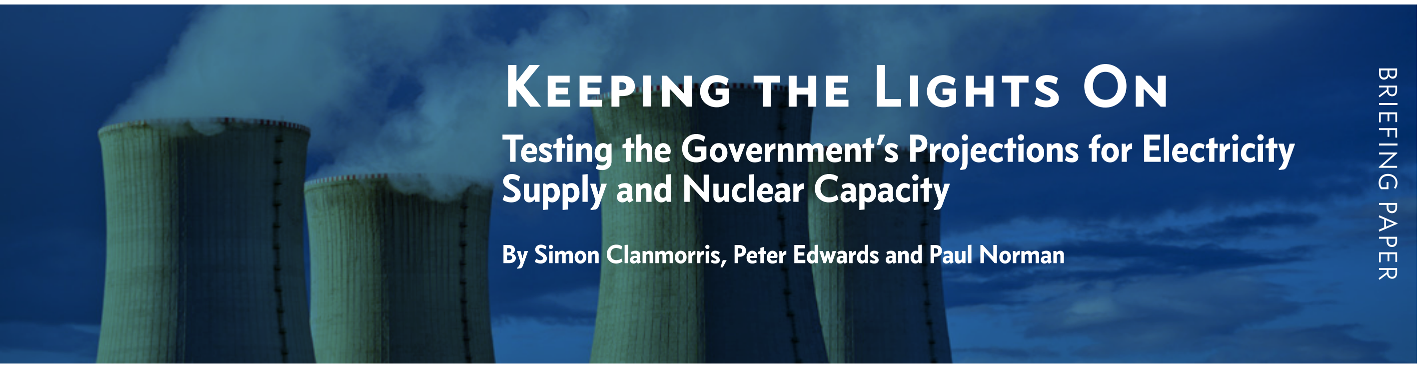

KEEPING THE LIGHTS ON

Testing the Government's Projections for Electricity Supply and Nuclear Capacity

By Simon Clanmorris, Peter Edwards and Paul Norman

BRIEFING PAPER

EXECUTIVE SUMMARY

- The Department for Business, Energy and Industrial Strategy (BEIS) is underestimating the UK's electricity demand in 2050;
    - In particular, it appears to be failing to take into account the fact that we will not be able to rely on Variable Renewable Energy—such as wind and solar—during periods of *Dunkelflaute* (when the sun doesn't shine and the wind doesn't blow);
- As a result, BEIS is also underestimating how much nuclear power will be required if the Government intends to maintain its goal of decarbonising the UK's electricity system by 2035;
- The Government plans to replace our current nuclear capacity with older generation nuclear reactors, which are costly and unlikely to be built in time to meet decarbonisation targets;
- Modern Small Modular Reactors (SMRs) and especially Advanced Modular Reactors could be a solution to address the shortfall in zero carbon electricity generation. Compared to conventional nuclear reactors, they are quick to build and have far smaller capital costs and space requirements;
- SMRs are also less of safety hazard owing to features such as their modern design and the fact that they are mostly low pressure, so regulation could be streamlined were the UK to fast-track any design that had been approved in the USA or Canada;
- In the medium term, Advanced Modular Reactors would be a better solution. If the UK were to fast-track regulatory approval, these could be supplied from 2030 onwards but rapid decision-making is required and time is of the essence.

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THE PROBLEM

It is naturally difficult to predict how much energy the UK will require in 2050. Whether it is more, less, or about the same as now depends on forecasting the UK's macroeconomic changes, notably whether the manufacturing industry will strengthen or decline, which is beyond the scope of this paper. But in a zero carbon context, we can assume that almost all energy will be in the form of electricity, unlike in 2021 when only 19.2% or 24.6 million tonnes of oil equivalent (Mtoe) of our energy consumption was met by electricity.[1] Total energy consumption in 2021 was 170.1 million tons of oil equivalent ('Mtoe') which equates to 1,978 terawatt hours ('TWh') of electricity and a supply capacity requirement of 225.8 GW.[2] We therefore assume the need for energy in 2050 will remain at least the same as our current requirements.

Some argue that a figure of 1,978 TWh for total demand in 2050 is too high. The authors of this paper think the BEIS figures of 575 TWh to 765 TWh for final energy demand are far too low.[3] The latest Future Energy Scenarios (FES 2022)[4] published by the Electricity System Operator ('ESO') forecast a range of 1,123 TWh to 1,406 TWh which may be more realistic.[5] Adopting the mean of this range (1,265 TWh) also implies that 25% nuclear capacity would be 36 GW. Given the volatility of wind we think that is risky: BEIS planners should aim for too much capacity rather than too little. On balance, this paper stays with the 1,978 TWh demand forecast.

The above mentioned FES report also includes a range for capacity expressed in GW which they put at 236 GW to 298 GW, plus storage and interconnector capacity of between 35 GW and 79 GW. They also forecast that unless we continue to rely on gas, between 84% and 94% of our energy[6] will be sourced from wind, solar, nuclear and bioresources. The detailed breakdown of one of their scenarios shows that only 7.8% (92 TWh or 23 GW) will come from nuclear, 63% (737 TWh or 186 GW) will come from Variable Renewable Energy, 21% (250 TWh or 63 GW) will come from bioresources, and the remaining 9% will come from other sources such as gas and imports.

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[1] BEIS, 'UK Energy in Brief 2022', p.10: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1094025/UK_Energy_in_Brief_2022.pdf

[2] The conversion factors used are: 1 Mtoe/85980= TWh 197.8 TWh/365/24 = 225.8 GW

[3] BEIS, 'Net Zero and the Power Sector Scenarios', February 2022: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1059067/annex-o-net_zero-and-the-power-sector-scenarios.pdf

[4] National Grid ESO, 'Future Energy Scenarios', July 2022, p.15: https://www.nationalgrideso.com/document/264421/download

[5] Ibid., pp. 174-175

[6] Ibid., pp. 173-176

In a statement to the House of Commons on 19th April 2022 the then-Business Secretary Kwasi Kwarteng stated:

> *"We aim to deliver up to 24 GW of nuclear power by 2050 - approximately three times more than today. This represents 25% of our projected energy demand."*[7]

But that implies total energy demand will only be 100 GW. We have shown that demand is likely to be 225.8 GW and therefore meeting 25% of this demand from nuclear would in fact require 56 GW.

In the same announcement, Kwasi Kwarteng stated that by 2030 the UK would have 50 GW of wind capacity. However, wind capacity does not equate to usable, on-demand electricity. Analysis of the National Grid's Balancing Mechanism Reporting System[8] (BMRS) shows that in 2021, wind derived electricity used by the grid was 48,619 TWh: only 20.5% of the nominal capacity of 237,658 TWh. In 2020, it was 25.2% of nominal capacity. The BMRS statistics also show that between 196 and 228 days in the years 2019-2021, wind produced less than 4 GW at some stage of the day or night (average demand is 30 GW and typical peak demand is often in the range of 40-45 GW).[9]

Put simply, we will not be able to rely on wind and solar—variable renewable energy (VRE)—for those *Dunkelflaute* periods (dark doldrum days when the wind does not blow and the sun does not shine).

In the British Energy Security Strategy paper of April 2022, it was stated that:

> "*By 2030, 95% of British electricity could be low-carbon; and by 2035, we will have decarbonised our electricity system"*[10].

It is inconceivable that these targets could be achieved by building more renewables or *large* nuclear power stations. All but one of our existing nuclear power stations have already had their life extended and are due to shut down by 2028: Sizewell B is scheduled to shut down in 2035 but could have its life extended. Hinkley Point C and Sizewell C (with a combined total output of 6.52 GW) will only replace what has been lost and will supply less than 12% of the 2050 requirement of 56 GW. 25% of the 2050 need requires eight times more nuclear electricity generation than that. We have seen no plans from BEIS or HM Treasury to deliver that level of capacity.

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[7] Hansard, 'Energy Security Strategy', Volume 712, April 2022: https://hansard.parliament.uk/commons/2022-04-19/debates/2F7E48E5-75DD-40D6-A7A8-27708E5855AE/EnergySecurityStrategy

[8] Balancing Mechanism Reporting Service, 'Generation by Fuel Type': https://www.bmreports.com/bmrs/?q=generation/fueltype/current

[9] Ibid.

[10] Gov.uk, 'British energy security strategy', April 2022: https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy

In a judgement dated 18 July 2022, Mr Justice Holgate found that there was no credible route to a net zero carbon 2050 for the UK based on current policies[11]. He also ruled that Greg Hands, the Minister responsible, had approved the strategy without being provided with sufficient information to be satisfied that the carbon budgets could be met. The Government's net zero strategy therefore breaches its obligations under sections 13 and 14 of the Climate Change Act 2008. The Court held that Section 14 requires the Secretary of State, as soon as reasonably practicable after a carbon budget is set, to lay a report before Parliament setting out his proposals and policies for meeting the carbon budgets. The report must also cover other matters such as the timescales over which those policies are expected to take effect and how they affect different sectors of the economy.

The court decided that a report under section 14 is important not only to enable Parliament to scrutinise the Secretary of State's policies and to hold him to account, but also to provide transparency so that the public can properly understand how the Government intends to meet its statutory targets. The court ordered the Secretary of State to lay before Parliament a fresh report before the end of March 2023.

There has been criticism too from the Public Accounts Committee: "…*the government has no clear plan for how the transition to net zero will be funded, nor a reliable estimate of what net zero will cost consumers, businesses or the government itself.*"[12] Whilst it is a valid criticism, one recognises that speculating about prices in 2050 (particularly given the impending price increases) is even more hazardous than estimating the total electricity requirement. We too will not venture into that territory but make the price comparisons below using current prices.

THE SOLUTION

This section looks at the alternative types of small nuclear reactors that could be used to fill the electricity supply gap discussed above. In this field the following terms are used: small modular reactors ('SMRs'), advanced modular reactors ('AMRs') and molten salt reactors ('MSRs'). All AMRs are SMRs (i.e. small and modular) and all MSRs are regarded as advanced. The International Atomic Energy Agency has produced a comprehensive guide to SMRs which gives full details of all SMR projects but they use a different method of classification. SMRs are usually defined as those which are capable of being produced in volume in a factory and shipped to the site.

In the tables set out below comparisons are made between (a) large reactors using design variations of the older pressurised water technology e.g. Hinkley Point C (b) currently available pressurised water reactors ('PWRs') or boiling water reactors

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[11] Courts and Tribunals Judiciary, 'Friends of the Earth vs. Secretary of State for Business, Energy and Industrial Strategy', 2022 (summary): https://www.judiciary.uk/wp-content/uploads/2022/07/FoE-v-BEIS-summary-180722.pdf

[12] House of Commons Committee of Public Accounts, 'Achieving Net Zero: Follow up', February 2022: https://committees.parliament.uk/publications/9012/documents/159059/default/

(BWRs) (c) high temperature gas cooled reactors ('HTGRs') (d) Rolls Royce pressurised water SMRs (e) molten salt reactors that are either land-based or barge-mounted and (f) micro reactors.

All nuclear reactors produce heat from which electricity is generated. Only AMRs and some micro reactors use low pressure, which increases the safety factor, and high heat. The output heat of water based reactors or light water reactors is under 300°C whereas most newer technology reactors have an output heat in the range 565°C to 700°C. The higher temperatures are better for heat storage and later conversion into electricity and for hydrogen production. Below 550°C and in the temperature range of light water reactors, heat energy is very difficult to store efficiently although research is ongoing.

Molten salt reactors based on thorium are not a new technology; they are based on a successful experiment carried out at the Oak Ridge National Laboratory in the 1960s.[13] Thorium nuclear reactors were abandoned in favour of uranium reactors mainly because the latter were able to produce weapons grade plutonium.

Fusion is a much researched possibility but current estimates for the ITER fusion project in France are that it will cost $65 billion[14] and there is no current estimated completion date.

COST COMPARISONS

AMRs offer significant cost advantages over older generation nuclear reactors. The cost advantages do not derive solely from the fact that they are small. The fission technology plus the choice of molten salt as fuel means that some AMRs—and nearly all MSRs—will have a much higher thermal efficiency (in the range 40% to 45% compared with the 33% of PWRs and 35-36% for Hinkley Point C). This brings lower costs per MWh.

Operating at low pressures implies that there will be a reduced cost for containment structures whilst operating at high temperatures. This means that AMRs can be used in process industries including, importantly, the production of zero carbon hydrogen. Smaller reactors often use natural circulation based on thermal differentials thereby negating the need for expensive and fault-prone pumps.

The fact that an AMR plant design will be modular, manufactured off-site and transported to where it is needed is a benefit, but is not the prime driver of low costs, nor is it the primary differentiator for AMR designs. Many other nuclear projects claim modularity in design and construction. Offsite construction is however a major reason why all SMRs of whatever type can be delivered very quickly.

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[13] Oak Ridge National Laboratory, 'Time Warp: Molten Salt Reactor Experiment—Alvin Weinberg's magnum opus': https://www.ornl.gov/molten-salt-reactor/history

[14] New Energy Times, 'Full Financial Disclosure for ITER Reactor Could Be Painful', June 2022: https://news.newenergytimes.net/2022/06/07/full-financial-disclosure-for-iter-reactor-could-be-painful/

In reviewing costs, a distinction clearly needs to be made between the first-of-a-kind design ('FOAK') where there are considerable initial costs involved in getting design approval and subsequent production of the same design (*nth* of a kind or 'NOAK' design). The cost estimates which follow are estimated NOAK costs based on published information or confidential information from many of the companies which have nuclear reactor projects.

Costs can be expressed either as a capital cost per MWe of capacity or else as the levelised cost of electricity ('LCOE'). There are many variables in LCOE including the cost of fuel and the interest discount rate. Interest rates have gone up since many of the above LCOEs were calculated; therefore the LCOEs quoted below may well be understated. Sensitivity analysis shows that for large projects built over many years a large increase in interest rates can easily double the cost.[15] The cost per MWe of capacity is a better indication, as this is a metric which will influence HM Treasury.

TECHNOLOGY	COST PER MWE[16]	LCOE MWH
Hinkley Point C/Sizewell C	£6.25-7.8 million	£80-£112
PWRs (1000 MWe)	£9-11 million	£80-£85
HTGRs (210 MWe)	£4.8 million	£70
BWR (300 MWe)	£3.95 million	£50
Rolls Royce SMR (470 MWe)	£4.3 million	£57
Barge-mounted MSRs (300 MWe and 1000 MWe)	£2.1-3 million	£33-£50
Micro reactors	£3 million	£41-£66

Some original sources were in dollars and have been converted to £s using a US dollar conversion rate of £1 = $1.20.

For the purposes of comparison, the capital cost of new build offshore wind is estimated to be in the range of £3-5 million per MWe and the LCOE is estimated to be in the range £125-£150 per MWh[17]. The offshore wind costs exclude the cost of transmission lines which is a significant cost for offshore wind coming from Scotland, The unsubsidised LCOE of new build biomass is estimated to be in the range £75-£125 per MWh[18].

SPEED OF CONSTRUCTION

Speed of roll out is a factor which is vital if the target of zero carbon electricity by 2035 is to be achieved. The following table sets out the estimated construction time for the various types of nuclear power station. Construction time is taken as

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[15] International Energy Agency, 'Projected Costs of Generating Electricity: 2020 Edition', p.84: https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf

[16] The estimates of cost per MWe and MWh are based on a survey of publicly available information and websites plus confidential and commercially sensitive information supplied to the authors.

[17] Global Warming Policy Foundation, 'Offshore Wind: Cost Predictions and Cost Outcomes', 2021: https://www.thegwpf.org/content/uploads/2021/02/Offshore-Wind-LCOE.pdf

[18] International Energy Agency, 'Projected Costs of Generating Electricity: 2020 Edition', p.46: https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf

either the time taken to construct on site or, in the case of small modular reactors, the time taken to produce one unit in a factory environment which is geared up for volume production. Volume construction in a factory brings the additional benefit of easier quality control. The estimates set out below are production timescales and assume that design and site approval has been obtained. They also assume that site preparation and turbine installation can take place whilst units are being constructed.

TECHNOLOGY	CONSTRUCTION TIME
Hinkley Point C/Sizewell C	10-15 years[19]
Generation III PWR (1000 MWe)	8 years
Rolls Royce SMR (470 MWe)	2 years plus 2 years for commissioning
HTGRs (210 MWe)	2 years plus 12 months for commissioning
BWR (300 MWe)	2 years plus 12 months for commissioning
Barge-mounted MSR (1000 MWe)	1 year plus 1 year for commissioning
MSR (100-300 MWe)	2-3 months per unit plus 6 months for commissioning
Micro reactor (10-50 MWe)	2-3 months per unit plus 6 months for commissioning

FOOTPRINT AND SITE REQUIREMENTS

The footprint and site requirements are set out below. However, small modular reactors offer other advantages in addition to size. Older reactors required large amounts of water for cooling, and as a result of this they have usually been sited by the sea or on a large river. SMRs employing molten salt as a coolant do not have to be sited near water and are therefore suited to remote locations. Some smaller units can be located underground, which is an additional safety factor consideration.

TECHNOLOGY	SITE REQUIREMENTS
Sizewell C (3,260 MWe)	371 hectares onshore / 639.9 ha. offshore[20]
PWR (1000 MWe)	200 hectares (site)
Rolls Royce SMR (470 MWe)	1 hectare (reactor) / 4 hectares (site)
BWR (300 MWe)	1 hectare
Barge-mounted MSR (1000 MWe)	1.2 hectares (plant on barge)
Molten Salt Reactor (100-300 MWe)	350m^2 (reactor) / 2-7 hectares (site)
Micro reactor (10-90 MWe)	30m^2 (reactor) / 1.3 hectares(site)

LOAD FOLLOWING CAPABILITIES

Older style nuclear reactors cannot quickly be ramped up or down to meet variable demand. Several AMR designs can be ramped up and down. If there is heavy reliance on wind, the ability to ramp up quickly when the wind is low or non-existent is a major advantage. All SMRs which use molten salt as a fuel or as a coolant can be

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[19] World Nuclear News, 'EDF revises Hinkley Point C schedule and costs', May 2022: https://www.world-nuclear-news.org/Articles/EDF-revises-Hinkley-Point-C-schedule-and-costs#:~:text=The%20start%20of%20electricity%20generation,has%20announced%20following%20a%20review

[20] Planning Inspectorate, 'The Sizewell C Project: Main Development Site Design and Access Statement Part 1 of 3', May 2020: https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010012/EN010012-002203-SZC_Bk8_8.1_Design_and_Access_Statement_Part_1_of_3.pdf

ramped up and down to meet variations in demand. Either the reactor itself can be ramped up and down (e.g. Terrestrial Energy, Arc Energy, Flibe Energy, Thorcon, NuScale) or else the plant could have an add-on in the form of a molten salt storage unit which can be drawn on in times of high demand. (e.g. Moltex, TerraPower, Kairos). In both cases the speed of response is likely to be determined by the response time of the generator rather than the response time of the reactor.

SAFETY ASPECTS

Safety, understandably, is a huge issue, with many aspects to it, and is thus beyond the scope of this paper to consider in great detail. Subject to this proviso, though, we note that many AMRs (and all molten salt fuelled reactors) operate at low pressure. This is an advantage from a safety perspective[21] as they do not require massive containment structures to contain a Chernobyl-type internal explosion. However, AMRs have other safety aspects which derive from their designs such as:

- The integration of primary reactor components into sealed, replaceable vessels which can be replaced at regular intervals (5-7 years). It is worth noting that many more general SMRs are also integral, although often don't come with readily replaceable vessels. Integration of components into the vessel reduces external pipe circuitry and hence reduces the possibility of breaks to such external pipework
- 'Walk away safe' so that a reactor is not envisaged as requiring human intervention to shut down. There are different potential ways of doing this, for different reactor designs. As an example, in MSRs the idea is typically that a plug melts if the reactor overheats, thus allowing the reactor fuel to drain down into tanks which disperse the material enough to shut off the chain reaction and for safe cooling to ensue
- Using molten salt as a coolant in MSRs means that it cannot boil away (as is possible for example in water cooled reactors, which then carries the possibility of reducing the amount cooling to such an extent that fuel overheating can occur).

FUEL AND COOLANT CONSIDERATIONS

SMRs use the following fuels: Low Enriched Uranium - LEU (under 5%); LEU+ (up to 10%) or High Assay LEU - HALEU (up to 19.75%). Thorium can also be used and some designs can incorporate minor actinides from spent nuclear fuel. The fuel can be liquid, or solid (either encapsulated in coated particles (TRISO) and incorporated into compacts (prisms or pebbles) or metallic in the form of a uranium zirconium alloy. In a molten salt reactor, molten fluoride or chloride salts act as both the coolant and as the solvent for the nuclear fuel. The chemical composition of the salts varies between development companies.

It is beyond the scope of this paper to go into the technical merits of each of the above options except to say that low enriched uranium is widely available, LEU+ could be available by 2024 and HALEU could be available by 2028/29 with government support. Thorium is also widely available and cheaper than enriched uranium

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[21] International Atomic Energy Agency, 'Technology Neutral: Safety and Licensing of SMRs', August 2020: https://www.iaea.org/newscenter/news/technology-neutral-safety-and-licensing-of-smrs

but it requires additional fissile material such as enriched uranium to start the process.

REGULATORY APPROVAL AND DATE OF FIRST OPERATION OF SMRS

The Chinese High Temperature Gas Reactor is already operational, and their thorium based molten salt reactor (demo unit) is now cleared for start-up.

The Akademik Lomonosov SMR floating power plant started operations in 2020. It has 2 x 35 MWe reactors.[22]

Hinkley Point C Unit 1 is scheduled to start operations in 2027 but might be delayed.[23]

NuScale now has full regulatory approval in the USA for its SMR design.[24] They are now gearing up for production in volume.[25]

GE Hitachi hopes to have their BWRX-300 operating in Ontario, Canada by 2028.[26]

Rolls Royce hopes to have a unit operating in 2029.[27]

The main constraint on the early operation of SMRs is the very slow progress of regulatory approval. Because of this, the estimated start dates for SMRs are the mid to late 2020s for small demo units and 2029-2030 for medium-sized fully operational units.

There is some hope for a speedier approval process in the medium term. The International Atomic Energy Agency has started an initiative for the harmonisation of the approval of nuclear reactor designs.[28] Canada and the US have agreed to share considerable portions of the licensing process without duplication of effort. The Office for Nuclear Regulation ('ONR') is talking to Canada on the subject. Generic Design Assessment costs and times for SMRs licensed in Canada are expected to fall markedly. We hope the UK will also speed up the process- BEIS needs to explore the subject of fast-tracking UK approval for designs which have already been approved in the USA or Canada.

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[22] World Nuclear News, 'More nuclear heat for Arctic town', July 2022: https://www.world-nuclear-news.org/Articles/More-nuclear-heat-for-Arctic-town

[23] World Nuclear News, 'EDF revises Hinkley Point C schedule and costs', May 2022: https://www.world-nuclear-news.org/Articles/EDF-revises-Hinkley-Point-C-schedule-and-costs

[24] World Nuclear News, 'US regulator to issue final certification for NuScale SMR', August 2022: https://www.world-nuclear-news.org/Articles/US-regulator-to-issue-final-certification-for-NuSc

[25] World Nuclear News, 'SMR company NuScale pivots from development to delivery', June 2022: https://www.world-nuclear-news.org/Articles/SMR-company-pivots-from-development-to-delivery

[26] World Nuclear News, 'OPG chooses BWRX-300 SMR for Darlington new build', December 2021: https://www.world-nuclear-news.org/Articles/OPG-chooses-BWRX-300-SMR-for-Darlington-new-build

[27] World Nuclear News, 'Rolls-Royce hopes for UK SMR online by 2029', April 2022: https://www.world-nuclear-news.org/Articles/Rolls-Royce-hopes-for-UK-SMR-online-by-2029

[28] International Atomic Energy Agency, 'Accelerating SMR Deployment: New IAEA Initiative on Regulatory and Industrial Harmonization', April 2022: www.iaea.org/newscenter/news/accelerating-smr-deployment-new-iaea-initiative-on-regulatory-and-industrial-harmonization

CONCLUSION

The Government target of 25 GW of nuclear capacity by 2050 appears to be inadequate and should be set at a minimum of 56 GW. All existing nuclear generators are due to be closed by 2035. According to current Government plans, only the Hinkley Point C and Sizewell C will be providing nuclear power, leaving a gap of 50 GW. There is no way enough *large* nuclear power plants could be built in time to meet the target of 95% of electricity being carbon free by 2035, since the construction time for large nuclear power plants is between 8 and 15 years to which must be added another 5-10 years for the decision making process.

The authors of this paper also query why the Government is considering a future massive expansion of windfarms in preference to load-following advanced nuclear power stations. Windfarms have only been able to compete in the electricity market because they are given priority over other energy sources and because they receive direct and indirect subsidies. They require backup and often also need large investment in long transmission lines.

Many types of advanced nuclear reactor should soon be able to provide load-following electricity supply at a considerably lower cost than wind.

Small Modular Reactors (SMRs) are quick to build and have far smaller capital costs and space requirements than existing types of reactor. The cost per MWe of capacity could be half that of today’s large reactors. Although large numbers of small nuclear power plants would be needed this need not present a problem for site selection as several could be grouped on one location. Furthermore, after the first one or two of each type, they could be financed by the private sector, relieving the burden on HM Treasury. Owing to their modern design and the fact that they are mostly low pressure, SMRs should also be less of a safety hazard and their regulation could be streamlined if the UK fast-tracked any design that had been approved in the USA or Canada.

Small Modular Reactors from Rolls Royce (if they can be delivered quickly) or proven technology Boiling Water Reactors are useful stop gaps but in the medium term, Advanced Modular Reactors are likely to prove a better solution.

If the UK fast-tracks regulatory approval, Advanced Modular Reactors could be supplied from 2030 onwards. But we would need rapid decision-making and action along the lines of finding, approving and manufacturing the Covid vaccine. Time is of the essence.

AMRs: Advanced Modular Reactors. Nuclear reactors which use novel and innovative fuels, coolants, and technologies to generate low-carbon electricity, and take advantage of the same modular-build principles as small modular reactors do. Many AMRs are also termed Generation IV Reactors.

BMRS: Balancing Mechanism Reporting System is a website run by National Grid ESO (q.v.) and provides near real time and historic data about the Balancing Mechanism which is used by the National Grid's Electricity System Operator as a means of balancing power flows onto and off the electricity Transmission System in Great Britain. It is an important resource for checking historical supply every half hour from all sources of electricity.

BWRs: Boiling Water Reactors. This is a type of light water nuclear reactor that is utilised to produce electric power. It is one of the most common nuclear reactors used to generate electricity. In this type of reactor, a single water loop acts simultaneously as both the core coolant and the turbine steam source. It is an established and well-proven technology.

ESO: Electricity System Operator. This is a legally separate entity within the National Grid. The National Grid owns the assets such as pylons and transmission lines. The ESO balances the electricity from various sources and passes it on as high voltage electricity to local distribution network operators who then reduce the voltage and distribute electricity to homes and businesses around the country.

FES: Future Energy Scenarios. This is a 2022 publication from the National Grid which outlines four different pathways for the future of energy between now and 2050. Each pathway considers how much energy we might need and its source.

FOAK: First-Of-A-Kind. New designs of nuclear reactor incur very heavy upfront expenditure on testing and licensing. Therefore, the first of a particular reactor will always be much more expensive than subsequent reactors or nth of a kind (NOAK).

GW: A Gigawatt, which is 1,000,000,000 (1×10^9) watts of power. In kilojoules (kJ) this is equal to one million (1×10^6) kJ per second. It effectively measures power at one particular moment in time.

GWh: One Gigawatt hour. A measure of energy used or produced over a one-hour period that is equal to sustaining 1,000,000,000 (1×10^9) watts over that hour or 3,600,000,000 (3.6×10^9) kJ in total. It measures a sustained amount of energy output or use.

HALEU: High-Assay Low-Enriched Uranium, that has been enriched so that the concentration of the useful isotope U-235 is between 5 and 20 percent of the mass of the fuel. This is higher than the 3 to 5 percent U-235 concentration, or "assay," of Low-Enriched Uranium that fuels existing light water reactors.

HTGRs: High Temperature Gas-cooled Reactors. In some respects a higher temperature version of the CO2 cooled reactors that have been in use in the UK but are now being phased out. This variant operates at higher temperatures and uses helium gas as a coolant. China has one HTGR in operation but has stated that the costs are the same as a PWR.

LCOE: Levelised-Cost-Of-Electricity is the discounted lifetime cost of building and operating a generation asset, expressed as a cost per unit of electricity generated (£/MWh). It covers all relevant costs faced by the generator, including pre-development, capital, operating, fuel and financing costs. It is highly sensitive to variations in interest rates.

LEU: Low-Enriched Uranium is a nuclear fuel that has enrichment levels up to nominally 4.95% and is the most widely available type of nuclear fuel.

MSRs: This is a class of nuclear fission reactor in which the primary nuclear reactor coolant and/or the fuel is a molten salt mixture. They operate at, or close to. atmospheric pressure, rather than the 75-150 times atmospheric pressure of a typical light-water reactor (LWR). MSRs can also be refuelled while operating, which LWRs cannot (although there are some other reactors that have done so, such as the UK Magnox and AGRs, as well as the Canadian CANDUs). A further key characteristic of MSRs is operating temperatures of around 700°C - significantly higher than traditional LWRs, at around 300°C, thus providing greater thermal efficiency, the possibility of grid-storage facilities, economical green hydrogen production, and, in some cases, process heat opportunities.

Mtoe: Million tonnes of oil equivalent. A unit used to convert all sources of energy to the same unit for the purpose of analysis

MW: A Megawatt, which is 1,000,000 (1 x 10^6) watts of power. In kilojoules (kJ) this is equal to one thousand (1 x 10^3) kJ per second (see also GW above). MWh Megawatt hours, a measure of energy used or produced over a one-hour period that is equal to sustaining 1,000,000 (1 x 10^6) watts over that hour (see also GWh).

MWe/MWt: There are two values normally assigned to a powerplant: Megawatts electric (MWe), and Megawatts thermal (MWt). The former refers to the electricity output capability of the plant, whilst the latter refers to the thermal energy produced in the first place (to then be converted into electricity). The ratio MWe/MWt is defined as the thermal efficiency. Most nuclear power plants express their capacity in MWe, but because some nuclear reactors aim only to produce heat (for process industries) they express their capacity in terms of MWt.

NOAK: Nth-Of-A-Kind. This is used in relation to costs of nuclear power stations. It refers to a manufacturer's claim that, after the initial cost heavy upfront expenditure on testing and licensing the first unit, subsequent units will be cheaper.

ONR: The Office for Nuclear Regulation is the UK's independent nuclear regulator. Its task is to regulate nuclear safety and civil nuclear security. This includes regulating the existing fleet of operating reactors, fuel cycle facilities, waste management and decommissioning sites. It also regulates the transport of civil nuclear and radioactive materials by road, rail and inland waterways. ONR's remit also includes the regulation of the design and construction of new nuclear facilities.

PWRs: Pressurized Water Reactors. A type of light-water nuclear reactor. PWRs constitute the large majority of the world's nuclear power plants and are thus a well-established technology. In a PWR, the primary coolant (water) is pumped under high pressure to the reactor core where it is heated by the energy released by the fission of atoms. That hot water then passes its heat to a secondary loop of water that is converted into steam. This steam spins a turbogenerator to create electricity. They are used in big reactors, many SMRs, and also as submarine reactors.

SMRs: Small Modular Reactors are advanced nuclear reactors that have a power capacity of up to 500 MW(e) per unit, which is roughly about one-third of the generating capacity of traditional big nuclear power reactors. SMR systems and components can be readily factory-assembled and transported as a unit to a location for installation.

TWh: Terawatt hours, a measure of energy used over a one-hour period that is equal to sustaining 1,000,000,000,000 (1×10^{12}) watts over that hour (see also GWh above).

VRE: Variable Renewable Energy Sources such as solar energy and wind power. Due to its variability, it always needs to be complemented with storage or baseload generation.