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Delivering advanced nuclear energy: **the role of Government**

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Foreword

It is now clear that the UK Government sees a significant role for nuclear energy both in meeting the UK's legally binding commitment to net zero, and in enhancing energy security.

It has also been clear for many years that new nuclear development in the UK will not be a state enterprise; rather the role of the state is seen as creating an environment in which the private sector is willing to make the huge capital investments associated with delivering nuclear energy.

For each of the three 'waves' of nuclear energy envisaged in the 2019 Energy White Paper, Government's enabling activities will be rather different. In the Third Wave, a wide range of competing Advanced Modular Reactor (AMR) technologies exist, with the High Temperature Gas-cooled Reactor (HTGR) being preferred. Many of these AMR technologies are relatively immature, and prospective developers face a range of commercial, regulatory and political challenges. In this paper we explore the actions that only Government can take, which will smooth a path to a UK demonstration of HTGR technology by the early 2030s, and without which there is little prospect of progress.

This Position Paper was written in July 2022, a period during which the UK Prime Minister resigned, the Government was entering a period of transition which is likely to last at least several months, energy prices reached their highest in a generation and the UK experienced an episode of record-breaking temperatures. In addition, on 6 July 2022, the French Government announced its intention to nationalise EDF. It remains to be seen how these events impact the deployment of nuclear energy.

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Executive Summary

Government and advisory publications of the last two years have suggested a *de facto* endorsement of the 'Three Wave' rollout of nuclear energy to aid progression to net zero by 2050.

The three waves can be broadly defined as large, Light Water Reactors (LWRs), followed by their scaled down successor Small Modular Reactors (SMRs), and finally Advanced Modular Reactors (AMRs) in the form of High Temperature Gas-cooled Reactors (HTGRs). While Waves 1 and 2 will be dedicated to electricity generation, HTGRs provide high temperature heat for various applications.

Despite positive endorsement and favourable levelised costs of electricity, the large capital costs (dominated by the costs of financing) and long lead-times of new nuclear plants have meant that they have not been delivered by the market. Government action is clearly needed to deliver successful nuclear projects. Given that large numbers of reactors will likely be needed to achieve a net zero energy future in coming decades, effective facilitation by Government is urgently needed. Part of this role is communicating clearly future estimates as to demand for nuclear energy to enable the sector to plan accordingly.

Recommendation one:* *Government should develop, and communicate to the market, estimates of the size and utilisation of the potential HTGR fleet, including the power output of reactors envisaged, and the end use of the heat output.

Further to this, Government has a role in providing certainty to the market with any decisions and future competitions they hold. Any decisions and commitments should be clear, and given the long lead-time for nuclear projects, assurance should be given that whatever support is provided will be consistent over many years.

Recommendation two: Clear decisions should be made by Government, for example in Government-led competitions, to provide certainty to the market. While this will create winners and losers, Government should be clear, consistent, and courageous in its decision making.

Recommendation three: Government should make a clear, decades-long commitment to support advanced nuclear systems.

Recent failures in nuclear projects, for example Horizon and NuGeneration which failed due to financing issues within three months of each other in 2018/19, made it clear that urgent action needed to be taken to revive the prospects of new LWRs in the UK. An alternative financing model took three years to be put in place. Nuclear programmes are moving slowly and need to progress much faster if net zero by 2050 is to be achieved. Government must move equally rapidly to facilitate progress.

Recommendation four: Nuclear programmes must move at the pace required to meet the 2050 net zero deadline, and Government processes need to be able to keep up.

The UK has an unusual 'goal-based' approach to nuclear regulation, providing developers with flexibility in the way they evidence their safety claims. There is considerable clarity within the regulatory domain. Generic Design Assessment (GDA) provides a clearly defined process to enable developers to work with regulators to deliver effective final reactor designs and plan site development. Early efforts should be made to engage with this process, and end of life activities should form part of this development.

Recommendation five: Developers should make efforts to engage early with regulators, to finalise a mature design and to establish a clear plan for the development of a site licence holding entity. This should cover the whole span from reactor building, to decommissioning, and vacation of the site.

Competitions (such as the currently running AMR RD&D programme) have been a favoured tool of Government for encouraging R&D into new nuclear systems in recent years. Government must be careful to ensure that the competition format does not impact the effectiveness of any future nuclear fleet by being too frequent, or for too narrow a scope.

Recommendation six:* *Fleet build of SMRs and HTGRs, combined with modular construction, are essential to achieve acceptable economics for these reactors. Competitions must be for quanta of work that are sufficiently large to justify investment by developers and sufficiently infrequent that they do not add significant delay to the programme.

The UK is following the EU in developing a taxonomy for assessing the sustainability of new endeavours. Poor judgement was applied in the development of the EU taxonomy, leading to the exclusion of the only dispatchable, low carbon generating option (i.e. nuclear) from the taxonomy. Such an exclusion would have been extremely damaging to the nuclear sector in Europe, making financing even more expensive than it is presently. The decision was eventually partially reversed, and now both nuclear and natural gas are considered as transition technologies in the EU taxonomy. Nuclear energy is a sustainable energy source, and as such it is important that the UK assesses the sustainability benefits and drawbacks of all energy generators fairly within its upcoming taxonomy.

Recommendation seven:* *To enable early, cost-competitive financing of nuclear investments, Government should ensure that its developing Green Taxonomy properly reflects the sustainability benefits of nuclear energy and does not exaggerate its drawbacks.

1 Introduction

The last two years have seen a wealth of publications which define the possible roles of nuclear energy in the UK in the context of net zero by 2050.

The main output of these Government and advisory publications is the *de facto* Government endorsement of the 'Three Wave' rollout of nuclear energy, with the three waves broadly defined thus:

1. Gigawatt-sized Light Water Reactors (LWRs) for electricity production, such as the EPR pair at Hinkley Point C, and continuing with EDF building a sister station at Sizewell C in Suffolk.
2. Light water Small Modular Reactors (SMRs), also for electricity generation. For example, the Rolls-Royce-designed SMR.
3. Advanced Modular Reactors (AMRs) in the form of High Temperature Gas-cooled Reactors (HTGRs), providing high temperature heat for applications such as efficient hydrogen production and hard-to-decarbonise industries such as steelmaking and cement manufacture.

The British Energy Security Strategy gives a provisional size of the marketplace for Waves 1 and 2, stating intentions for increasing investment in nuclear energy in the UK by [1, p. 21]:

> *"Increasing our plans for deployment of civil nuclear to up to 24 GW by 2050 – three times more than now and representing up to 25% of our projected electricity demand."*

Adding that [1, p. 21]:

> *"Depending on the pipeline of projects, these ambitions could see our nuclear sector progressing up to eight more reactors across the next series of projects, so we improve our track record to deliver the equivalent of one reactor a year, rather than one a decade."*

The origin and significance of the 24 GW figure is further examined in the relevant section of the Appendix. Suffice to say that it does not relate directly to the number of reactors mentioned (eight), but does appear to include both Gigawatt-sized reactors and SMRs. Rolls-Royce stated in 2021 its ambition to build "16 SMRs in the UK, each with a generation capacity of 470 MW", a total capacity of ~7.5 GW, by 2050 [2, p. 25].

There has been no equivalent capacity quoted for Wave 3, but Government activity in this area has been considerable, with a project currently in progress to select and fund the first phase of an AMR Research, Development, and Demonstration (AMR RD&D) Programme [3, 4]. The remainder of this paper focuses primarily on the Government's role in Wave 3, with the overall driver being to oversee a successful, economic programme which contributes to achieving net zero emissions by 2050.

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HTGRs: Current Position

"The HTGR is a helium-cooled graphite-moderated nuclear fission reactor technology that uses fully ceramic fuels. It is characterised by inherent safety features and excellent fission product retention in the fuel and graphite compared to conventional nuclear reactor technology (GIF, 2020). Its reactor outlet temperature, typically between 750°C and 950°C, is significantly higher than that of conventional nuclear reactors; for example, a standard outlet temperature for PWRs is around 320°C." [5, p. 15]

The Third Wave of reactors was recommended to be HTGRs by NIRAB [6], and this was subsequently confirmed by initiation of a Department for Business, Energy & Industrial Strategy (BEIS) competition [4], which would provide "up to £2.5 million in innovation funding to support the development and demonstration of High Temperature Gas Reactor (HTGR) technology in the UK" [7]. This AMR RD&D Programme specifies a budget for up to four initial reactor studies, with a maximum of £500,000 available per pre-FEED (Front End Engineering Design) study [4, p. 8].

Government has provided no guidance as to the timing and size of the potential high temperature heat market, nor is there any information given on the preferred size of the individual reactors. Therefore, there is uncertainty as to how BEIS will select the competition winners, and how applicants will view the size, timing and 'geographical granularity'* of the future high temperature nuclear heat market in the UK.

Various estimates have been made of the potential for nuclear energy to contribute to carbon-free heat provision. Notably, a 2021 study by the National Nuclear Laboratory [8] examined a range of nuclear deployment scenarios by 2050, with scenarios incorporating heat provision from nuclear sources ranging from 498-974 TWh total nuclear energy supply [8, p. 319]. This energy supply range equates to 48 GWt of required HTGR nuclear capacity for the "Base Case Nuclear Deployment Scenario" (assuming a 90% load factor) [8, p. 438], and 204 GWt for the "Greater Nuclear Ambition Deployment Scenario" [8, p. 440]. With HTGR reactors at, for example, 600 MWt capacity, this would involve siting between 80 and 340 reactors.

With its overall perspective on the prospects of decarbonising to net zero by 2050, it should be safe to presume that BEIS has a view on the size and timing of these markets, which would enable it to put the applications into an overall UK energy picture. Certainly, such a perspective is essential for any orderly approach to both nuclear energy and net zero, as the likely number of reactors presents a completely different siting challenge to any the UK has faced before, rendering past experience in the methodology of reactor siting largely irrelevant.

It is notable that most previous nuclear generation sites now either belong to the Nuclear Decommissioning Authority (NDA) or, in the case of EDF's current AGR reactors, are at least partially reverting to NDA ownership at the end of their generating lives. NDA's mission is (on behalf of

** Geographical granularity reflects the drivers which point towards the clustering of industrial heat generation adjacent to existing or developing industrial clusters. Several regions are already planning the sort of hydrogen-using clusters that are envisaged, and some are even examining nuclear energy generation for the purpose.*

Government): "to clean up the UK's earliest nuclear sites safely, securely and cost effectively" [9, p. 7]. This surely points to the need for Government to have an overall role in the fate of former generation sites and their potential for re-use. Recommendations on this matter have been made in a previous Dalton paper, for example [10, p. 19], to Government:

> *"Recommendation one: The UK Government should develop an integrated framework for delivery of nuclear energy in the UK to ensure the whole lifecycle is understood.*
>
> *Recommendation two: The UK Government should integrate the NDA mission into this framework, supporting waste management and site clearance for reuse."*

And to developers and operators:

> *"Recommendation seven: Within this framework, any nuclear development, fission or fusion, needs to define at the start the entire lifecycle of its technology and sites, and communicate this openly and effectively to current and potential future host communities and other stakeholders."*

3 The Role of Government in Decarbonisation

3.1 Market Expectation

The Oxford English Dictionary defines Government as "the body of people charged with the duty of directing or controlling the actions and affairs of a country or state". It is accepted that a current principle of Government is that the supply of services (in this case carbon reduction) should largely be devolved to the market, but here the size of the market will be set on an overall UK basis in the form of a carbon curve which reaches net zero by 2050. This curve will be defined by changes, many of which will be driven by Government action, in various activities.

Government should therefore have views on the potential market sizes in various areas, and indeed the "24 GW by 2050" [1, p. 21] nuclear ambition is an example of this. Notably, this does not say who will supply which reactors, but does present an aspiration for firm, low carbon sources of nuclear electricity, presumably compatible with ambitions of reaching net zero. In the case of Wave 3, which is not very well understood, a Government view of the anticipated market size for low carbon, high temperature heat would be a case of Government helping to define the marketplace, not manipulating it.

It is generally accepted that, were the economics of HTGR heat supply not to reach the level required for uptake by the market, then the construction and operation of a demonstrator would be the price to pay for ruling out what is currently an ostensibly promising low carbon technology. Presumably, a similar conclusion would be made regarding Carbon Capture, Utilisation and Storage if its demonstration failed to capture and store the necessary fraction of its CO_2 arisings to be effective.

Using this logic, it is essential that Government has a view of the carbon curve and the plausible range of contributions of individual industries, actions and methodologies that might make net zero a reality. In the case of nuclear energy's Wave 3, such a broad view would enable reactor vendors to have a reasonable grasp of the numbers of reactors necessary and their required power outputs and target outlet temperatures. These same figures would enable the Government to examine numbers and locations of sites for nuclear development. Indeed, if Government does not have such an overall view of the path to achieving net zero, there is surely no assurance that the path is achievable.

The necessity of a Government view on market and reactor size can be illustrated by the not atypical 2020 study on hydrogen production by Lucid Catalyst. This gave an estimate [11, p. 28] that 360 reactors, each of 600 MWt, would be needed to supply the national annual 700 TWh demand specified by the Committee on Climate Change (CCC) in its "Full Hydrogen" scenario [12, p. 97]. To put this in context, the Nuclear Innovation and Research Advisory Board (NIRAB) has recommended a 'near-FOAK'* design for any HTGR demonstrator, with 600 MWt probably the upper limit for modularly constructed HTGRs [13]. It is evident why such context will be crucial knowledge for reactor suppliers, and for BEIS itself as it examines the provision of new nuclear sites. Certainly, any programme involving anywhere near the numbers suggested here would require a very different approach to that process which began with the EN-6 report in 2011 [14, 15].

It is clearly crucially important to have these, or other 'approved' figures, in mind before making any decision on the size of the HTGR demonstrator reactor, anticipated in the early 2030s [16, p. 12].

***Recommendation one:* Government should develop, and communicate to the market, estimates of the size and utilisation of the potential HTGR fleet, including the power output of reactors envisaged, and the end use of the heat output.**

3.2 Programme Risk

In this discussion, the term, 'programme risk' describes obstacles that impede the successful delivery (or not) of new nuclear energy as a project or programme. There are clearly safety, security and environmental risks and hazards, but these are mitigated by the regulatory approval process. Also, the basic economics of a future programme must be founded on the concept of a fleet of reactors to the same design, which in the case of HTGRs should be close to identical to the demonstrator scheduled for the early 2030s [6, 17]. All the mechanisms for siting and financing this fleet need to be in place so that developers have a firm vision of the market they are entering. However, recent history has given several examples where such visibility and resulting investment certainty have been considerably lacking.

As of July 2022, only one nuclear development has started construction in the UK since the 2008 White Paper [18], which revived the prospect of new nuclear power in the UK, but was explicit that investing in new nuclear development was a commercial decision for the private sector [18, p. 10]. For less mature designs, for example the HTGR, Government has recognised that it has a role to foster development and has chosen to do this by stimulating competition. This has led to a stop-start approach, for example, the AMR Feasibility and Development Project, where limited funding was provided to a HTGR, a Lead-cooled Fast Reactor (LFR), and a tokamak fusion reactor.† There has been no obvious further progress since, especially as the LFR has since been excluded from any future plans [19]. This competition has had no visible impact on the current advanced nuclear programme.

***Recommendation two:* Clear decisions should be made by Government, for example in Government-led competitions, to provide certainty to the market. While this will create winners and losers, Government should be clear, consistent and courageous in its decision making.**

Given that the sole nuclear development currently underway (Hinkley Point C) is being funded by state-owned French and Chinese energy companies, with all other projects proving unsuccessful, the UK nuclear market seems still to present barriers to developers. Overcoming some of those barriers requires Government action; most obviously, Government is responsible for establishing the regulatory and commercial frameworks in which new nuclear developments will be delivered, and in particular, the Government must put in place arrangements that will assure investors of 'adequate return for adequate performance'.

Because nuclear power is a multi-generational undertaking, and given the extent to which the commercial sector requires certainty, there must be a clear commitment over decades, or as far as is possible given the political timescales. Across the sector, large amounts of time and money have been expended for little return since 2008, so it is particularly important to re-establish confidence through decisive action.

***Recommendation three:* Government should make a clear, decades-long commitment to support advanced nuclear systems.**

3.3 The Commercial Environment

It is well known that the cost of nuclear power is dominated by the cost of capital, due to the vast sums required and the long period of time which elapses before any return on investment. These factors led to the setting of a strike price of £92.50/MWh for Hinkley Point C in 2012. Major reductions in the time to deployment and capital cost (particularly financing costs) for nuclear are therefore essential if it is to be competitive.

It is instructive to compare the costs of offshore wind over the same period. This was originally higher than £92.50 but reduced slowly through the 2010s, only dropping below £92.50 in 2019 and falling to around £38 in July 2022 [20].

** Where FOAK is 'First of a Kind'.*
† The call for the two-phase AMR Feasibility and Development Project opened in December 2017 [49]. In August 2018, phase one announced eight candidate developers [48] and in July 2020, phase two downselected to the three candidate projects [50].

This price reduction was triggered by Government action – the establishment of an Offshore Wind Investment Organisation enabled large scale fleet build of offshore wind, and there are lessons for the nuclear sector.

Following the 2008 White Paper [18], Government identified a number of prospective sites and moved to make other arrangements. Several candidate projects were subsequently initiated, but most failed. The Horizon Nuclear Power project provides a useful example.

Horizon was established in 2009 through a joint venture between E.ON UK and RWE npower. Both are subsidiaries of German parent companies and, partly due to Germany's post-Fukushima decision to phase out nuclear power, they sold Horizon to Hitachi in 2012. As well as eventually building reactors at Oldbury, Hitachi intended initially to build two Advanced Boiling Water Reactors at Wylfa but suspended the project in 2019, citing uncertainties over the financing of the project and arrangements for building and operating the nuclear power stations. Hitachi subsequently ended the project in 2020. The Horizon project is estimated to have cost Hitachi around £2 billion [21].

Recognising these problems, Government developed and sought to apply the Regulated Asset Base (RAB) model, previously used for several major infrastructure projects, to the nuclear sector through the recent Nuclear Energy (Financing) Act [22]. This application of RAB was approved in March 2022 – too late to have any effect on the demise of Horizon.

The RAB model effectively allows some of the upfront costs to be charged to consumers before generation begins, reducing financing costs and limiting risk to the developer, provided a series of designation criteria are met to ensure value for money for consumers and taxpayers [23, Sec. 3]. For Sizewell C, essentially a clone of Hinkley C, EDF estimates that use of the RAB model would be a significant contribution to the reduction in the cost of electricity to £40-60/MWh [24].

The RAB is a response to the disproportionate contribution of financing to the cost of building a nuclear plant, and nuclear programmes need to move at pace to avoid spiralling financing costs. The lesson that should be learned from this is that Government processes need to be able to keep up with any challenges that arise. On the matter of financing specifically, it was widely acknowledged at the time that the 2012 strike price for electricity from Hinkley Point C under the Contracts for Difference (CfD) scheme was expensive for the end user, and that this financing method was ill-suited to delivering large nuclear plants – yet it has taken until 2022 to put an alternative model in place.

***Recommendation four:* Nuclear programmes must move at the pace required to meet the 2050 net zero deadline, and Government processes need to be able to keep up.**

Other reactor concepts, for example the Rolls-Royce SMR, seek to reduce costs by both having a smaller, simpler, cheaper reactor, and by adopting new approaches to manufacturing and construction. Nevertheless, they would obviously benefit from any greater certainty over a UK nuclear programme and may also benefit from changed financial models.

3.4 The Regulatory Environment

In a global context, the UK has an unusual approach to nuclear regulation. It is 'goal-based', not prescriptive, and requires a developer to provide evidence-based arguments to underpin their claims of safe operation [25, p. 17]. This both provides the developer with a lot of rope, with which they can potentially hang themselves, and also considerable freedom to present their safety case as they see fit.

In the UK, the nuclear safety regulator is the Office for Nuclear Regulation (ONR), and the relevant environmental regulators are the Environment Agency (EA) in England, Natural Resources Wales and the Scottish Environmental Protection Agency (though Scottish Government policy prevents new nuclear development). Since the 2008 White Paper, the regulatory regime has become much better coordinated through an approach where both ONR and the relevant environmental regulator work together in assessing proposals, and the explicit adoption by ONR of an 'enabling' approach to regulation, defined as [26, p. 3]:

> *"A constructive approach with dutyholders and other relevant stakeholders to enable effective delivery against clear and prioritised safety and security outcomes."*

In practice, enabling regulation seeks to develop good communication between regulator and duty holder and includes, for example, strong encouragement to engage early with regulators.

Generic Design Assessment (GDA) is a phased approach to regulatory assessment of a proposed design, developed jointly by ONR and EA [27, 28]. Entry to GDA is controlled by Government since deployment of any particular reactor design is ultimately a national strategic matter. The GDA process is clearly defined and widely publicised, and is expected to take around four years to complete. In practice, the time taken to complete GDA will depend greatly on the maturity of the proposed design. Successful completion of

GDA marks regulatory acceptance that a proposed design is safe, but deployment still requires site-specific applications for the necessary consents, licences and permits. These will include establishing an entity to act as the operator, which is judged by ONR as being capable of holding – and discharging the responsibilities of – a nuclear site licence. In practice both GDA and development of the operator can proceed in parallel.

In the regulatory domain, therefore, there is considerable clarity. Organisational responsibilities are explicitly stated, and the processes by which the necessary regulatory approvals are obtained are well defined. Obviously, there is risk associated with both getting a design through GDA and establishing a credible operator, but those are ultimately a matter of commercial judgement that can be mitigated by having a mature design and a good understanding of the requirements of holding a nuclear site licence in the UK. There is a clearly defined path to regulatory approval for developers and operators with mature designs and detailed plans for completion. Notably, this path must include the 'end of life' activities that, while not yet capable of being detailed, must include the principles of site development, reactor operation, reactor decommissioning and vacating the site.

***Recommendation five:* Developers should make efforts to engage early with regulators, to finalise a mature design and to establish a clear plan for the development of a site licence holding entity. This should cover the whole span from reactor building, to decommissioning, and vacation of the site.**

3.5 The Political Environment

The typical timescales of political change are generally much shorter than the time required to deliver a nuclear project to completion. Long-term strategic activities such as the provision of nuclear energy, and indeed the entire process required to achieve decarbonisation to net zero by the targeted 2050 date, present a basic problem to the UK system. Consequently, it is important both to achieve the fullest possible political buy-in to such long-term strategies, and to embed their progress into the most stable organisations and structures that can be achieved.

Writing in mid-July 2022, recent political events provide a sobering contrast to this aspiration. The resignation of Prime Minister Boris Johnson has triggered a period of uncertainty which will last several months, at the very least, and could lead to significant policy shifts. Moreover, the French Government is taking EDF fully into state control to enable the building in France of at least six, and potentially 14, new reactors. This must raise questions over EDF's long term interest in the UK, both as a developer and potentially as an operator of nuclear power plants. Although this is a statement of the blindingly obvious, the changes in UK Government must give any prospective developer of, or investor in, new nuclear in the UK, pause for thought, while the changes in EDF illustrate the vulnerabilities arising from the UK's dependency on overseas developers and overseas finance.

The demise of at least three well-founded major reactor projects in the 2010s* was, in the main, down to Government not having an adequate appreciation of the needs of the market. This was illustrated, for example, by devising the improved RAB finance system several years too late to help the schemes that needed it. It is therefore evident that the requirements of commercial nuclear schemes should be examined and, as far as possible, catered for in Government plans over an appropriate timescale. Failures such as that of Horizon Nuclear Power give a severe disincentive to companies and organisations seeking to enter the nuclear energy market.

While it is difficult to assume international relationships will stay constant over long periods, it is essential that the effect of future changes be explicitly considered, and the vulnerability of proposed arrangements expressly debated and understood within Government.

Currently, there seems to be an overall political acceptance that fleet build of reactors (both SMRs and HTGRs) combined with modular construction are essential to achieve acceptable economics for these reactors. Though bought into at the strategic level, there is still evidence that previous incremental ideas and methods are still being proposed at lower levels of Government. Progress requires Government to become comfortable with a contractual format that does not exactly conform to its instincts for 'competition at every project stage', particularly as this inevitably introduces long delays and leads to faltering progress.

***Recommendation six:* Fleet build of SMRs and HTGRs, combined with modular construction, are essential to achieve acceptable economics for these reactors. Competitions must be for quanta of work that are sufficiently large to justify investment by developers and sufficiently infrequent that they do not add significant delay to the programme.**

** The NuGeneration Moorside project in November 2018 [51], and the Horizon Oldbury and Wylfa projects in January 2019 [21].*

3.6 The UK Green Taxonomy

As noted in Section 3.3, Government can strongly influence the commercial environment surrounding nuclear development. Many investors, including leading pension funds, are now very focused on the sustainability of their investments and, to be attractive to them, nuclear energy must therefore be deemed 'green'. In late 2020, the UK Government announced its intention to develop its own 'Green Taxonomy', enabling identification of activities that can be considered environmentally sustainable when judged against a set of objective criteria [16, p. 27, 29]. The UK's Taxonomy is intended to align with the EU Taxonomy, with adaptations to suit the UK market.

While previous sections of this paper have focused primarily on advanced nuclear power systems, the Taxonomy applies to all three waves of nuclear development (i.e. LWRs, SMRs and AMRs). If nuclear energy is to form part of the future economy of the UK, it is of crucial importance that it is not excluded during the Taxonomy process, as was the case initially with the EU Taxonomy. Furthermore, nuclear energy is sustainable and should be considered as such within any UK Taxonomy. As has been discussed, raising the necessary capital to build nuclear plants has been the main obstacle to the construction of new stations, such that alternative financing methods such as the RAB have been sought. Realistic cost breakdowns for levelised costs of nuclear electricity already estimate that two-thirds of the total cost is to cover financing [30, p. 30] – if exclusion from the Taxonomy would result in financing proving even more expensive, this could make new nuclear and our resulting energy security impossible.

The development of the EU Taxonomy has been lengthy and controversial. In March 2020 the final Taxonomy report from the Technical Expert Group (TEG) on Sustainable Finance excluded nuclear power from the Taxonomy on the basis that [31, p. 210]:

> *"Given [limitations regarding waste], it was not possible for TEG, nor its members, to conclude that the nuclear energy value chain does not cause significant harm to other environmental objectives on the time scales in question."*

While aspiring to set "performance thresholds for economic activities" to help investors "navigate the transition to a low-carbon, resilient and resource-efficient economy" [32, p. 2], seemingly arbitrary qualifications were added beyond the six clearly defined environmental objectives [31, p. 205]:

> *"To aid transition to net-zero, some technologies, such as solar, wind and tidal energy are derogated from the requirement to conduct Product Carbon Footprints assessments on the basis that these technologies perform significantly below the emissions intensity threshold."*

To avoid these pitfalls, the UK Taxonomy [33] which is still in development should devise and apply one set of objective criteria to the evaluation of all energy technologies, and not seek to arbitrarily exclude certain technologies from metrics as important as lifetime greenhouse gas emissions.

In the summer of 2020, the European Commission's Joint Research Centre carried out an assessment of nuclear energy [34] in response to the TEG Taxonomy report, leading to an amendment to the Delegated Act in March 2022 to bring nuclear and natural gas within the Taxonomy [35].

The six environmental objectives of the UK Taxonomy [33, p. 23], and the tests which must be met in order to be considered Taxonomy-aligned [33, p. 24], are identical to those in the TEG EU Taxonomy [32, p. 2]. Activities must make a substantial contribution to one of the six environmental objectives (each of the subheadings below), while doing no significant harm to the other objectives and meeting some minimum safeguards.

Climate change mitigation

Nuclear energy is internationally recognised as a low carbon, resilient energy source and there is extensive data to clearly show that nuclear energy can fully meet this criterion. In particular, the United Nations Economic Commission for Europe (UNECE) report [36] concludes that nuclear has a lifecycle carbon dioxide footprint of 5.1-6.4g CO_2/kWh of electricity [36, p. 7], the lowest of all electricity sources (Figure 1 – page 14). In total, the use of nuclear power has avoided more than 70 billion tonnes of CO_2 emissions globally since 1971, according to the IAEA [37, p. 25]. In addition to low lifetime emissions, it should also be noted that nuclear energy (along with hydro) is the only dispatchable generation option with average lifetime emissions below 100 g CO_2 eq./kWh. A modern economy requires dispatchable energy, and this should be considered when comparing with other low lifetime emission generators such as solar and wind, which are still without a solution to the intermittency problems they face. It may well not be possible to make the necessary emissions reductions and maintain a modern economy without adoption of nuclear energy, such is the extent of the contribution that nuclear can make to this environmental objective.

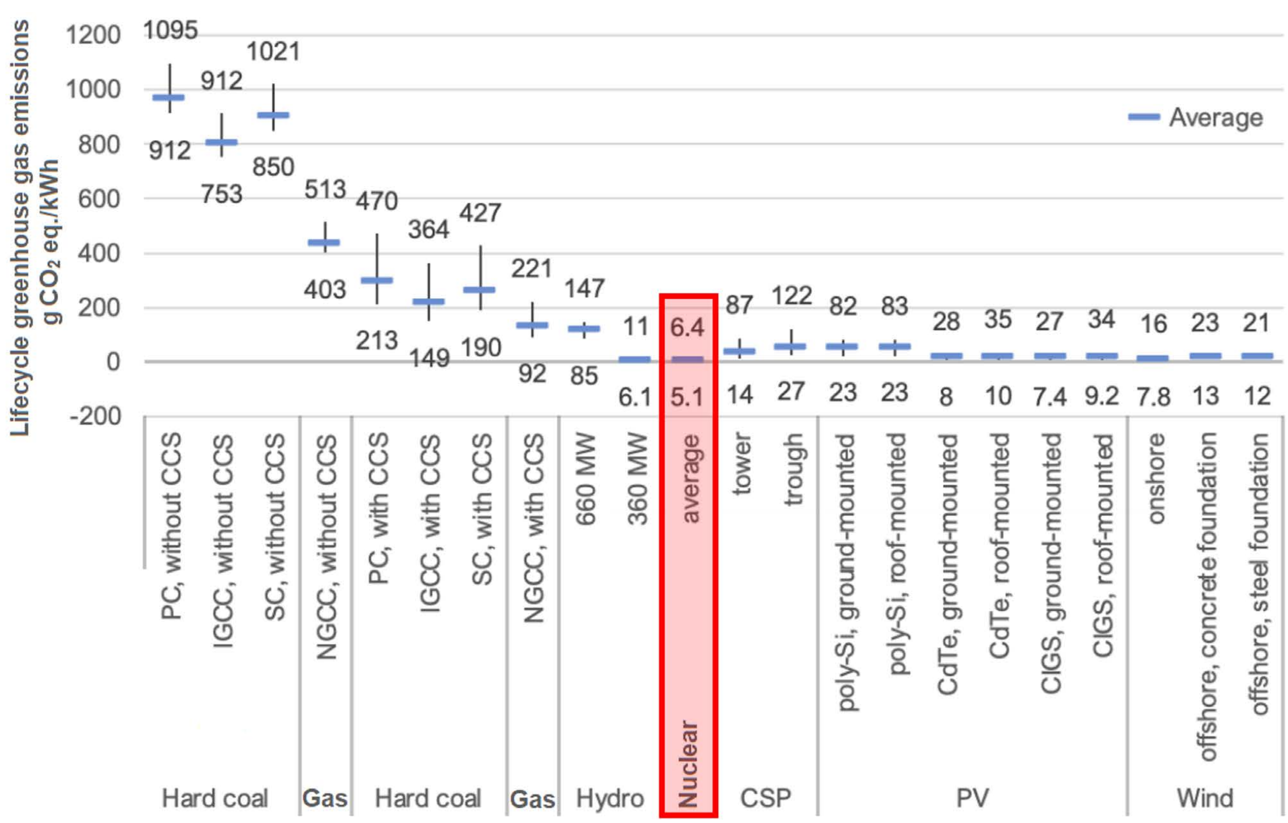

Figure 1. Lifecycle greenhouse gas emissions, regional variation, 2020, taken from [36, Fig. 1].* Solar is split into two categories; Concentrated Solar Power (CSP) and Photovoltaic (PV).

Climate change adaptation

Climate change adaptation of any activity has two facets, requiring mitigation of adverse impacts of climate change, or of the risks of climate impact on itself or on people, nature or assets. Clearly, by producing low carbon energy, thus reducing the impacts of climate change, nuclear power meets the first requirement. Since nuclear plants are often sited near estuaries and coastal locations, flooding and coastal change are the major climate-related risks associated with nuclear plants. However, mitigation of these risks is already an integral part of the design and siting requirements for any new nuclear plant [38], providing confidence that nuclear power also meets the second requirement, and so contributes to this environmental objective.

Sustainable use of water and protection of marine resources

Nuclear plants, like all thermal power stations, require significant cooling. Nuclear plants in the UK implement direct cooling (sourcing water from estuaries or the sea), rather than relying on cooling towers (used when water is in short supply). This provides several advantages over the use of cooling towers, including increased generation efficiency, reduced complexity, no water consumption, zero noise pollution and visual impact, and no landfill waste upon decommissioning. The downside of direct cooling is the high water abstraction demands, which if unaddressed may have detrimental consequences for marine life in the area. Nuclear plants are comparable to other thermal plants in this regard [39, p. 197], but have additional concerns around radiological emissions.

** Abbreviations used in Figure 1: CCS Carbon (dioxide) Capture and Storage; PC Pulverised Coal; IGCC Integrated Gasification Combined Cycle; SC Supercritical (coal); NGCC Natural Gas Combined Cycle; poly-Si Polycrystalline Silicon; CIGS Copper-Indium-Gallium-Selenide.*

A 2010 report from the Environment Agency included a study on whether direct cooling should still be considered best available practice for cooling large power stations [39, p. v]:

> *"[The study indicates] that direct cooling can be best available technology for estuarine and coastal sites, provided that best practice in planning, design, mitigation and compensation are followed."*

Concerning marine life, planned mitigation measures at the LWRs under construction at Hinkley Point C comprise low velocity side intake heads to reduce risks to fish in the area, and a fish recovery and return system. Predictions by Cefas on the impingement effects from Hinkley Point C with these mitigation strategies stated that [40, Sec. 7.4]:

> *"The analyses presented [for Hinkley Point C] with low velocity side entry intakes and fish recover and return systems fitted demonstrate that for all of the species assessed, which are representative of both the fish assemblage and all of the Habitats Regulations Assessment designated conservation species, that impingement would have a negligible effect."*

Regarding thermal, chemical and radiological pollution, all UK nuclear projects must receive a specific permit for the discharge of cooling water and liquid effluents, and operators are required to demonstrate that impacts of cooling water discharges are minimised [41]. Nuclear energy is strictly regulated at all levels of operation. This is the case for the UK's operating reactors and for Hinkley Point C, and will remain so for the second and third waves of reactor systems.

With all necessary planning, design and mitigation efforts, nuclear energy provides no significant harm to achieving this environmental objective.

Transition to a circular economy

This environmental objective is a challenge for most energy producers to meet, and many that already qualify as 'green' have done so by demonstrating a trajectory towards meeting this criterion at some point in the future, rather than its attainment at present. Four sub-criteria are defined, and nuclear energy is well placed to meet all of these (see Table 1) and, in future, there is the potential to go much further. A previous Dalton Nuclear Institute position paper has explored how, at the macro-level, nuclear sites can be reused or repurposed [10, Fig. 2] and, while current technologies are based on an open fuel cycle, a far more resource-efficient closed fuel cycle is technically possible. The closed fuel cycle is presently uneconomic, but a major expansion of nuclear energy and associated increase in uranium price could render the closed cycle competitive in future decades. Two recent articles [42, 43] review the economic and environmental implications of varying approaches to the nuclear fuel cycle.

Nuclear energy currently provides no significant harm to achieving this environmental objective, and in the future also has the potential to make a substantial contribution.

Table 1. Commentary on four sub-criteria within transition to a circular economy.

Sub-criterion	Comment	Ref
Resource depletion	Extremely favourable; uranium has limited application beyond energy generation and potential for very high utilisation	[34]
Materials recyclability	Favourable; comparable to other low carbon energy sources	[44]
Land use	Extremely favourable; far better land use metrics compared with all other clean energies	[36, Fig. 43]
Waste	Highly regulated, stringent waste management arrangements and strategies in place to minimise waste production through a waste hierarchy approach in place	[44]

Pollution prevention and control

There are significant data available to underpin the fact that nuclear energy production creates minimal pollution compared with other low carbon technologies [34]. In addition, stringent environmental legislation and regulatory requirements exists. Nuclear energy provides no significant harm to meeting this environmental objective, and since it also displaces more polluting alternative sources of dispatchable energy, nuclear energy makes a substantial contribution to achieving this objective.

Protection and restoration of biodiversity and ecosystems

Biodiversity and ecosystems are negatively impacted by human land use. Nuclear energy meets this objective better than most other low carbon producers, mostly because its demand for land is much smaller than most other types of energy production. Figure 2 charts the lifecycle impacts on ecosystems for various energy generation methods, including the effects from climate change. Climate change effects overwhelmingly dominate these figures, and land occupation is the next largest contributor to this metric [36, Fig. 49]. Nuclear energy provides no significant harm to meeting this environmental objective, however by displacing other, more ecologically impactful alternatives, can also be justified as making a substantial contribution to this objective.

Recommendation seven: ***To enable early, cost-competitive financing of nuclear investments, Government should ensure that its developing Green Taxonomy properly reflects the sustainability benefits of nuclear energy and does not exaggerate its drawbacks.***

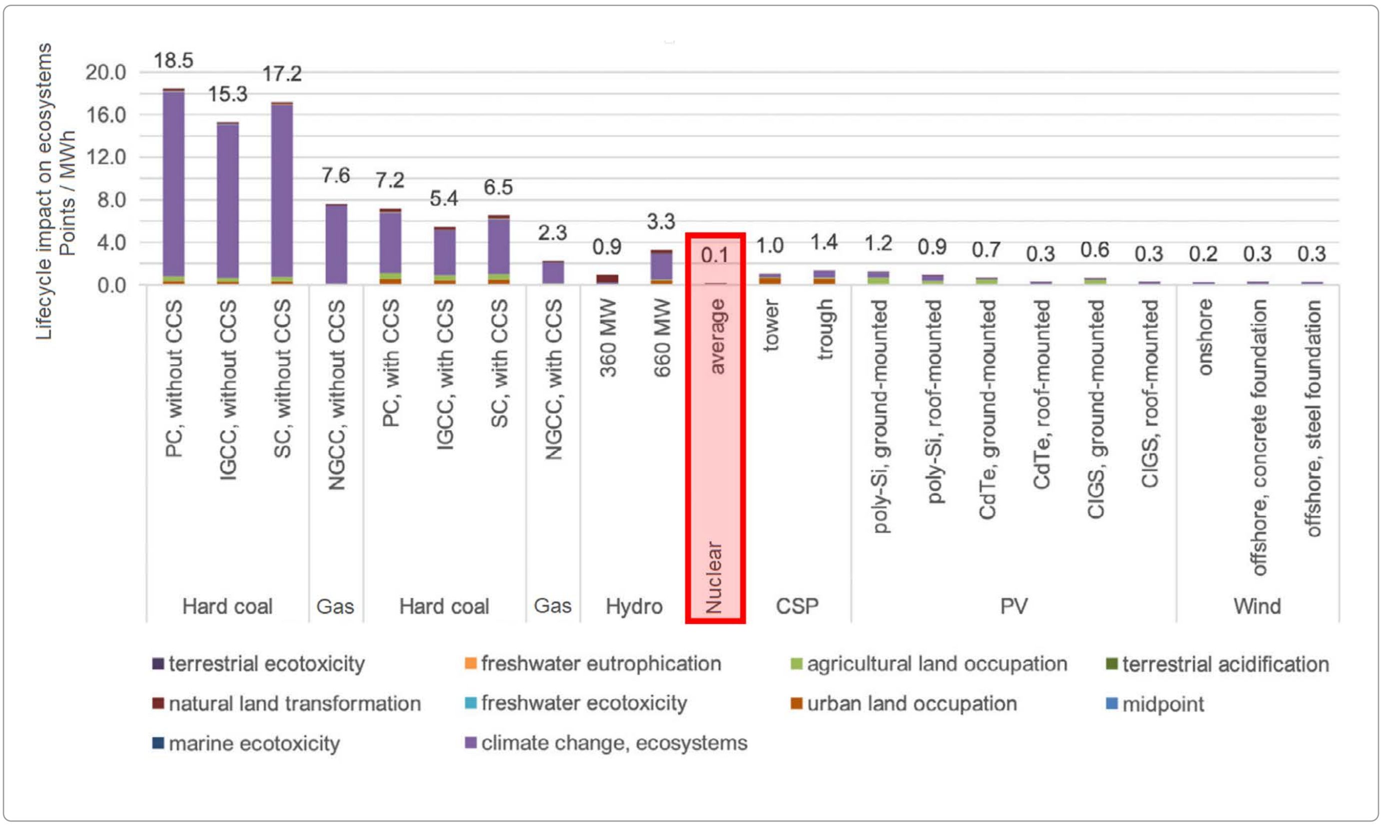

Figure 2. Lifecycle impacts on ecosystems, including climate change, taken from [36, Fig 48]. One "point" is equivalent to the impacts (in species-year) of one person (globally), over one year. For abbreviations, refer to the footnote for Figure 1.

4

Conclusions

The success of the UK's future nuclear sector relies on Government (or, given the long-term nature of the commitments required, successive Governments) making clear, consistent, and courageous decisions to shape and direct it.

This runs contrary to what has been standard practice since the sector's privatisation, which has been to leave things largely to the market to deliver – a strategy which has failed to deliver success in the nuclear sector for well over a decade. Ironically, the potential for Government action to have a positive effect is very clear in the offshore wind sector, where Government support and direction have led to major expansion and substantial cost reductions.

In the past, a nuclear sector that was unable to compete in the short-term with other generation technologies might be left to quietly wind-down. However, it is very difficult to see how national net zero and energy security needs can be met without a successful nuclear sector, so nurturing the sector is in the national interest.

New nuclear systems need not be fully delivered by the state; indeed, it is probably beyond the UK state's capabilities to do so. However, Government facilitation is needed if such a long-term and capital-intensive industry is to deliver what is needed. The essential actions have been presented as recommendations in this paper, but can be boiled down to:

- Clearly communicating the desired role(s) of future nuclear systems.
- Promptly making clear and consistent decisions when they are needed.
- Maintaining commitments for many years into the future.

The Government has endorsed a Three Wave strategy with the intention to deliver LWRs, SMRs and AMRs in succession. While each wave has different specific requirements, the same leadership mindset from Government is needed for all three. Areas most urgently in need of direction from Government include:

- Delivering a successful financing model, which to be effective, needs to inspire confidence from investors.
- Progress to ensure that the necessary regulation is ready and fit-for-purpose in time for new reactors; including ensuring that the necessary site numbers are available for fleet build and new modes of deploying nuclear power.
- Ensuring its upcoming Green Taxonomy offers a level-playing-field to all candidate energy technologies.
- Communicating a clear role for the Third Wave AMRs, to ensure that the early-2030s demonstrator paves the way quickly for a fleet of successor reactors.

The nuclear energy sector has not held as much potential for a generation; however continued action from Government is needed to ensure that this current promise is not wasted because of indecision, lack of clarity, or lack of pace.

5 Recommendations

Recommendation one

Government should develop, and communicate to the market, estimates of the size and utilisation of the potential HTGR fleet, including the power output of reactors envisaged, and the end use of the heat output.

Recommendation two

Clear decisions should be made by Government, for example in Government-led competitions, to provide certainty to the market. While this will create winners and losers, Government should be clear, consistent, and courageous in its decision making.

Recommendation three

Government should make a clear, decades-long commitment to support advanced nuclear systems.

Recommendation four

Nuclear programmes must move at the pace required to meet the 2050 net zero deadline, and Government processes need to be able to keep up.

Recommendation five

Developers should make efforts to engage early with regulators, to finalise a mature design and to establish a clear plan for the development of a site licence holding entity. This should cover the whole span from reactor building, to decommissioning, and vacation of the site.

Recommendation six

Fleet build of SMRs and HTGRs, combined with modular construction, are essential to achieve acceptable economics for these reactors. Competitions must be for quanta of work that are sufficiently large to justify investment by developers and sufficiently infrequent that they do not add significant delay to the programme.

Recommendation seven

To enable early, cost-competitive financing of nuclear investments, Government should ensure that its developing Green Taxonomy properly reflects the sustainability benefits of nuclear energy and does not exaggerate its drawbacks.

Appendix: Views on Relevant Publications

2022 is probably the first time in decades that there is a discernible UK Government strategy on nuclear energy. This has been built up by a succession of advisory and policy publications which have combined to form a reasonably coherent policy across three technology types with several roles to contribute to the decarbonisation of UK society.

The last two years have seen a wealth of publications which have defined the possible roles of nuclear energy in the UK in the context of net zero by 2050. Clearly, plotting the path taken, its significance, and strengths and weaknesses are subject to interpretation of the contents and implications of the various publications (both advisory and Government policy) of this period.

This appendix gives a summary of the points made in the evolution towards the current position on nuclear energy, and these points and their interpretation help form the information base on which this document is constructed. The sections below review the published steps in the UK's journey towards a major contribution from nuclear high temperature heat in the UK's programme of decarbonisation towards net zero by 2050, and gives the Dalton Nuclear Institute's interpretation of the current position, and what this reveals about the necessary roles required from Government to turn strategy into reality.

Achieving Net Zero: The Role of Nuclear Energy in Decarbonisation

NIRAB, April 2020 [6]

This NIRAB publication was the culmination of the second incarnation of the board, and was generally well received. The document envisaged a continuation of the existing Gigawatt-scale LWR programme, followed by a fleet of Small Modular Reactors (SMRs) and a fleet of Advanced Modular Reactors (AMRs).

There was a firm recommendation for fleet build of a single reactor design, as indicated below [6, p. 21]:

> *"For this to be at the lowest cost they should, as far as possible, be the same design in order to maximise cost reduction opportunities including, where possible, factory build. Repeat build of a fleet of the same design should also maximise opportunities for the UK supply chain. Deploying several First of a Kind reactors in the UK will not result in the lowest price for consumers…Many studies have shown reductions in cost from fleet rather than individual reactor build."*

And on the need for demonstration [6, p. 29]:

> *"NIRAB believes that AMRs can make a significant contribution to meeting the UK's net zero target by 2050. This will require commercial plant to be deployed by 2040. To meet this timescale, it is most likely that the science of the selected technology will have already been demonstrated and be at a mid-level technology readiness. This then needs to be progressed to an engineering demonstration of the proposed design in the period 2030 to 2035 as a precursor to full commercialisation."*

The recommendations from this publication were couched against the HTGR being viewed as the reference system.

Recommendations

Recommendation one: Government should, in partnership with industry, deploy a Small Modular Reactor fleet, with the first commercial operating reactor by 2030.

Recommendation two: Government should enable nuclear contribution to wider energy decarbonisation, by:

- Developing a more detailed technical and commercial understanding of the role that advanced reactors can play in an evolving market for competitive low-cost heat, hydrogen and synthetic fuels;
- Investing in the development of reactor systems that give access to more efficient high temperature outputs.

This should be supported with the development of hydrogen and synthetic fuel generation systems (utilising the high temperature heat reactor output), and advanced manufacturing methods of fuels for such reactors.

Recommendation three: Government should enable an Advanced Modular Reactor demonstrator in the period 2030 to 2035. An appropriate down selection should be completed as soon as possible, against a baseline of High Temperature Gas Reactors.

Recommendation four: Publicly funded UK nuclear innovation activities should be shaped by the strategic goal of cost-effective deployment of advanced nuclear technology, supporting a decarbonised energy system, in time to make a significant contribution to decarbonisation by 2050.

Recommendation six: Government should ensure best value for money and increased impact of nuclear on net zero by facilitating integration of investment and delivery between the UK fission and fusion programmes.

The recommended public investment, for the 5-year period starting in April 2021, is £400M for research and development and £600M for demonstration, exclusive of any potential investment in a UK SMR.

The Ten Point Plan for a Green Industrial Revolution

HM Government, November 2020 [16]

Point 3 concerns the delivery of new and advanced nuclear power [16, p. 12]:

> *"We are also committing up to £170 million for a research and development programme on Advanced Modular Reactors. These reactors could operate at over 800°C and the 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. Our aim is to build a demonstrator by the early 2030s at the latest to prove the potential of this technology and put the UK at the cutting edge against international competitors."*

As presented, AMRs are clearly HTGRs – and have links with the production of synthetic fuels and hydrogen. SMRs and AMRs are independent from each other.

Energy White Paper: Powering our Net Zero Future

HM Government, December 2020 [45]

On advanced nuclear innovation [45, p. 51]:

> *"We are also committing up to £170 million of the Advanced Nuclear Fund to a R&D programme on AMRs – the next generation of nuclear technologies. Our aim is to build a demonstrator by the early 2030s at the latest to prove the potential of this technology."*

However on hydrogen [45, p. 11]:

> *"We will generate new clean power with offshore wind farms, nuclear plants and by investing in new hydrogen technologies."*

And [45, p. 128]:

> *"A variety of production technologies will be required to satisfy the level of anticipated demand for clean hydrogen in 2050. This is likely to include methane reformation with CCUS, biomass gasification with CCUS and electrolytic hydrogen using renewable or nuclear generated electricity."*

This is the only mention of nuclear with respect to hydrogen production, and it specifically states utilisation of nuclear generated electricity. There is no mention of hydrogen being produced from high temperature nuclear.

Industrial Decarbonisation Strategy

HM Government, March 2021 [46]

Addressing how to accelerate innovation of low carbon technologies [46, p. 68]:

> *"In the near term, the Net Zero Innovation Portfolio will continue to build on the UK's leadership role and existing projects in the deployment of CCUS, hydrogen and nuclear advanced modular reactor technologies, with dedicated workstreams furthering production, supply and use, feasibility and safety."*

Specifically on AMRs [46, p. 73]:

> *"We are investing up to £170 million in an ambitious programme of R&D with the aim of an operational AMR demonstrator in the early 2030s. Some designs have the potential to produce high-quality, high-temperature heat up to 950°C which could significantly extend the opportunity for industrial heat use."*

Nuclear Energy for Net Zero: A Strategy for Action

Dalton Nuclear Institute, June 2021 [17]

This June 2021 paper from the Dalton Nuclear Institute of The University of Manchester received a good reception and has been referred to in several influential meetings and documents. There was certainly no concerted comeback which questioned whether the recommendations were fit for purpose. It is instructive to examine the current situation on the paper's eight recommendations.

Recommendations

Recommendation one: The state of development of UK and world AMR technology affirms that the demonstration reactor mentioned in the energy white paper should feature HTGR technology, with major consideration also paid to demonstrating hydrogen generation using nuclear heat.

The first part of this recommendation seems to be being pursued, with current AMR activity firmly favouring the HTGR. There is little evidence however of consistent attention being given to hydrogen generation using nuclear heat.

Recommendation two: The task of specifying, developing and pursuing the path to a UK-based HTGR demonstrator should be given to a suitable body that is equipped and empowered to deliver the HTGR project. This would include directing all R&D necessary to define an optimum route, monitoring whether and how these optima change as studies progress, and re-optimising programmes accordingly.

Apart from the mention of a Great British Nuclear (with a currently undefined role), there seem to have been no moves towards centralised direction of UK HTGR R&D.

Recommendation three: R&D into closed fuel cycles should be continued to allow the UK to track developments in these systems and to gauge whether, or when, such systems will find a place in the UK energy market.

The response to this will unfold as future R&D programmes are defined, with success being defined as a system that keeps the UK sufficiently aware of global trends to avoid being surprised by developments.

Recommendation four: An ongoing UK view of the developments in AMR systems should be maintained and led by a body unconflicted by claims and lobbying by any particular system proposer. The Generic Feasibility Assessment has provided an example of a platform that could host this task, but a suitably 'interest-free' organisation would need to be set up with exemplary peer review.

This recommendation has not been addressed.

Recommendation five: A suitable broadly-based advisory body should be engaged to offer advice to Government on the forward nuclear programme. This could be NIRAB, or a successor, but NIRAB would appear to have established the possible extent and value of such advice.

NIRAB would appear to be best fitted to this role, though the test will be whether any of the advice already submitted will be acted upon.

Recommendation six: The Climate Change Committee should explore, with suitable assistance, the possibilities of a wider role for nuclear in the net zero path.

There is no obvious sign that the CCC's narrow view of nuclear energy is being modified.

Recommendation seven: The Energy Systems Catapult should, with assistance from other modelling expertise, set up and run transparent level playing field models to monitor economic developments. This will motivate improvements and detect unrealistic optimism.

No obvious progress in this area.

Recommendation eight: A platform such as that recommended for nuclear energy in recommendation four should be established for all energy sources present in the net zero path, to give a clear and unbiased view of the current status of net zero.

No movement in this area.

Net Zero Strategy: Build Back Greener

HM Government, October 2021 [47]

On hydrogen production [47, p. 115]:

> *"Alongside the scale of production that CCUS-enabled methane reformation or 'blue' hydrogen can bring, our renewables can support the growth of electrolytic or 'green' hydrogen, bringing down costs and increasing production capacity whilst new production technologies such as hydrogen from nuclear and biomass are developed. Supporting a variety of different production methods will enable us to develop low carbon hydrogen rapidly at scale during the 2020s and 2030s to deliver what is needed for CB6 and net zero."*

Almost all mention nuclear concerns large scale nuclear; there is virtually nothing on HTGRs.

AMR RD&D Programme: Indicative Programme Outline

BEIS, February 2022 [3]

This document aimed to [3, p. 4]:

> *"Inform stakeholders with an interest in the development of HTGRs including materials, fuels, supply chain, manufacturing & construction processes, innovation in the nuclear sector more generally, and potential end-users of high-temperature heat. This information aims to gather feedback from the Sector ahead of a formal Invitation To Tender (ITT) for Phase A of the Programme which is anticipated for launch in Spring 2022"*

The programme overview was described thus [3, p. 5]:

> *"In December 2021, following underpinning analysis and a Call for Evidence, the technology focus for the Programme was confirmed as High Temperature Gas Reactor (HTGR) technology. As a result, going forward the Programme will focus on HTGR technology with the ambition for this to lead to a HTGR demonstration by the early 2030s.*
>
> *The aim of the Programme is to demonstrate that HTGRs can produce high temperature heat which could be used for low-carbon hydrogen production, process heat for industrial and domestic use and cost-competitive electricity generation, in time for any potential commercial AMRs to support Net Zero by 2050.*
>
> *Certain HTGR designs have been demonstrated which highlight the early stages of technology feasibility. BEIS would like the sector to demonstrate a HTGR, to be sited in the UK, which has innovation at the centre of its design, build and application– with the ambition for this to result in the most cost-effective solution shaped by end-user requirements and delivered by the early 2030s."*

The key subsequent development was an introductory session, hosted by BEIS on 29th April 2022 which had a wide enough attendance for the information given to be included in this review:

AMR RD&D Programme

This programme:

- Is built upon the Advanced Modular Reactor (AMR) Feasibility and Development (F&D) Project [48], but is not a follow on from it.
- Aims to increase confidence and reducing risk.
- Focuses on innovation and demonstration throughout.

Heat end user requirements were described as being "highly diverse", and attendees were assured that this was their "chance to drive the programme scope".

Objectives are to:

- Decide what to demonstrate.
- Identify and develop ancillary technologies.
- Demonstrate heat extraction from an HTGR.
- Develop the UK's supply chain, skills and intellectual property.

The competition opened with a submission deadline of 1 June, contract start 11 July, Early Summary Report 3 November, and final report 13 January.

This means that the demonstrator specification cannot be known until at least November 2022, perhaps January 2023. The only programme guidance will be the information from the four projects, so if these have a large span of reactor capacities, anything to do with the number of reactors and/or number of sites will be uncertain. In short, it will only take the inclusion of one micro-reactor to provide uncertainly.

Siting Implications of Nuclear Energy: A Path to Net Zero

Dalton Nuclear Institute, March 2022 [10]

This paper was published after the AMR RD&D Programme: Indicative Programme Outline [3], but before the hosted introductory session.

This paper concentrates on the methods of achieving an optimum siting programme for the Third Wave of reactors of the UK nuclear energy programme (i.e. HTGRs). It starts from the premise that this will be a co-ordinated national programme, and notes that [10, p. 4]:

> *"At present, there is little overall vision of how the Three Waves might interact in time and in the energy market. There is a need for a framework which identifies the range of possible programmes and ensures that a 'cradle to grave – and beyond' approach is considered and modelled.*

Recommendation one: The UK Government should develop an integrated framework for delivery of nuclear energy in the UK to ensure the whole lifecycle is understood."

It is the absence of progress in (or indeed acceptance of the need for) an integrated framework which raises questions on the ability of Government programmes to fully meet intended Government policy.

British Energy Security Strategy

HM Government, April 2022 [1]

In the area of nuclear energy, this publication concentrates on future LWR reactors and SMRs, and gives a commitment to [1, p. 21]:

> *"Increasing our plans for deployment of civil nuclear to up to 24 GW by 2050 – three times more than now and representing up to 25% of our projected electricity demand.*
>
> *Within this overall ambition, we intend to take one project to FID this Parliament and two projects to FID in the next Parliament, including Small Modular Reactors, subject to value for money and relevant approvals. This is not a cap on ambition, but a challenge to the industry to come forward and compete for projects and aim to come online this decade.*
>
> *Depending on the pipeline of projects, these ambitions could see our nuclear sector progressing up to 8 more reactors across the next series of projects, so we improve our track record to deliver the equivalent of one reactor a year, rather than one a decade."*

This makes it clear that the 24 GW (presumably 24 GWe) is conditional on all proceeding according to plan, and also includes GW-sized LWRs and SMR. There is no mention of AMRs being included in this total. The 'eight reactors' discussed is not consistent with the 24 GW total (for example, eight EPRs gives a maximum output ~13 GWe). Overall it is not at all clear how the 24 GW was determined. It is presumed that the 'next series of projects' is for a period considerably earlier than 2050.

There is a commitment to setting up Great British Nuclear (GBN) in 2022 [1, p. 21]:

> *"…[which will be] tasked with helping projects through every stage of the development process and developing a resilient pipeline of new builds. We will work with industry to scope the functions of this entity starting straightaway – building on UK industrial strengths and expertise."*

Attention to the HTGRs/AMRs is limited to [1, p. 21]:

> *"We will also collaborate with other countries to accelerate work on advanced nuclear technologies, including both Small Modular Reactors and Advanced Modular Reactors."*

The treatment of hydrogen in the paper is somewhat imprecise, stating that [1, p. 22]:

> *"Hydrogen can be produced in many different ways. Sometimes colours are used to describe this process.*
>
> - *Blue hydrogen splits natural gas into hydrogen and carbon dioxide, with the carbon captured and stored.*
> - *Green hydrogen uses electrolysis, passing electricity through water to separate out the hydrogen and oxygen.*
> - *Pink hydrogen also uses electrolysis, but with energy from a nuclear power plant."*

Note that hydrogen from electrolysis using nuclear electricity (thermochemical generation of hydrogen is not mentioned) is termed 'Pink', while 'Green' hydrogen can use any other source of generation including, presumably, coal without CCUS. This is clearly not intended, and a clear definition is needed before this commitment is enacted [1, p. 23]:

> *"We will offer clear long-term signals alongside immediate support by…levelling the playing field by setting up a hydrogen certification scheme by 2025, to demonstrate high-grade British hydrogen for export and ensure any imported hydrogen meets the same high standards that UK companies expect."*

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