carbon abatement, but cites delivery risks around nuclear, highlighting the absence of an overarching delivery plan or strategy for full de-carbonisation of electricity generation by 2035 as required by current Government policy.

Nuclear technologies and their potential deployment in the GB electricity mix

Large-scale reactors

Large-scale nuclear reactors are generally considered to be over 700 MW in size, although modern large reactors tend to be over 1 GW. The first civil nuclear project was located in the UK - the 196 MW Calder Hall reactor[34] was the first nuclear power station in the world to produce electricity for domestic use. Designed to last 20 years it operated for 47 years before closing in 2003. The station had 4 Magnox reactors of the gas-cooled graphite-moderated type, using carbon dioxide. During its 47 years of operation, Calder Hall generated enough power to run a three-bar radiator for 2.85 million years[35].

Since then, 19 nuclear power stations have been built in the UK, with five still in operation, and one under construction. With the exception of Sizewell B which is a PWR, the other UK reactors are all AGRs:

UK nuclear reactors in operation / under construction

[32] https://www.nationalgrideso.com/future-energy/future-energy-scenarios

[33] https://www.theccc.org.uk/publication/2022-progress-report-to-parliament/

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

[35] https://nda.blog.gov.uk/decommissioning-the-worlds-first-commercial-nuclear-power-station/

Plant	Capacity (MW)	Opening date	Expected closure	Comments
Hartlepool	1,185	1989	March 2026	Life extended by 2 years in 2022
Heysham 1	1,155	1989	March 2026	Life extended by 2 years in 2022
Heysham 2	1,200	1989	March 2028	Life shortened by 2 years in 2021
Sizewell B	1,194	1995	2035	EDF considering life extension to 2055
Torness	1,226	1988	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 may still be subject to further delays. It is also 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[36], and the recent extensions announced for Hartlepool and Heysham 1 are subject to regular graphite inspections[37]. Torness and Heysham 2 had previously been expected to run until 2030, but their closure dates were brought forward by two years in 2021 following the issues at Hinkley Point B and Hunterston B[38].

European Pressurised Water Reactor

The only large-scale nuclear technology currently being developed in Europe is the European Pressurised Water Reactor or "EPR", developed by EDF and Areva. The EPR is a third generation technology, and a development from previous PWRs, designed to have increased safety and enhanced economic competitiveness[39]. The four-loop 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;
- Two-layer concrete wall with a total thickness of 2.6 m, designed to withstand impact by aeroplanes and internal overpressure.

This technology has been plagued with problems. A recent report[40] 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[41], 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[42] and almost €10 billion over budget. The UK EPR project at Hinkley Point C has not escaped from the issues of delays and cost over-runs. Its costs have ballooned from the initial estimate of £18.1 billion to £32 billion and it may not open before September 2028[43].

[36] https://www.onr.org.uk/pars/2021/hinkley-point-b-20-026.pdf
[37] https://www.edfenergy.com/media-centre/news-releases/edf-provides-update-uks-existing-nuclear-fleet
[38] https://www.edfenergy.com/media-centre/news-releases/agr-lifetime-reviews-carried-out
[39] https://web.archive.org/web/20071129121411/http://www.areva-np.com/common/liblocal/docs/Brochure/EPR_US_%20May%202005.pdf
[40] https://www.assemblee-nationale.fr/dyn/16/organes/autres-commissions/commissions-enquete/ce-independance-energetique
[41] https://www.globalconstructionreview.com/14-years-late-finlands-new-reactor-olkiluoto-3-starts-generating-power/
[42] https://web.archive.org/web/20141014020153/http://www.world-nuclear-news.org/newsarticle.aspx?id=14496
[43] https://www.edf.fr/sites/groupe/files/2023-04/2023-04-28-edf-book-q1-2023.pdf

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 off-line for a year while issues with its fuel assembly were corrected[44] – there was 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 re-nationalised, is committed to the next generation EPR2 technology, and against a backdrop of wider financial difficulties for the company and the loss of its Chinese partners for political reasons, it is not clear that EDF will genuinely have the 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 the EDF board, with one board member resigning in protest[45]. Until the board approves Sizewell C, doubts will remain as to its future.

Westinghouse AP1000

In the US, the large-scale reactors being built use the Westinghouse AP1000 model, however, this like the EPR, is suffering with major delays and huge cost overruns. The AP1000 was previously proposed for the Moorside site in Cumbria, backed by Toshiba, with Design Acceptance Confirmation ("DAC") being granted by the ONR in March 2017[46], but the project collapsed[47] in November 2015 as Toshiba exited its overseas nuclear business and was unable to find a buyer for the project.

First licenced[48] in the US in 2002, the AP1000[49] is a two-loop Pressurised Water Reactor which evolved 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. It has a core cooling system including passive residual heat removal by convection, improved containment isolation, 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 rector has four.

Like EDF, Westinghouse had a long hiatus in building new reactors, and problems with the Vogtle project in Georgia and the VC Summer project in South Carolina led to it filing for bankruptcy[50] in 2017. Westinghouse had planned a revolutionary modular approach to building the AP1000, with sections of the plant being pre-fabricated off site in a drive to lower the cost of new nuclear projects. However, it miscalculated the time it would take, and the possible pitfalls leading to an estimated US$13 billion in cost overruns at the time its bankruptcy. 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. Several Westinghouse officials were later indicted[51] on charges of conspiracy, wire fraud, securities fraud, and causing a publicly-traded company to keep a false record. Officials at the owners of the state utility, which was also forced into bankruptcy, were charged with various offences in relation to the project. By the time the project was cancelled, 20% consumer electricity bills in the state was due to the costs of the scheme.

[44] https://www.neimagazine.com/news/newschina-restarts-taishan-1-after-a-year-of-repairs-9937188
[45] https://www.ft.com/content/3209004a-54ca-11e6-befd-2fc0c26b3c60
[46] https://www.onr.org.uk/civil-nuclear-reactors/moorside.htm
[47] https://www.neimagazine.com/news/newstoshiba-liquidates-uk-nugen-and-cancels-uk-moorside-project-6843979
[48] https://www.nrc.gov/reactors/new-reactors/large-lwr/design-cert/ap1000.html
[49] https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx
[50] https://www.nytimes.com/2017/03/29/business/westinghouse-toshiba-nuclear-bankruptcy.html
[51] https://thebulletin.org/2021/08/us-attorney-details-illegal-acts-at-construction-projects-sealing-the-fate-of-the-nuclear-renaissance/

The other two US AP1000 projects, Units 3 and 4 at Vogtle, continue to be developed, with Vogtle 3 expected to finally open this summer, and Vogtle 4 late this year / early next year. Construction of unit 3 began in March 2013 and unit 4 in November 2013. 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. Vogtle 3 reached full power output on 29 May 2023[52].

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[53].

Advanced Boiling Water Reactors

While there is no current proposal for an Advanced Boiling Water Reactor ("ABWR") in GB, this technology was initially proposed for the Wylfa Newydd[54] site. The Advanced Boiling Water Reactor design[55] was derived from a General Electric design in collaboration with Toshiba. Two examples were built by Hitachi and two by Toshiba in Japan, while two which were 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 ABWRs were each built in 39-43 months on a single-shift basis. Unlike previous Boiling Water Reactors in Japan, the external recirculation loop and internal jet pumps are replaced by coolant pumps mounted at the bottom of the reactor pressure vessel.

In December 2017, ONR, the Environment Agency and Natural Resources Wales granted Design Acceptance Confirmation and a Statement of Design Acceptability[56]. However, the Wylfa project collapsed in early 2019 with Hitachi withdrawing after failing to enter into an acceptable funding agreement with the Government, despite the Government offering to take a one third stake in the project[57]. Given an urgent need to deliver additional large-scale nuclear capabilities to replace closing reactors, a sensible strategy would be to focus on proven technologies – ABWRs were built on time (in under 5 years) and on budget[58] in Japan prior to the Fukushima disaster, and although they had limited operating time before the country-wide nuclear closures that followed the 2011 earthquake, a construction time half that of the EPR deserves serious consideration.

Chinese HPR1000

There had been plans for EDF and China General Nuclear Power Group ("CGN") to build two HPR1000 rectors at the Bradwell B[59] site in Essex. The Generic Design Assessment for the UK HPR1000 nuclear reactor technology was successfully completed on 7 February 2022, with the issuing of a Design Acceptance Confirmation[60] from the Office for Nuclear Regulation and a Statement of Design Acceptability from the Environment Agency[61].

In late 2022, the project progressed to the feasibility study stage[62], however there are significant question marks over its future given the involvement of CGN. CGN had also been EDF's partner on the Hinkley Point C project until it was forced to withdraw due to wider concerns over Chinese involvement in critical infrastructure within the UK. It is unlikely that Bradwell B will be allowed to go ahead with Chinese involvement and using Chinese technology. It also seems doubtful that EDF would pivot to developing an EPR at the site, although as a site

---

[52] https://www.georgiapower.com/company/news-center/2023-articles/vogtle-unit-3-reaches-100-percent-energy-output.html
[53] https://publications.parliament.uk/pa/cm5803/cmselect/cmwelaf/240/report.html
[54] http://www.hitachi-hgne-uk-abwr.co.uk/reactor.html
[55] https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.aspx
[56] https://www.onr.org.uk/new-reactors/uk-abwr/index.htm
[57] https://neutronbytes.com/2019/01/20/hitachi-freezes-plans-to-build-four-abwrs-in-the-uk/
[58] https://publications.parliament.uk/pa/cm201213/cmselect/cmenergy/117/11705.htm
[59] https://bradwellb.co.uk/
[60] https://www.onr.org.uk/new-reactors/uk-hpr1000/index.htm
[61] https://www.gov.uk/government/publications/gda-decision-and-soda-uk-hpr1000-reactor
[62] https://www.geplus.co.uk/news/bradwell-b-progresses-to-feasibility-studies-29-09-2022/

referenced in the current Nuclear Policy Statement (valid until 2025), the site is officially designated as a potential site for new nuclear projects.

Small Modular Reactors and Advanced Modular Reactors

Since the inception of nuclear power, nuclear reactors grew in size to capture economies of scale. However, at the same time, progress was made on developing very small scale reactors in the marine propulsion sector. Work began in the 1940s, with the first nuclear-powered submarine, USS Nautilus[63], being launched in 1955. In the UK, Rolls-Royce PWR technology has powered nuclear submarines since 1966[64]. Nuclear power is also used for surface ship propulsion, for example in US aircraft carriers and Russian ice breakers.[65]

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 using module factory fabrication, pursuing economies of 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 and Molten-Salt Reactors ("MSRs") – there is some overlap in definition with Advanced Modular Reactors. The main focus is on advancing LWR designs as they are seen to have 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.

Initial SMR studies in the UK

In 2014, the UK Government commissioned a report[66] on SMR concepts, feasibility and potential. The report 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 SMR market, was estimated to be approximately 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[67] that it would invest at least £250 million over five years in nuclear R&D including SMRs. In March 2016, the Department of Energy & Climate Change ("DECC") called for expressions of interest in a competition[68] to identify the best value SMR for the UK. This 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[69] it would invest up to £44 million to establish an Advanced Modular Reactor feasibility and development programme, where AMRs were defined as a broad group of advanced nuclear reactors which use pressurised or boiling water for primary cooling. Organisations could apply for a share of up to £4 million to develop feasibility projects for AMRs. 20 bids were

[63] https://ussnautilus.org/history-of-uss-nautilus/

[64] https://fissilematerials.org/library/uk11.pdf

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

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

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

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

[69] https://apply-for-innovation-funding.service.gov.uk/competition/80/overview

received by the initial deadline of 7 February 2018 with eight organisations[70] being awarded contracts to produce feasibility studies. In July 2020, BEIS awarded[71] £10 million to each of:

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

A further £5 million would be 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[72] of SMRs, which explored the following technologies: Integral Pressurised Water Reactors ("IPWRs"); Pressurised Water Reactors ("PWRs"); High Temperature Gas 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 compared with 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 period 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[73] 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 for design, manufacture and deployment of the different AMR technologies. 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, 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 support these needs was highly variable. 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 personal. On the supply chain side, it found that key UK manufacturing needs exist 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[74] 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 Future Nuclear Enabling Fund closed at the beginning of this year.

UK Government interest in High Temperature Gas Reactors

In July 2021, the Government published research paper[75] from the Nuclear Innovation & Research Office which assessed the most promising AMR technologies to support the UK's objective of meeting net zero climate change targets by 2050. The analysis indicated that high temperature gas reactors were the preferred technology, with

[70] 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

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

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

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

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

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

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[76] 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 a HTGR demonstration;
- Phase B: FEED phase where applicants develop their HTGR solution to enable a FEED output study to be used as a basis of the detailed design and engineering, including accurate total investment and lifecycle costs, how the demonstration would be sited, and overall project delivery planning;
- Phase C: Permissioning, Construction, Detailed Engineering & Operation - this phase could see a successful 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[77] that five organisations had received funding across 6 projects, testing the feasibility of HTGR technology and coated particle fuel. Early evidence from these projects was received by the end of the year.

Phase B was launched in December 2022[78], 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[79] funding worth up to £60 million to kick start 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.

High Temperature Gas Reactors

High Temperature Gas Reactors and Very High Temperature Gas Reactors ("VTGRs") are Generation IV reactors[80] that are primarily dedicated to the cogeneration of electricity and hydrogen. Their high outlet temperature makes them attractive also for the chemical, oil and iron industries.

The HTGR[81] is similar in concept to the AGR, using uranium fuel, a graphite moderator, and gas as coolant - in this case, helium. The advantage of the HTGR is that both the moderator, graphite, and the coolant, helium, can operate at high temperatures without reacting or deteriorating. A typical HTGR will operate at a pressure of 100 atm and at a temperature up to 900°C, which enables better thermodynamic conditions, 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

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

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

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

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

[80] https://www.gen-4.org/gif/jcms/c_42153/very-high-temperature-reactor-vhtr

[81] https://www.sciencedirect.com/book/9780080983301/power-generation-technologies

internal temperature without failing. Several attempts have been made to build HTGRs, but none has so far entered commercial service.

HTGRs can be built in relatively small unit sizes, with generating capacities between 100 MW and 200 MW. In theory, the modular form would allow plant expansion through the addition of new modules, however, no reactors of this design have yet entered commercial service.

Small Modular Reactors

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

In 2015 Westinghouse presented an unsolicited proposal[82] 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, launched in 2023, the AP300[83] is a 300 MW integral PWR with all primary components located inside the reactor vessel, which utilises the AP1000 technology. Westinghouse believes it could deliver its first SMR by the end of the decade[84].

In 2018 the UK Government convened a working group to advise on how SMR projects could raise investment in the UK. In its report[85], the group concluded that the UK could be well placed to develop first-of-a-kind small reactor projects, 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 through assisting with their financing through a new infrastructure fund (seed funded by HMG) and/or direct equity and/or HMG guarantees; and through the use of funding support mechanisms such as a Contract for Difference, Power Purchase Agreement or Regulated Asset Base model. For next-of-a-kind projects it expected the market to be self-sustaining.

In November 2019, the Government initiated the Low Cost Nuclear Challenge[86,87], with a commitment to invest up to £18 million in the creation of SMRs. In Phase 2[88] of the Challenge, announced in November 2021, a government grant of up to £210 million was matched by £258 million of private funding, through a new Joint Venture led by Rolls-Royce. It aims to move the programme towards a final design concept as well as completing the second stage of the Generic Design Assessment ("GDA") process with the UK nuclear regulators. UKRI[89] is the delivery body for the project, which is expected to be completed by March 2025.

In November 2022, Rolls-Royce announced[90] that it had identified four priority sites for to SMRs: Trawsfynydd, Wylfa, Oldbury and land neighbouring the Sellafield site. The locations are all on land owned by the UK Nuclear Decommissioning Authority ("NDA"), although in the case of Wylfa and Oldbury the land is currently leased to third parties. In April 2023, the Rolls Royce SMR passed the first step of the GDA process[91] and proceeded to step

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

[83] https://www.westinghousenuclear.com/energy-systems/ap300-smr

[84] https://www.world-nuclear-news.org/Articles/Westinghouse-unveils-AP300-small-modular-reactor

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

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

[87] 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

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

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

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

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

two including public engagement (there are three steps in total[92]). However, there have been reports[93] that the project may run out of money by the end of 2024.

Great British Nuclear is in the process of being officially set up (for the time being it is operating under the legal entity of the largely defunct British Nuclear Fuels Ltd), and its first priority is to launch a competitive process to select the best SMR technologies[94]. This began in April with market engagement[95], and there are plans for a down-selection process to be launched in the summer, with an ambition to assess and decide on the leading technologies by autumn.

Another US company, NuScale has also expressed an interest in deploying its SMR technology in the UK. In 2017, the company set out a five-point action plan[96] that would see its reactors in operation by the mid-2020s. The NuScale SMRs, named VOYGR[97], are scalable power plants that can accommodate up to 12 Power Modules. Each Power Module is a pressurised water reactor with all the components for steam generation and heat exchange incorporated into a single 77 MWe generating unit. In September 2020, a NuScale design became the first SMR to receive design approval from the US Nuclear Regulatory Commission[98]. Last year the company indicated[99] that it was also interested in the Trawsfynydd site in Wales as a site for its reactors.

Micro-reactors

In March 2019 BEIS released a 2016 report[100] 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, in comparison to larger SMRs. The report projected a global market for micro-reactors of around 570 units by 2030, totalling 2,850 MW.

Although some micro-reactors have evolved from LWR technology, they are typically high temperature gas reactors, liquid metal cooled fast reactors or molten salt reactors, using the more efficient Generation IV concepts that 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 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[101] micro-reactor, that 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 done in just 30 days. At the end of its life, the reactor, complete with any spent fuel, would be fully removed from the site requiring minimal remediation. The company is currently engaging part in pre-application processes with the US nuclear regulator[102].

Earlier this year, US company Last Energy announced[103] it had sold 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[104]

---

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

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

[94] https://www.gov.uk/government/organisations/great-british-nuclear/about

[95] https://www.niauk.org/great-british-nuclear-invitation-to-participate-in-a-market-intelligence-gathering-exercise/

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

[97] https://www.nuscalepower.com/en/products/voygr-smr-plants

[98] https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/nuscale.html

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

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

[101] https://www.westinghousenuclear.com/energy-systems/evinci-microreactor

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

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

[104] https://www.lastenergy.com/technology

is a single loop PWR with a continuous output of 300°C, is being offered for both grid-scale and behind-the-meter applications where customers effectively lease the units under Power Purchase Agreements 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. 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[105].

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

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 developing other reactor technologies[106]: Gas-cooled Fast Reactors, Lead-cooled Fast Reactors, Molten Salt Reactors, Supercritical Water-cooled Reactors, Sodium-cooled Fast Reactors and Very High Temperature Reactors. Several advanced reactors are in pre-application discussions with the US nuclear regulators[107].

Both 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. Fast neutron reactors ("FNRs")[108] 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.

The first ever nuclear reactor to generate electricity was an FNR cooled by liquid sodium – the Experimental Breeder Reactor[109], at the US Idaho National Laboratory, which, in 1951, produced enough electricity to illuminate four 200W light bulbs. The 60 MW Dounreay Fast Reactor[110] in the UK opened in 1962 and was the world's first FNR to provide electricity to the national grid. A second, 250 MW FNR[111,112] was later built on the same site which 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 to FNRs after several failures with test projects, which suffered from corrosion and leaks in their cooling systems.

Although FNR development effectively ended in Europe and the US by the 1990s, it continued in Russia, China[113] and India, where there are now five FNRs[114] in operation and several more under development. Russia's BN reactors have already proved the commercial viability of sodium-cooled FNRs, while its lead-cooled Brest reactor

[105] https://www.onr.org.uk/new-reactors/assessment.htm

[106] https://www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

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

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

[109] https://inl.gov/experimental-breeder-reactor-i/

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

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

[112] https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjfyuKV9Z__AhUIUcAKHUtmAKkQFnoECAgQAQ&url=https%3A%2F%2Finis.iaea.org%2Fcollection%2FNCLCollectionStore%2F_Public%2F28%2F026%2F28026107.pdf&usg=AOvVaw0A26NC-xB6Lw9GKMXyNCoM

[113] https://spectrum.ieee.org/china-breeder-reactor

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

and associated ODEK project are on track to demonstrate the feasibility of a completely closed fuel cycle based on FNRs.

Interest is now reviving in Europe through the Sustainable Nuclear Energy Technology Platform ("SNETP")[115]. In the US, an intermediate-scale liquid metal experimental facility known as the Mechanisms Engineering Test Loop Facility ("METL")[116] has been built at the Argonne National Laboratory. Fast reactor components have been tested at METL since 2018. In July 2022, the US Department of Energy announced plans to build a sodium-cooled fast test reactor at the Idaho National Laboratory, which, if appropriated by Congress, would be the first fast spectrum test reactor to operate in the USA in nearly three decades. Although Congress did not provide funding in 2022, a new request has been made in 2023.

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[117]. However, the project has experienced delays[118] and cost over-runs, but despite these and historic challenges with fast breeder reactors, India is persevering, in part due to increasing difficulties in obtaining uranium. India is also developing thorium reactors[119].

Nuclear fusion - tokamak

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 are fused together to form one heavier atom. To achieve fusion, the fuel must be heated to extreme temperatures - the centre of the sun is estimated to be at 15 million °C. In terrestrial fusion reactions, the most efficient reaction is between two types of hydrogen – deuterium and tritium – which only fuse at temperatures over 100 million °C. At these temperatures the fuel becomes an electrically charged gas or plasma, a fragile material a million times less dense than air. There are currently two distinct approaches: in Europe projects such as STEP[120] in the UK and ITER[121] in France are developing magnetic confinement fusion, while in the US, a laser driven inertial confinement approach is being developed (see below).

In a magnetic confinement system, the fusion plasma is heated and confined in a ring-shaped bottle known as a tokamak, where it is controlled with strong magnetic fields. In the tokamak, deuterium and tritium fuse to produce helium and high-speed neutrons, releasing approximately 10,000,000 times more energy per kg 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 heat this provides being converted into steam to drive turbines.

Magnetic containment fusion

[115] https://snetp.eu/esnii/

[116] https://www.anl.gov/nse/mechanisms-engineering-test-loop-facility

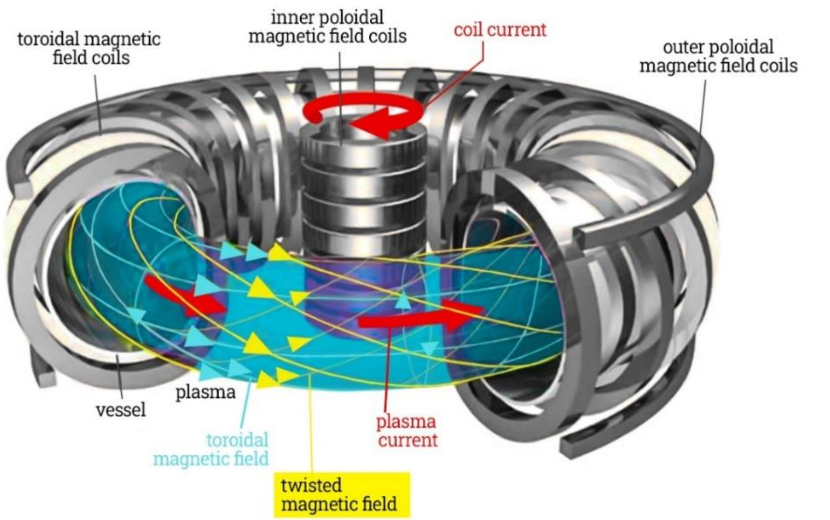
[117] https://www.world-nuclear-news.org/Articles/India-gives-update-on-nuclear-construction-project

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

[119] https://www.barc.gov.in/randd/tfc.html

[120] https://step.ukaea.uk/

[121] https://www.iter.org/



Source: Max-Planck Institut für Plasmaphysik, Watt-Logic

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, outlining the design of the major systems in the plant is due to be completed in 2024. In phase two, the design will be developed and all consents and permissions to build the plant will be sought. In phase three a prototype power plant will be constructed, targeting completion around 2040. Five sites were shortlisted in 2021[122], including 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[123] (having replaced Ratcliffe due to site availability issues[124]). In February 2023, the Government set up UK Industrial Fusion Solutions Ltd[125], to deliver the STEP fusion prototype.

The UK is also a partner in the European ITER (and has remained so despite Brexit[126]), which had been scheduled to start generating its first plasma in 2025 before entering into high-power operation around 2035 – although there could be some delays due to the pandemic[127]. 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[128]. ITER is being designed to:

- Achieve a deuterium-tritium plasma in which the fusion conditions are sustained mostly by internal fusion 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 as 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

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

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

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

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

[126] https://www.gov.uk/guidance/nuclear-research-from-1-january-2021

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

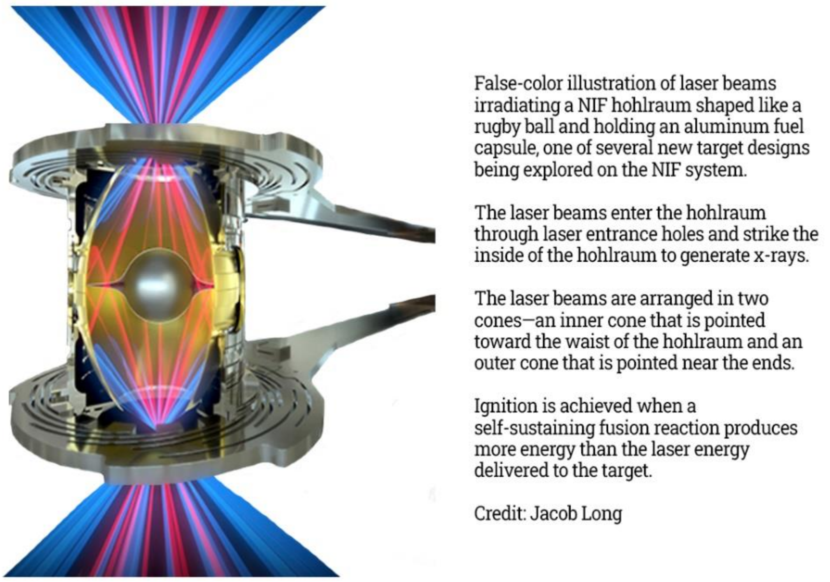
[128] https://ccfe.ukaea.uk/programmes/joint-european-torus/

containment. The technology will need to be developed further to yield even higher thermal gains (of at least another order of magnitude), to off-set this parasitic load.

Nuclear fusion - laser

The US approach[129] involves firing 192 high energy lasers at a peppercorn-sized lump of hydrogen atoms. Last December the National Ignition Facility at the Lawrence Livermore National Laboratory achieved "ignition"[130] 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.

Illustration of laser beams irradiating a NIF hohlraum



Source: National Ignition Facility

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 ^{o}C. The resulting x-rays heat and blow off, or 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.

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. This process can generate energy equalling or exceeding the energy delivered to the target, a condition known as ignition. 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[131].

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.

[129] https://lasers.llnl.gov/about/how-nif-works

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

[131] https://bigthink.com/the-future/fusion-power-nif-hype-lose-energy/

Economics of electricity generation in GB

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 to run. 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.

The Balancing Mechanism[132] is the primary tool used by the transmission system operator, National Grid ESO, to balance the transmission system 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, however it is less suited to baseload operators such as nuclear power plants.

All transmission-connected generators participate to some degree in the provision of balancing/ancillary services[133] such as reactive power, however, many of the services require a degree of operating flexibility which nuclear reactors lack. There are growing opportunities for the provision of inertia as the replacement of conventional thermal generation with inverter-based resources such as wind and solar reduce grid strength and stability.

Local flexibility markets[134] 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.

A major source of income for existing nuclear has been the Capacity Market[135], where participants receive payments in exchange for being available to operate at times of system stress. Prices are set through actions which take place four years before delivery, with a smaller top-up action one year before delivery.

Finally, generators may be eligible for subsidies, intended to support the financing of their 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")[136]. One of the motivations for the Review was concerns that GB electricity prices are based on the price of generating

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

[133] https://www.nationalgrideso.com/industry-information/balancing-services

[134] https://smartgrid.ukpowernetworks.co.uk/flexibility-hub/

[135] https://www.gov.uk/government/collections/electricity-market-reform-capacity-market

[136] https://www.gov.uk/government/consultations/review-of-electricity-market-arrangements

electricity using gas, since this is almost always the marginal source of generation (ie the last plant 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 consumers 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 quicky, and most respondents to the consultation 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, such as a green power pool and moving more generation on to CfDs. A second consultation is expected in 2023 to consider next steps.

In the meantime, concerns that renewable generators have benefitted from 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[137]. 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.

Funding models for nuclear power

The Nuclear Energy (Financing) Act 2022[138] ("NEFA 2022"), came into force in May 2022, and sets out the new Regulated Asset Base ("RAB")[139] funding model for new nuclear power projects in the UK, replacing the previous Contracts for Difference ("CfD") scheme which was used to support the Hinkley Point C project. The Hinkley Point C deal was evaluated by the National Audit Office[140], which found it did not maximise the chances that value for money would be delivered given its high cost and the level of risk in a changing market.

Nuclear power is difficult to finance in the private sector due to a 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. The difficulties of relying on the private sector to deliver such projects are apparent from their absence, leading the Government to offer subsidies, however, there has been a desire to keep the costs of new nuclear power plants off the government balance sheet.

Under the CfD model, developers bear all the project delivery risk and only receive a guaranteed minimum income stream (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 GW 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 with a high strike price, 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 projects, which led it to revise the funding model in the hope of making it more appealing to investors. The RAB model differs from the CfD 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.

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

[138] https://www.legislation.gov.uk/ukpga/2022/15/contents/enacted

[139] https://www.gov.uk/government/news/future-funding-for-nuclear-plants

[140] https://www.nao.org.uk/reports/hinkley-point-c/

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 returns 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, tax and incentives/ penalties applied by the regulator to ensure expenditure is in the interests of consumers.

The model also has financial implications for the government as construction is likely to appear on the government's balance sheet[141]. A similar RAB funding model has been used to finance the £4.13 billion construction of the Thames Tideway Tunnel[142] and the £4.3 billion construction of Heathrow Terminal[143], 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 must be a "nuclear company", meaning it must hold an electricity generation licence in respect of a nuclear energy generation project and it must be designated by the Secretary of State to deliver that project. There are two designation criteria that must be met: the Secretary of State believe the development of the project is sufficiently advanced to justify the designation (the "maturity" test); and, the Secretary of State must 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"[144] which explains how to meet the criteria.

The maturity test assessment will focus on evaluating whether there is a credible strategy and plan for the design, construction, operation and ultimately 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 as compared with the costs of the electricity system if alternative projects or generation technologies were built.

In addition to applying the two designation tests, the Government must consult on the proposed designation of a nuclear project with a broad list of statutory consultees including Ofgem, the Office for Nuclear Regulation 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 in relation to protecting national security interests, and ensuring significant stakes cannot be sold without the government's knowledge or consent.

Although the designation process is intended to occur early in the construction process for a new nuclear plant, a significant amount of upfront investment and effort will be necessary in order to achieve designation status. 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 allowed revenue the nuclear company may receive and how it is calculated;
- details on how the construction risk and associated development costs will be shared;

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

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

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

144 https://www.gov.uk/government/publications/nuclear-regulated-asset-base-rab-model-statement-on-procedure-and-criteria-for-designation

- permitted and prohibited activities and how any permitted activities 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 the “financing cap” - cost over runs 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 above the cap, costs are expected to be covered through a government 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 the level at which is unlikely to be reached 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[145] of the RAB model which 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.

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 they may well be missed.

In terms of large-scale nuclear projects, the Government needs to urgently off-set 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 come forward, while Hinkley Point C could be subject to further delays. As concerns over energy security grow, the urgency of the task of replacing closing AGRs similarly 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 ABWR. Currently there are no signs of this happening.

Similarly, ambitions for SMRs have slipped, in part due to delivery issues by developers whose initial ambitions to have projects running by the mid-2020s have been 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 – it should ensure that this happens in practice so that UK regulators do not duplicate the work of US and Japanese regulators in particular. And it should accelerate research into advanced technologies, particularly in the sphere of alternative fuel models to address concerns over uranium supplies.

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.

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 to 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[146].

[145] https://www.gov.uk/government/consultations/revenue-stream-for-the-nuclear-regulated-asset-base-rab-model
[146] https://www.gen-4.org/gif/jcms/c_42152/sodium-cooled-fast-reactor-sfr

The economic opportunities for nuclear power in GB are mixed outside the RAB model. The ability to provide non-intermittent 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. Although some nuclear reactors can notionally operate in load following mode, they suffer accelerated wear and degradation as a result. 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, but Ofgem's track record as the economic regulator to gas and electricity networks is mixed. Although Ofgem will not have the power to change the model as it does with the regulated income for network companies, it is likely to have discretion over calculation of the cost of capital and other inputs which determine the income received by nuclear generators (NEFA 2022 requires that statutory instruments are used to determine the revenue regulations). Ofgem's calculation of the cost of capital for network companies has attracted criticism[147], leading to significant tightening in subsequent price control periods. The RAB model contains the ability for Ofgem to set incentives and penalties - a core feature of the network price control regime where incentives have been significantly weakened of late. Developers may be nervous about an economic regulator which has faced significant pressure to reduce energy company profits.

Electricity generation is not the only source of potential income for future nuclear projects. As de-carbonisation 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 renewable sources of electricity generation. Nuclear reactors are able to produce heat, in some cases at very high temperatures, which would be able to replace the use of fossil fuels in a range of industrial applications, offering alternative income streams.

The UK Government recognises many of these factors, but its progress in addressing them is too slow and too timid. Arguably, the Government 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 on to the government balance sheet, which has obvious costs, 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 government 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 advancing closure of the AGR fleet, and over-arching climate ambitions make it vital that a more robust approach is taken to securing the next generation of nuclear reactors in Britain.

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