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Nuclear energy for net zero: **a strategy for action**

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Foreword

The UK's target of net zero by 2050 is extremely ambitious and we should all be careful not to underestimate the scale of the effort required in order to achieve it.

While encouraging steps have been taken to reduce reliance on fossil fuels in our electricity generation, natural gas still makes up the largest proportion, and moving to a future electricity grid with heavy reliance on intermittent renewables has its own challenges. To compound matters further, our existing nuclear reactors, a large chunk of our low-carbon generation, are due to be retired in the coming decade. This is still only part of the story. Beyond electricity, decarbonising other energy sectors such as transport, heating and industry, which represent by far the majority of UK energy consumption, will prove even harder and require diverse solutions to their differing challenges.

In such a landscape, it makes sense that the government has announced that new nuclear could have a vital role to play in achieving net zero. If this potential is to be realised however, there is much for the nuclear sector to do in the next three decades and important decisions lie ahead for policymakers. Many questions need to be answered: what needs to be done in order to deliver a safe, economic nuclear sector by 2050? How best to utilise the potential of nuclear: be it through providing process heat, electricity or hydrogen? What potential international collaborations are available? What sort of fuel cycle and supply chain should we realistically expect in the UK by 2050?

We must also acknowledge that time is short. The nuclear sector has historically been unable to move quickly. To make a difference to the 2050 target, any new reactor technology must be developed, demonstrated, licensed and built by the 2040s. This means that technology development must begin now and that the more exotic technology options will not be feasible on the timescale required. We are already on the critical path and we need to ensure that there is the leadership, consistency and commitment required to make a success of the endeavour before the opportunity is lost, which will happen in just a couple of years.

For these reasons, The University of Manchester's Dalton Nuclear Institute produced this report. It seeks to address aspects of the national discussion on nuclear energy which are currently underdeveloped, and provides a series of recommendations which we believe will support the nuclear sector in achieving its best potential.

Professor Francis Livens
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Executive summary

This paper sets out to examine the possible roles for nuclear energy in a 'level playing field' approach to net zero by 2050, making use of the various mechanisms on an overall best economics basis, with an objective, well-developed economic assessment system.

It is therefore essential that the potential roles for nuclear energy are set out and assessed clearly, recognising that they will not be adopted unless they are part of an optimum solution. It is also essential that similarly objective assessment mechanisms are applied to alternative decarbonisation options.

The roles of nuclear energy to provide firm power, district heating and high temperature heat are discussed. The various estimates which have been made of nuclear's role in meeting net zero by 2050 are examined, revealing a broad range of assumptions, which are mainly limited to the provision of firm power. In particular, few studies examine high temperature nuclear heat for hydrogen production or other uses in industrial processes. The energy white paper envisages a demonstration of high temperature nuclear heat in the UK, and the review of this area concludes (in agreement with the recommendation from the Nuclear Innovation and Research Advisory Board; NIRAB) that the High Temperature Gas-cooled Reactor (HTGR) should be the key technology, with rapid assessment and development of hydrogen manufacturing techniques also required. Such a demonstrator could match a 2030 timescale, but is already on the critical path, so rapid progress is required.

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.

Possible paths to an HTGR/hydrogen demonstrator are examined, with the key conclusion that a suitable body should urgently be set up to pursue this course, with valid parallels identified to the model currently being employed for progressing a fusion power demonstrator.

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.

The HTGR generally uses a once-through fuel cycle, for which existing uranium resources should prove adequate for at least the rest of the century. However, future developments could render closed cycles economic, and could transform the UK's current depleted uranium and spent fuel stocks into a valuable resource capable of providing the UK's energy for almost 1,000 years. Within this context, the UK should keep open the option of developing a closed fuel cycle and should remain at the forefront of R&D in this area to track future developments. This work will also provide the essential knowledge to assess proposals from reactor/fuel cycle vendors.

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.

Following this, the UK will need a viable system for assessing potential future systems, especially as many current closed-cycle proposals by private sector reactor vendors involve many of the fuel cycle/waste elements being assumed as 'obviously achievable' – often without much evidence.

***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.**

The siting of reactors and fuel cycle plants will also be important, especially with proposals to site SMRs close to population centres, high-temperature heat reactors adjacent to hydrogen manufacturing plants or other chemical users, and proposals such as the 'Gigafactory' with very high thermal capacity on a single site.

The current UK position on HTGR development points conclusively to the need for international teaming if an HTGR demonstration reactor is to operate by 2030 in the UK. The various international programmes in the HTGR field are reviewed, and recommendations to government in this area would be an urgent task for the body recommended to be set up in recommendation two.

Such significant steps must signal the need for the government to access informed and objective advice on the status of AMRs. A recent exemplar has been NIRAB, whose recommendations clearly informed the government's approach to the energy white paper.

***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.**

The level of transparency inferred by recommendation four points to the need for organisation within government to provide a platform for the properties and possibilities of all contributing vectors, and methods of weighting them to be discussed, if not agreed upon. It should be possible for bodies making major assessments of net zero futures to examine a range of nuclear possibilities and how these might underlay government policy as exemplified in the energy white paper. At present, the Climate Change Committee envisages a much more limited role for nuclear and it might be appropriate for such an important advisory body to undertake a wider examination of the subject.

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

As inferred by earlier recommendations, the level playing field to net zero 2050 envisaged by this report requires an objective assessment of progress and possibilities. Crucially, this requires non-partisan modelling of the economic path being plotted and the consequences of different approaches. The UK's expertise in such modelling is certainly adequate and could become crucial in plotting the path to net zero by 2050. Much of the modelling examined has been by the Energy Systems Catapult, though there are other centres of expertise.

***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.**

These modelling assessments must include all energy vectors and holistic solutions. For nuclear at least, there is a need for a better method to assess, or examine the assessments of the economics of various systems, as there are many examples of proposed systems which produce 'the right answer' in terms of electricity or hydrogen cost, but often offer little supporting evidence.

Much of the range of opinions on nuclear energy is driven by differing value-sets between environmental and socio-economic views of the world – with a spectrum of views on the magnitude, likelihood and importance of a benefit or disbenefit. Fortunately, there is evidence that groups of stakeholders can, given time and expert mediation, reach agreement on the facts, while remaining at variance on the importance to be attributed to those facts. This does, however, require an open and peer-reviewed assessment of the benefits and disbenefits of any system, be it: the radiation doses from nuclear energy; the carbon intensity of Carbon Capture and Storage; or the resource needs of batteries or solar power.

***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.**

The examination of sustainability reveals a variety of assessment methodologies, many of which are not easy to explain outside of highly specialist fora. These complexities are discussed, and the lack of an agreed balancing methodology permeates this and other sections of the report.

The great reason for optimism is that the government has embarked on a 30-year action plan, which will require a steady, long-term path, and this paper outlines the attributes of such a path for the contribution from nuclear energy. The action plan needs to be based on credible and verifiable assessments of all its component parts, and there is the need for openness to be achieved, while allowing a sensible role for commercial competition. Many of the current decarbonisation vectors, including nuclear in some quarters, sell themselves as 'miracle cures' of various sorts. A key need at the beginning of the action plan must therefore be to find a mechanism to achieve credible and verifiable assessments, without discouraging or discrediting successful innovation.

Overall, the key message of this study is that it seeks the implementation of nuclear energy where appropriate and advantageous, but examines ways to avoid being side-lined by unsupported hyperbole. It is to be hoped that the 'best for the UK, best for the planet' message can be turned into reality. Regarding timescales, the present situation is crucial, with any delays immediately manifesting themselves on the critical path for a nuclear demonstrator by 2030, and by inference the strong prospect of negatively impacting the 2050 deadline.

1

Introduction

After decades in the doldrums, and with a new build programme currently confined to a single site, the net zero by 2050 policy [1] has reignited interest in nuclear power, and nuclear energy more generally, as the only proven, dispatchable, low-carbon energy source*.

This paper aims to give a broad background to the ways in which nuclear energy could help to make net zero by 2050 possible, in the context of overall UK energy usage. It also outlines the actions that need to be taken to ensure that nuclear energy, if it can be produced economically in the right quantities and on the right timescale, takes an appropriate place in a prosperous net zero UK.

This paper was compiled during a period of considerable development of government policy, and in parallel with publication of numerous studies relating to the UK's path to net zero greenhouse gas emissions by 2050. It has set out to consider the data and policy decisions available up to and including the government's announcement on 20 April 2021 of cutting emissions by 78% by 2035 compared to 1990 levels.

** Though gas with efficient Carbon Capture, Utilisation and Storage (CCUS) is presumed to be capable of near-zero-carbon.*

2

Net zero by 2050

2.1 The level playing field challenge

There seems to be a good consensus that the net zero by 2050 target will, if interpreted honestly, be extremely stretching – demanding a co-ordinated effort across the whole field of energy generation and usage in the UK. This commitment was emphasised by the government announcement on 20 April 2021 of a target of 78% reduction carbon dioxide (CO_2) emissions by 2035, in line with the Climate Change Committee's (CCC) *Sixth Carbon Budget* [2]. The target emphasises that the carbon reduction programme must incorporate the various mechanisms on an overall best economics basis, and an objective, well-developed economic assessment system is a pre-requisite for success.

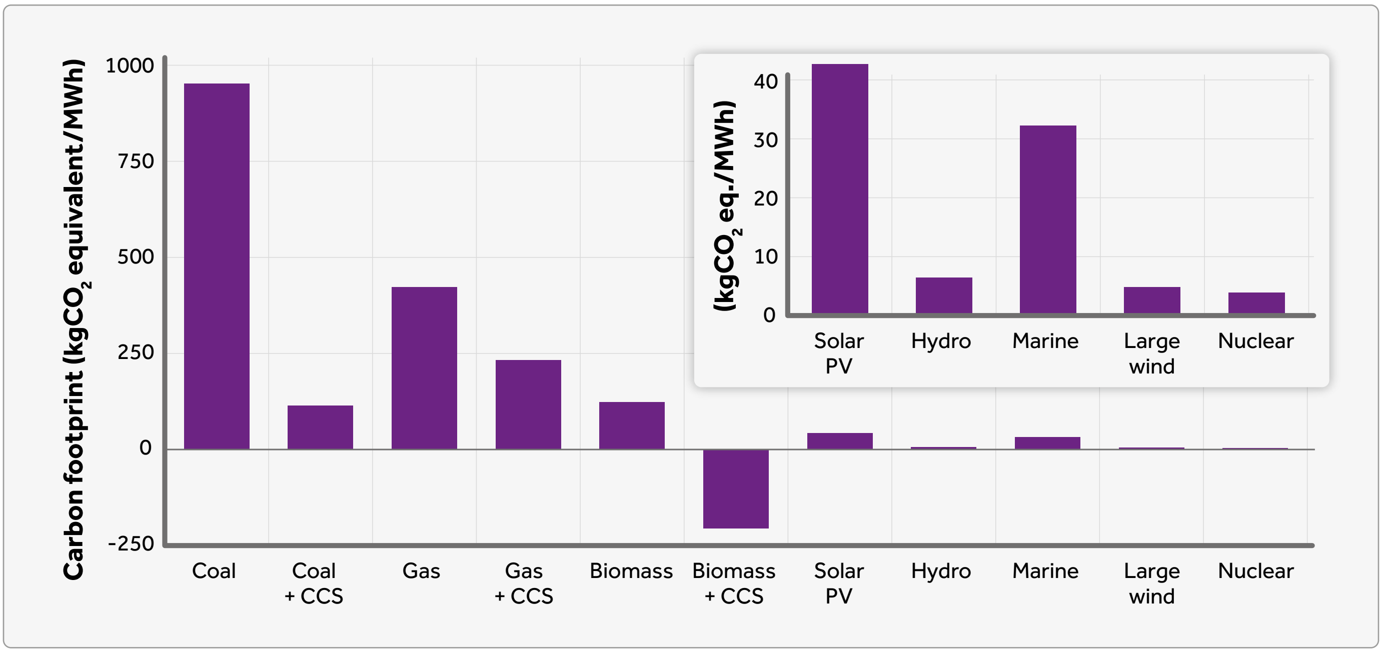
It is essential that the roles for nuclear energy are set out and assessed clearly, with the acknowledgement that they will not be adopted unless they are part of an optimised solution. It is also essential that similarly objective assessment mechanisms are applied to all decarbonisation options. This paper is placed firmly within this 'best overall' framework, building on the key evaluation programmes such as the Energy Systems Modelling Environment (ESME) planning capability [3, p. 12] from the Energy Systems Catapult (ESC), which works by finding minimum cost solutions across the whole energy system. If the most economic nuclear system does not figure in the best overall programme, then nuclear energy has simply priced itself out of at least that part of the market.

This 'all hands to the pumps' approach also means that the adoption of 'low-but-significant-carbon' energy sources could significantly increase the need for measures such as Direct Air Capture (DAC) [4], which would need to be assessed in the overall decarbonisation economics. A typical illustration of this is the use of natural gas with Carbon Capture, Utilisation and Storage (CCUS)*, which, depending on the efficiency of the CCUS, can be either very low carbon or merely 'lower' carbon. This can be illustrated from the unabated CO_2 yields given in Figure 1.

This gives unabated gas emissions in the UK and Europe as around 425 gCO_2/kWh. Simplistically this would put the emissions for the 90% to 99% CCUS efficiencies variously quoted at between 42.5 and 4.25 gCO_2/kWh†. The emissions from gas with CCUS can vary with capture efficiency between 'about the same as nuclear' and 'ten times that of nuclear'; updated figures on capture and storage efficiency will therefore be crucial to the tracking of net zero.

This approach of rigorously updating information on all aspects of decarbonisation is key to any realistic attempt at achieving net zero, and the attainment of a level playing field (see §5), with sober analysis replacing 'point-scoring' between proponents of different technologies across the whole energy appraisal system. This also applies to nuclear, where changes in available uranium resources and usage could change the effective emissions, though such variations would be expected to be small.

Figure 1. Carbon footprint of low-carbon electricity generation technologies (UK and Europe) [5].



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* *The International Energy Agency (IEA) defines CCUS as a suite of technologies that involves the capture of CO_2, which is compressed and transported to be used in a range of applications, or injected into deep geological formations for permanent storage [77, p. 19]. CCUS is often referred to as 'CCS', minus the 'utilisation' consideration.*

† *Although this does not account for the emissions from the natural gas production, transport and processing, power production and the capture and storage processes.*

3

Roles for nuclear energy in the UK

3.1 Firm power

Until recently, most recognised national level modelling studies of UK energy scenarios treated nuclear (if it was considered at all) solely as a provider of baseload electricity[*], and some major current studies maintain this view. The forward Light Water Reactor (LWR) programme is highly uncertain, with only Hinkley Point C station reasonably assured (Unit 1 expected in 2026). The Department for Business, Energy and Industrial Strategy (BEIS) provide potential deployment mixes in their Modelling 2050 report, stating that [6, p. 16]:

> ***'For example, to deliver a carbon intensity at or below 5 gCO_2/kWh at higher demand, combinations comprising 20 to 40 GW of nuclear and 15 to 30 GW of gas CCUS (at least 50 GW in total) are needed to provide low-cost solutions over all technology cost scenarios.'***

In October 2018, the Energy Technologies Institute (ETI) updated their *Options, Choices, Actions* study [3] and examined a range of firm nuclear power up to 35 GWe, though this was presumed to be constrained by the sites presumed to be suitable for GWe-scale Gen III+ LWRs. The ETI also examined higher capacities [7] to 40 GWe, with an 'exceptional extreme scenario' of 75 GWe. Later, the ESC produced *Innovating to Net Zero* [8] which gave a nuclear generation capacity of 33.2 GWe (at 90% capacity factor) for their 'clockwork' scenario, reducing to 20.4 GWe for the 'patchwork' case; and followed it with *Nuclear for Net Zero* [9] which examined scenarios resulting in up to 35 GWe of Gen III+, 22 GWe of SMRs, and 22 GWe of cogeneration Gen IV reactors.

By contrast, the *Sixth Carbon Budget* [2] from the CCC has only 5 or 10 GWe of nuclear across different scenarios and studies such as those by the Offshore Renewable Energy Catapult [10] and the Oil and Gas Technology Centre (OGTC) ignore new nuclear capacity, commenting only that [11, p. 64]:

> ***'Nuclear will also account for a decreasing proportion of the energy mix as old reactors are decommissioned.'***

The National Grid [12] describes scenarios between 34 and 101 TWh/a of nuclear generation – equivalent to 4.4-12.8 GWe at 90% capacity factor – but has no reference to nuclear heat.

Another input is from the National Infrastructure Commission (NIC) which, in their July 2018 National Infrastructure Assessment, only considered GWe-sized nuclear, and recommended that [13, p. 42]:

> ***'Government should not agree support for more than one nuclear power station, beyond Hinkley Point C, before 2025.'***

It also recommended that [13, p. 39]:

> ***'...the Commission is recommending a 'one by one' approach to new nuclear plants, as opposed to the current government policy to develop a large fleet. This is preferable to a 'stop start' approach, in which the nuclear programme is cancelled only to be restarted at a later date. It will allow the UK to maintain, but not expand, a skills base and supply chain. This allows the UK to pursue a high renewables mix, which is most likely to be the preferred option, without closing off the nuclear alternative.'***

This appears to ignore the economic effects of a programme which does not attain the economies of fleet build, but instead turns towards a succession of 'First-of-a-Kind' (FOAK) projects, which are inevitably far more expensive than would be the case if they were followed by similar 'Nth-of-a-Kind' (NOAK) successors. The Treasury response to the NIC's report [14] mentioned the higher levels of electricity generation envisaged after the shift to net zero by 2050, and referred to the then-forthcoming energy white paper [15]. The more recent National Infrastructure Strategy [16, p. 52] however is more positive, mentioning support for small modular and advanced modular reactors, though nuclear is not mentioned in the context of hydrogen production.

Notably, of the studies referenced, only the *Nuclear for Net Zero* [9] report included the use of high temperature nuclear heat from Advanced Modular Reactors (AMRs) for generating hydrogen – in the rest, the nuclear range of 5 to 40 (or 75) GWe is wholly made up of electricity generation, with the bulk of the electricity presumed to come from a mixture of GWe-sized Gen III+ LWRs and smaller, modular versions of LWRs (SMRs)[†]. This narrow use of nuclear has been superseded by the wider nuclear role envisaged in the recent *Ten Point Plan* [17] and energy white paper [15]. The main LWR UK nuclear capacity assumptions from the studies mentioned are summarised in Table 1.

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[*] *Baseload' refers to the minimum level of demand on an electrical grid, traditionally provided by nuclear generation because of its economic benefits from continuous operation. In the future, a system with large amounts of intermittent renewable generation will put a greater reliance on 'firm' power (i.e. reliable, dispatchable power)* [78, p. 2] *to support periods of low renewable supply. Firm, low-carbon generation is therefore highly desirable* [79].

[†] *It should be noted that there are differences between the UK (BEIS) and international usages of terms such as 'SMR' and 'AMR'. This is explained in* §4.1.

Table 1. LWR electricity generation capacity assumptions in referenced UK studies [2, 6, 8, 9].

Model	Installed capacity range in 2050 (GW)		Modelling tool	Energy vectors with nuclear included in energy modelling scenarios		
	Min	Max		Power	District heat	Hydrogen
BEIS Modelling 2050	5	40	UKTIMES (UCL)	Yes	Not in modelling numbers, but role recognised	Not recognised here, but roles in H_2 by electrolysis and AMR heat recognised in the white paper
CCC Sixth Carbon Budget	5	10	(BEIS) Dynamic Dispatch Model (DDM)	Yes	**No**	Not in modelling numbers, but electrolysis role recognised
ESC Innovating to Net Zero	15	35	ESC ESME	Yes	Not in modelling numbers, but role recognised	Not in modelling numbers, but electrolysis and heat roles recognised
ESC Nuclear for Net Zero	10	55+	ESC ESME	Yes	Yes	Yes

Model	Installed capacity range in 2050 (GW)		Modelling tool	Energy vectors with nuclear included in energy modelling scenarios		
	Min	Max		LWR	SMR	AMR
BEIS Modelling 2050	5	40	UKTIMES (UCL)	Yes	Not in modelling numbers, but role recognised	Not in modelling numbers, but electrolysis and heat roles recognised in the white paper
CCC Sixth Carbon Budget	5	10	(BEIS) Dynamic Dispatch Model (DDM)	Yes	**No**	**No**
ESC Innovating to Net Zero	15	35	ESC ESME	Yes	Not in modelling numbers, but role recognised	Not in modelling numbers, but electrolysis and heat roles recognised
ESC Nuclear for Net Zero	10	55+	ESC ESME	Yes	Yes	Yes

In these programmes, the technical aspects of LWR fuel provision are well known, but the Hinkley Point C first core and several reloads are already contracted to Orano in France. For the UK, a prime 'energy independence' preoccupation must surely be to preserve an indigenous fuel manufacturing capability with the fuel manufacture for any subsequent LWRs at Springfields in Lancashire. Similarly, there must be a driver to keep the URENCO enrichment capacity at Capenhurst in Cheshire* operational.

There will be a need for utilities to fund, and the UK to provide, long-term spent fuel storage and provision for eventual disposal (though such a decision has very important sustainability implications; see §5.4) together with reactor decommissioning and waste disposal.

3.2 District heating

All nuclear reactors produce heat which is not used in electricity production and which must be removed from the system, usually as hot water, and dispersed into the environment via cooling water into lakes, rivers or the sea, or via cooling towers into the atmosphere. For decades, some localities have utilised waste heat from nuclear power plants as 'district heating' – the provision of heat for site buildings and/or local neighbourhoods via dedicated hot water networks. Leurent et al. [18] studied 18 locations utilising nuclear heat recovery to district heating systems, among which four are in EU countries (Bulgaria, Czech Republic, Slovakia and Hungary). In addition to examining the 'local siting', the paper analyses the key factors in the economics

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* *This capability is even more necessary for reactors such as high temperature gas-cooled reactors using higher assay fuel.*

of district heating by nuclear energy, which include the cost of the network and the proportion of the building heat market which can be accessed. The relevance of nuclear district heating in the UK will clearly involve these factors, together with the success or failure in the local siting of SMRs and/or AMRs. This is not to say that schemes should not be considered for GWe-sized Gen III+ reactors, merely that the proportion of low temperature heat use is likely to be low for these large systems.

The ETI sponsored an extensive study on the use of SMRs for providing district heating [19]. This examined the possible modes of operation of SMRs in cogeneration mode, and provided estimates of the economics involved. This study validated previous conclusions that [19, p. 126]:

> *'...SMRs could play an important role in the UK's future energy system by operating as combined heat and power plants providing low-carbon heat to city-scale district heating networks'.*

These conclusions were accepted by the ESC, and introduced the element of political and social acceptance [8, p. 39]:

> *'SMRs (e.g. 300 MW) offer the potential for combined heat and power as part of a more distributed energy system, but will require these small reactors to be sited closer to population centres (e.g. within 20 km). Crucially, this will depend on political and social acceptance. Areas with a history of nuclear energy facilities and the associated job opportunities this can bring are likely to be the first to support early trials. In the meantime, local area energy planning will require careful phasing to maintain the option of plugging in nuclear SMRs subject to successful demonstration.'*

The potential for district heating via nuclear energy is therefore clear, but the economics will need to be studied in parallel with the development of installation and siting programmes, particularly for SMRs and AMRs.

3.3 **AMRs, hydrogen and heat provision**

Consideration of the potential market for nuclear energy beyond firm and mid-merit electricity has been relatively recent in the UK, and this has coincided with a growing appreciation that complete decarbonisation will require many changes beyond the electricity system. This includes the decarbonisation of transport, industry, and domestic heating. There has been rapidly growing interest in hydrogen as the energy vector in these areas, both for direct use and for the manufacture of ammonia and synthetic liquid fuels. Notably, the use of hydrogen featured extensively in the energy white paper [15], and was studied by the CCC [20], though this only included hydrogen production by electrolysis. There is an urgent interest in low-carbon methods of manufacturing the extremely large volumes of hydrogen that could be needed. A vital question that must be answered is: how to manufacture these potentially vast quantities of near-zero-carbon hydrogen?

Imperial College carried out an appraisal of the carbon footprint and levelised costs of hydrogen production including the potential routes using nuclear power [21]. The main methods of making hydrogen are listed in Table 2, with their associated Technology Readiness Level (TRL) [22], and Figure 2 and Figure 3 compare the carbon footprints and the levelised costs of these methods. There is still a lot of uncertainty, which can only be resolved when the less developed systems are designed and costed, but the information here is sufficient to understand the position of nuclear.

At the moment almost all hydrogen production is by steam methane reforming. This is an efficient process that requires a heat source, which could be produced by burning natural gas, using renewable electricity or by using heat from a nuclear reactor (an option being explored by Russia and the US [23]). The process is convenient for CCS since only hydrogen and CO_2 are produced by the endothermic reaction of methane with water. The process is efficient at 850°C, so for nuclear support of steam methane reforming, a VHTR* would be required to supply the heat without supplement from electricity. Use of nuclear power in this way reduces carbon emissions but does not have a large impact because most of the emissions would arise from the CO_2 produced during the reforming reaction. Coal gasification with and without CCS is added for comparison.

Methane pyrolysis is an interesting process which requires just heat and a catalyst to split methane into carbon and hydrogen. This makes the carbon capture process rather simple and there is a potential market for the resulting carbon. Pyrolysis requires temperatures just over 1,000°C to be efficient, but by using direct contact between molten metals (e.g. lead), this can be lowered to around 850°C [24]. Pyrolysis of biogas, driven by a VHTR, could be a useful negative carbon footprint contribution. Negative carbon footprints can also be obtained from biomass gasification with CCS. Although controversial, biomass, particularly from waste, will be an essential ingredient of the energy mix.

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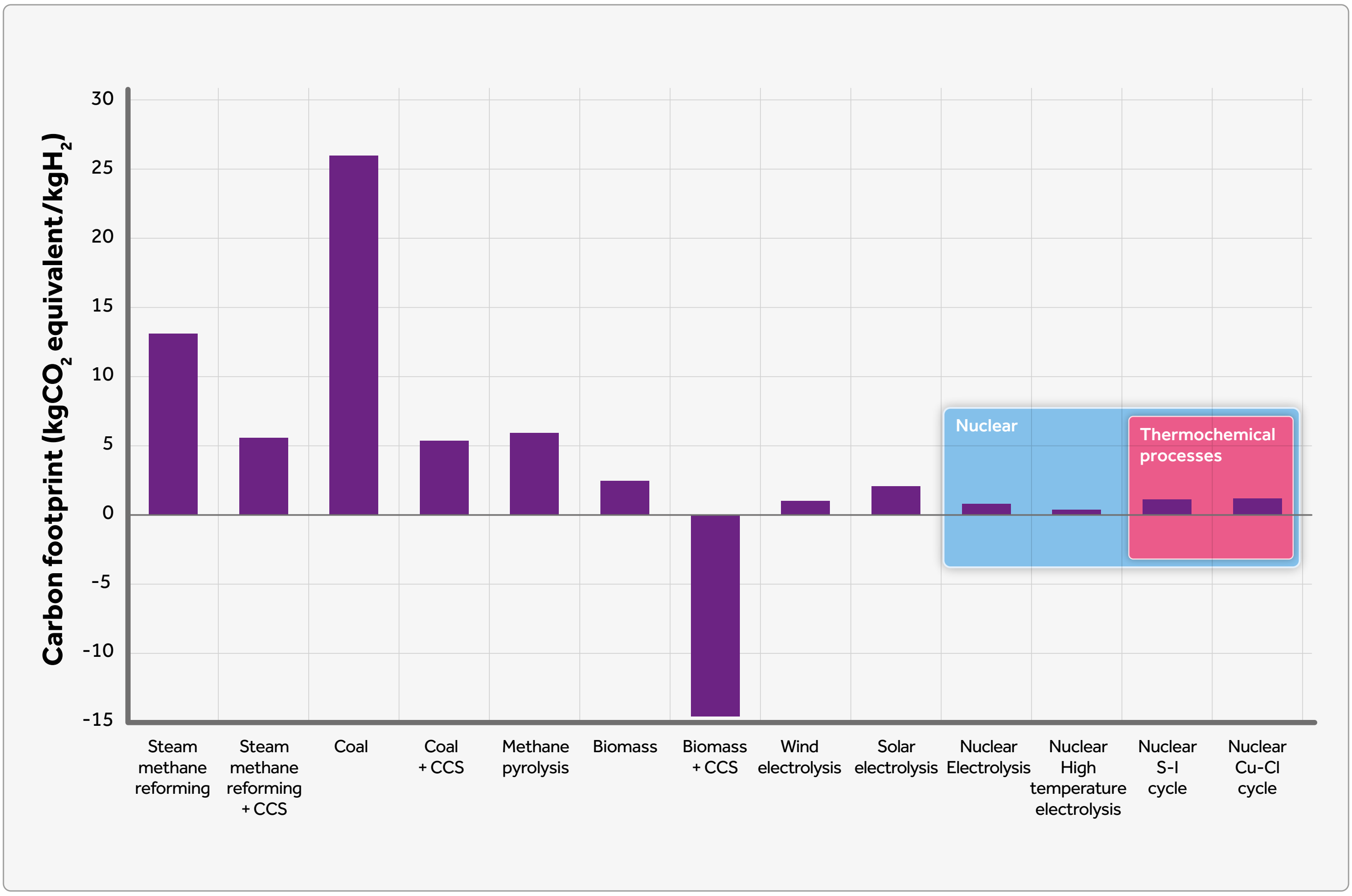
* *The terms 'HTGR', 'HTR' and 'VHTR' (High Temperature Gas-cooled Reactor, High Temperature Reactor and Very High Temperature Reactor respectively) are frequently used interchangeably. The nearest to a concrete distinction is probably from the IAEA, where HTGR is quoted as giving ≥700°C, with VHTR at ≥900°C [80].*

Table 2. Main methods of hydrogen production with current TRL levels, adapted from [21]. TRLs in brackets are our estimates. Contaminants do not include emissions from plant construction or external heating.

Method	Energy source	Input material	Main output materials (contaminants)	TRL level
Steam methane reforming	Heat	Natural gas	H_2+CO_2 $(CO+CH_4+NO_X)$	9 (using nuclear heat 6)
Steam methane reforming with CCS	Heat	Natural gas	H_2+CO $(CO+CH_4+NO_X)$	7–8
Coal gasification	Heat	Coal	H_2+CO_2+C (Many)	9
Coal gasification with CCS	Heat	Coal	H_2+CO_2+C (Many)	6–7
Methane pyrolysis	Heat	Natural gas	H_2+C (CH_4)	3–5 (using nuclear heat 3)
Biomass gasification	Heat	Biomass	H_2+CO_2 (Many)	5–6
Biomass gasification with CCS	Heat	Biomass	H_2+CO_2 (Many)	3–5
Electrolysis – wind	Electricity	Water	H_2+O_2	9
Electrolysis – solar	Electricity	Water	H_2+O_2	9
Electrolysis – nuclear	Electricity	Water	H_2+O_2	9
High temperature steam electrolysis	Electricity+Heat	Water	H_2+O_2	(7)
High temperature steam electrolysis – nuclear	Electricity+Heat	Water	H_2+O_2	(3–5)
Thermochemical water splitting (Cu–Cl) cycle	Electricity+Heat	Water	H_2+O_2	3–4
Thermochemical water splitting (S–I) cycle	Electricity+Heat	Water	H_2+O_2	3–4

Figure 2. Comparison of the carbon footprints of a range of hydrogen production methods*. Data points are mid-range values from [21], except for nuclear high temperature electrolysis which is from [25].



Low temperature electrolysis, using Proton Exchange Membrane (PEM) or alkaline processes, is quite efficient and well-established but, as can be seen from Figure 3, is a relatively expensive process. Part of the problem is the capital cost of the electrolysis plant and the short life of certain components. This makes the low temperature electrolysis route the most expensive method for both renewables and nuclear. Also, intermittency proves to be important. The load factors assumed in Figure 3 are generous for solar at 20%; in the UK the measured load factor for solar PV was lower at only 11% in 2019 [26]. Offshore wind can reach 40% load factors but the unpredictability means that production meets peak demand only some of the time. The consequent low usage of expensive electrolyser equipment means solar and wind are more expensive than nuclear for this route, as reflected in Figure 3. Because of these high electrolyser costs, low temperature electrolysis should not prioritise using 'cheap electricity' at times of low electricity demand [27]. However, low temperature electrolysis powered by nuclear electricity is certainly feasible and would yield very low-carbon hydrogen. One demonstration programme has already been proposed for Heysham nuclear power station [28], and another is detailed for Sizewell B (to supply the construction vehicles should Sizewell C go ahead), and a general review of nuclear hydrogen possibilities has been published by the Nuclear Industry Council [29].

Nuclear energy can supply heat as well as electricity and there are a range of lower TRL technologies that are potentially cheaper and more efficient than low temperature electrolysis. These all require higher temperatures than the 300°C that can be provided by contemporary LWRs. The range of Gen IV reactors now being explored in the AMR competition [30] for example, all have coolant outlet temperatures above 500°C. High temperature steam

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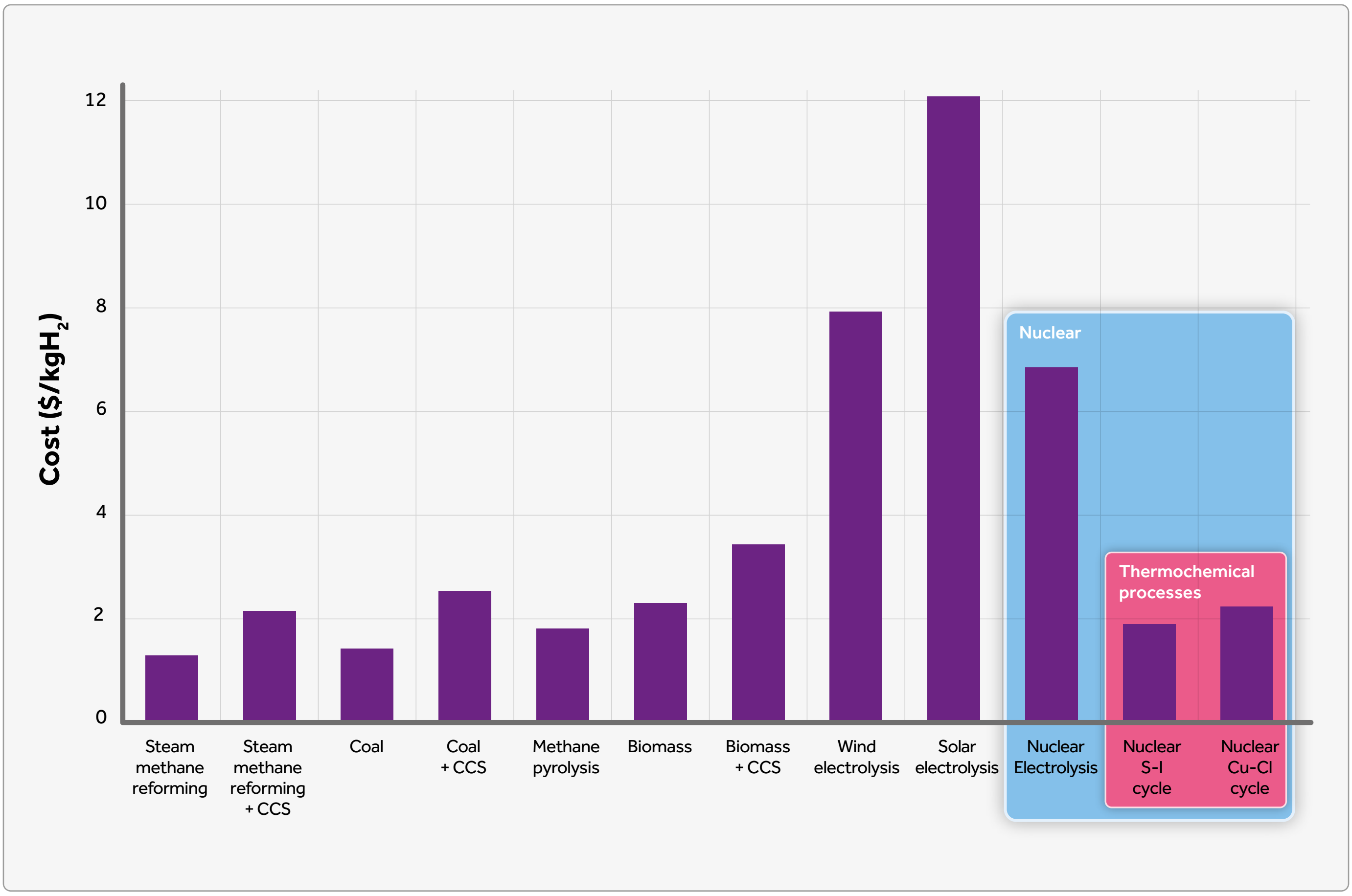
[*] *Note that in several sources on hydrogen production, 'SMR' is often used to denote 'Steam Methane Reformation'. This acronym is not used here as it is already reserved for 'Small Modular Reactors'.*

Figure 3. Comparison of the costs of a range of hydrogen production methods [21], no reliable value of the cost of high temperature electrolysis was available at the time of writing the report.



electrolysis uses a ceramic membrane in an electrolysis cell with increasing efficiency with temperature. Small units are already available and large-scale systems will be available in the near future. High temperature steam electrolysis could prove to be the cheapest method of hydrogen production; the alternatives are thermochemical systems, of which there are a number of possibilities. Two thermochemical cycles have been explored so far: the Cu-Cl cycle requires a heat supply of ~550°C, and so could be used with any of the Gen IV options; the S-I cycle becomes more efficient at higher temperatures, ideally ~950°C.

All of the possibilities mentioned above are significantly cheaper than low temperature electrolysis and high temperature electrolysis has a significantly lower carbon footprint than its low temperature counterpart. VHTRs can provide heat at temperatures approaching 1,000°C, and have the advantage of some operating experience with a range of new design concepts. This raises the possibility of fleets of high temperature reactors dedicated to hydrogen production, as discussed by Lucid Catalyst in 2020 [31]. This study proposes a Gigafactory of 36 reactors at 600 MWth – a total of 21.6 GWth. Finding sites able to handle such a large thermal loading (around 2.5 times the thermal output of Hinkley Point C) would be challenging. They suggest ten Gigafactories to satisfy the UK's hydrogen and zero carbon synthetic fuels needs by 2050, which would total 216 GWth.

The CCC's *Sixth Carbon Budget Methodology Report* does mention hydrogen generation from nuclear electricity [32]:

> *'However, the relative inflexibility of nuclear power production can lead to excess generation when demand is low. This surplus of electricity could be used to produce hydrogen via electrolysis, albeit at a higher energy cost than from renewables.'*

The 'higher energy cost' statement is unexplained and almost certainly in error as has been shown, with renewables tending towards a higher cost of hydrogen production due to their low capacity factors and intermittency. This is explored further in the Lucid Catalyst report [31].

The instinct that 'highest temperature is best' must be tempered by the fact that higher temperatures will increase the design challenges faced by any system, particularly in the area of materials selection and performance. Therefore, acquiring a clear understanding of the 'gradient of the cost/efficiency line' from low to high temperatures is an essential initial requirement. For example, taking an extra ten years and considerable expense to raise temperatures by 50°C is pointless if this yields only marginal benefit. Similarly if steam electrolysis at moderate temperatures turns out to be efficient and cheap, then this could begin to undermine the economic case for high temperature nuclear thermo-chemical hydrogen production in the near term.

An additional complication is that the required hydrogen purity is likely to vary considerably depending on its intended use, with a very pure product being required, for use in hydrogen fuel cells for example. Such purity might entail additional processing steps and might well mean the use of a 'premium price' hydrogen for such applications. Whatever the answers to this plethora of hydrogen questions, the sooner the answers are known, the better. Finding the optimum solution will require further understanding of the routes to hydrogen production and the building up of research capacity in this area in the UK.

The area of high temperature nuclear heat provision was examined by the Nuclear Innovation and Research Advisory Board (NIRAB) [33], which recommended studying the availability and economics of higher temperature reactors, with HTGR as the reference system.

These recommendations were essentially accepted in the government's *Ten Point Plan* [17] and white paper [15], with a specific aim to build a demonstration reactor to demonstrate high temperature heat generation by the early 2030s.

The *Ten Point Plan* mentions [17, 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 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.'***

This is mirrored in the white paper with statements such as [15, p. 51]:

> ***'[AMRs] may offer new functionalities (such as industrial process heat). These reactors could operate at over 800°C and the high-grade heat could unlock efficient production of hydrogen and synthetic fuels'***
>
> ***'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.'***

...and [15, p. 38]:

> ***'We will invest £1 billion in UK's energy innovation programme to develop the technologies of the future such as advanced nuclear and clean hydrogen'.***

Another reaffirmation is contained in the government's *Industrial Decarbonisation Strategy* [34, 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.'***

None of these points, however, should infer that AMRs will not be used for electricity production, or will not be dual purposed. What is definite is that a considerable amount of work is necessary, much of it already on the critical path, if an AMR demonstrator is to be ready to start operation by around 2030. The rest of this paper will presume that the 'AMR demonstrator' in question will be an HTGR, on the basis that this is the reference system in the NIRAB report [33], and that it is probably the only high temperature system that could plausibly be delivered as a demonstrator by the early 2030s.

On this narrow timescale, international teaming will almost certainly be necessary for the demonstration reactor design, with several countries including China, Japan and the US currently active in the HTGR field. A detailed and rapid assessment and action on a teaming arrangement will be essential to maintaining the critical path. Regarding the fuel cycle, the BEIS-funded and National Nuclear Laboratory (NNL) led Advanced Fuel Cycle Programme (AFCP) is addressing many of the aspects of AMR (and particularly HTGR) fuel, but most AMR (and all HTGR) fuel will require enrichment to >5% ^{235}U (termed High Assay Low Enrichment Uranium; HALEU) for which the Urenco technology at the Capenhurst site would, with suitable reconfiguration, be uniquely suitable [35]. There is also action in the US, where the United States Department of Energy (USDOE) has announced a jointly funded programme to produce HALEU using the previously abandoned US centrifuge technology. Urenco has made at least two presentations on HALEU, one in the UK and one in the US, with the UK presentation suggesting a move of the UF_6 deconversion and fuel technology facilities from Springfields to Capenhurst. Such a proposal would need to be fundamentally evaluated against the optimum positioning, effectiveness and economics of UK fuel cycle technology. Such a reactor/fuel cycle programme will need to be clearly co-ordinated. For delivery of a demonstrator, a suitably empowered NNL would be the obvious candidate, but there is an urgent need for clarity of defined roles and responsibilities.

Note also that TRISO* HTGR fuel is probably the most suitable fuel for direct disposal and the least suitable for recycle. In the longer term, systems with recycle options may become essential, providing further motivation for AFCP to address longer term market possibilities and lower TRL technology. Furthermore, any longer term fuel cycle assessment must be teamed/co-ordinated with research and assessment on reactors, and any artificial organisational barrier between the two areas should be explicitly avoided. A high-level study with a title such as *'Long-term UK assessments of reactors, nuclear fuel cycles and their place in future net zero energy scenarios'* is urgently needed.

The alternative to using nuclear energy to provide the bulk of the hydrogen production can be seen in an IEA presentation in March 2021 [36]. Countries which pursue a hydrogen economy and reject nuclear generation will produce expensive hydrogen by electrolysis from renewable energy during periods of low electricity demand, while relying on fossil fuels with CCS to produce the bulk of hydrogen at lower cost. In this situation, achieving net zero would be very difficult.

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.

3.4 An HTGR demonstrator in the UK

The energy white paper contains the specific statement [15, p. 51]:

> *'Our aim is to build a demonstrator by the early 2030s at the latest to prove the potential of this technology.'*

The challenge for the UK is how to organise and finance this, with considerable urgency in that most of the estimates of the timescale for such a demonstrator put us already on the critical path for a demonstrator by 2030 [37]. Much will depend on what form the demonstrator is to take. The presumption here is that a demonstrator which would best facilitate the critical path to an NOAK HTGR series build is one which closely matches the characteristics of a FOAK in that series. A fundamental reason for this stance is the fact that HTGR design and TRISO fuel formed part of the UK's Dragon reactor project in the 1960s. There is catching up to be done, and there may well be a case for some sort of a testing reactor to test fuels and materials, but in extremis this could be done overseas. The key UK step is to build a reactor that proves that the design works at scale, preferably also demonstrating the hydrogen production process. This will envisage a demonstrator of appropriate size both to satisfy the scale of the potential market (see previous section) and to approach the capacity which will minimise the cost of high temperature heat. This is expected to be of the order of 600 MWth. However, the first stage of any demonstrator process will be to test this proposed route and to specify the reactor. This will depend on the degree of international teaming which has been agreed. It is felt that a UK siting of the demonstrator is essential, but this too must be formally agreed.

The choice of HTGR technology will be dealt with after considering international developments (§4), with the high-level choice between 'prismatic' and 'pebble bed' designs. It is essential that the technology choice, and the teaming arrangements, are holistically specified and pursued and this will decide what can be achieved by 2030.

Once the destination of the critical path is decided, the obvious questions are 'how' and 'by whom' will this objective be pursued and achieved in the UK? The answer would seem to be far from obvious with the major nuclear industry powers already committed to Gen III+ and/or SMRs. These projects will surely present themselves as achieving 'cheap power and cheap hydrogen via electrolysis', negating any need for production using high temperature heat.

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* *Tristructural-isotropic (TRISO) fuel consists of sub-millimetre particles of uranium ceramic, coated with layers of carbon and silicon carbide to produce a robust fuel design.*

The UK has a successful history of commissioning demonstration reactors, notably the Dragon HTGR. However, as illustrated in Table 3, five demonstration reactors were commissioned between 1959 and 1974. All had (by today's standards) very short construction periods and all were project managed, built and operated by a single consolidated entity – the United Kingdom Atomic Energy Authority (UKAEA).

Without attempting to debate the appropriateness or otherwise of a government-owned entity undertaking this range of roles, it is indisputable that this arrangement transparently gave total responsibility for the projects to a single entity, minimising the likelihood of any deviations in motivation from competing parts of the same project, which have arguably led to the progressive consolidation of the UK's nuclear decommissioning activities under the Nuclear Decommissioning Authority (NDA).

It would be comparatively easy to define the optimum structure for the HTGR Demonstrator Project Management Organisation, but more of a challenge to envisage how such an efficient entity could be set up under the current structures. This is the challenge which must be surmounted if the aims of the white paper [15] are to be achieved – and is likely key to the whole sector of an optimum net zero programme which should rely on supply of low-cost, low-carbon hydrogen.

Given the UK's lack of involvement with HTGRs since 1976*, a demonstrator project coming to fruition by 2030 will inevitably require teaming with at least one other international programme. A decision on international teaming will be the first test of government/project co-ordination – and is already on the critical path. A short summary of other nations' HTGR actions is provided in §4.

This study lacks the structural knowledge of government nuclear interests to begin to suggest project structures, but it would be difficult to ignore the facts that:

- fusion power is at a fairly early stage of development in comparison to many AMRs. It has received continuous government funding for many decades, and is currently being funded to produce a conceptual design by 2024†. The objective is then for the STEP (Spherical Tokamak for Energy Production) programme to design and construct a prototype fusion power plant. It is undertaking a consultative process to select a separate site and will make a recommendation on this to the Secretary of State for BEIS;
- it is immediately noticeable that the entity co-ordinating this entire project, with apparent excellent effect, is the UKAEA which has maintained the overall project responsibility for fusion energy, which once extended to fission energy;
- it is difficult to avoid the view that an overall entity with responsibility for the HTGR demonstrator would be the key way of minimising the risk of not meeting the desired date and of minimising the cost of getting there.

***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.**

Table 3. UK demonstration reactors.

Reactor	Project manager/ operator	Build start date	First criticality	Build time (years)	First grid connection	Shutdown
DFR [38]	UKAEA	Mar 1955	Nov 1959	4.7	Oct 1962	Mar 1977
WAGR [38]	UKAEA	Nov 1958	Aug 1962	3.8	Feb 1963	Apr 1981
SGHWR [38]	UKAEA	May 1963	Sept 1967	4.3	Dec 1967	Sep 1990
Dragon [39]	UKAEA	Apr 1960	Jan 1964	3.7	Operated from Jul 1965	Sep 1975
PFR [38]	UKAEA	Jan 1966	Mar 1974	8.2	Jan 1975	Mar 1994

** The UK's existing Advanced Gas-cooled Reactor (AGR) fleet operates in excess of 600°C and (like HTGRs) they are gas-cooled and graphite moderated. The materials expertise gained from experience with the AGRs is very relevant.*

† In addition to the mainstream funding of the Spherical Tokamak for Energy Production (STEP) project, BEIS has also funded Tokamak Energy (a private venture) in the second phase of its current AMR programme [30].

3.5 Fuel cycles

The LWRs currently envisaged for the bulk of the net zero nuclear electricity operate on a once-through fuel cycle, with the spent fuel not being recycled, but stored for eventual disposal. Most other countries also operate once-through fuel cycles, though France is an exception to this. In the French system, spent fuel from its LWR fleet is reprocessed, and recovered plutonium and uranium is recycled as Mixed Oxide (MOX) and Reprocessed Uranium (RepU) fuel; spent MOX and RepU fuel is stored. The UK did reprocess all the spent fuel from its Magnox reactor fleet and a significant amount of the AGR spent fuel, but has not recycled the recovered materials. The presumption for the Gen III+ and SMR fleets is a once-through fuel cycle, with the spent fuel stored. The once-through fuel cycle utilises only ~1% of the uranium mined for its use.

AMRs, on the other hand, can operate with a once-through fuel cycle or a closed fuel cycle. A closed fuel cycle is designed to produce as much fissile material as it consumes. The spent fuel is reprocessed and the recovered materials refabricated into fuel and fed back into the reactor. In principle, closed cycles utilise far more of the energy in uranium, giving an increase in energy per teU of a factor of 50 or more over the once-through fuel cycle.

The drivers for moving towards a closed fuel cycle can be:

- economics – overall cheaper power/heat cost than from a once-through fuel cycle;
- uranium usage – particularly if uranium becomes scarce and/or expensive, though expensive uranium can increase nuclear power costs, with a possibility that economic exclusion from the market would dominate over maximising uranium efficiency;
- self-sufficiency – converting the UK's current depleted uranium inventories [40] from a waste into a source of energy would be sufficient to generate 385 TWh in fast reactors – equivalent to almost 1,000 years of current UK usage. This provides a stark background to any decision to put this uranium stock out of reach in a Geological Disposal Facility (GDF);
- waste minimisation – recycling systems can burn many of the radioactive isotopes which would end up as waste, leading to smaller quantities of waste with shorter half-lives. Care must, however, be taken to also consider the effect on economics as the savings from smaller waste volumes are relatively minor [41].

The use of TRISO fuel makes the HTGR an unlikely candidate for a closed fuel cycle. However the very large advantages of a closed fuel cycle outlined above give compelling reasons for at least keeping open the option of closed fuel cycles; and of remaining at the forefront of R&D in these systems to track developments in the importance of these advantages. This work will also provide the essential knowledge to assess proposals from reactor/fuel cycle vendors, as described below.

***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.**

3.6 System and market tracking and evaluation

The enlargement of the UK nuclear market beyond simple provision of baseload power, and the need to ensure net zero long beyond 2050, gives a much broader long term interest in reactor systems and fuel cycles – over timescales which meet net zero by 2050 but have a much longer sustainability horizon. This must be a programme that aims at the most likely forward path, but also covers all the other possibilities at lower effort/TRL – so that the UK always knows where it is in the market, does not become blindsided and can capitalise on developments in science and technology.

A feature of the last decade has been the proposal of many reactor systems for entry into the world and UK market, many of them AMRs. Many of these proposals have a heritage gleaned from early reactor demonstrations, mainly in the US. This appears to give many proposals the latitude to claim that 'this system was extensively demonstrated in Oak Ridge National Laboratory in the 1960s'. This reveals nothing about the current developmental state of the system or of its ability to engage with the UK's flexible, but extremely demanding, regulatory system. The regulators (the Office for Nuclear Regulation and the Environment Agency; ONR and EA respectively) successfully used the Generic Design Assessment (GDA) to examine the basic suitability of Gen III+ LWR designs for deployment in the UK from around 2010, and this is currently developed for use with AMRs. In many ways, using a knowledge of the questions which will be posed by the GDA is a good guide to the severity of the challenges facing new designs. Indeed, BEIS have already invested in developing the regulators to understand AMR technologies and this will continue to be important.

In the UK, the first coordinated attempt to assess the readiness of AMR reactor systems for introduction to the market in recent decades was made in the Techno-Economic Assessment (TEA) programme [42–47][*], particularly Lot 3, which centred on the Generic Feasibility

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[*] *It was following the TEA programme that 'SMR' was adopted as the term for small, modular versions of LWRs; and other modular reactors were given the acronym 'AMR'.*

Assessment (GFA) methodology [45][*]. This methodology can provide an up-to-date view of the relative advantages and challenges of the various reactor systems in both the short and long term, together with the feasible date for NOAK availability. This can be compared against the views on the likely long-term markets as well as factors such as uranium availability/price. In particular, the TEA GFA supported a relatively early date for potential operation of an HTGR system.

The need to survey international AMR developments places a priority on the assessment of the progress made on the range of different AMRs in different countries. Reactor systems progress tracking is essential – with continuously updated GFA as the public domain data source, supported where necessary by more commercially sensitive examinations. There is an ongoing need for understanding of reactor system and fuel cycle economics, and also of potential market challenges (including uranium supply); plus up-to-date knowledge of the possible rate of migration between systems [48]. The clarification of likely drivers of system change and their probable timescales will be an important and urgent piece of work.

It is often stated that the fuel cycle can look like a relatively small economic player for systems operating a once-through fuel cycle, but it is clearly much more determining for a closed fuel cycle. Any move to license a system must be accompanied with a thorough and convincing demonstration of the total fuel cycle, together with a supportable view on siting of reactors, fuel cycle plants and waste storage/disposal. It is a feature of many current closed fuel cycle proposals by private sector reactor vendors that many of the fuel cycle/waste elements seem to be taken as 'obviously achievable' – but with very little evidence that it is so. Mercifully, this approach stands no chance of working in the UK.

Consequently, to judge the likely progress and ultimate availability of any system, a good overall knowledge is required across the reactor/fuel cycle system, supported and maintained by R&D activity at an appropriate TRL level, together with up-to-date assessments of overall economics.

***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.**

3.7 Siting

Siting is key for all systems – and the advent of new programmes, particularly of SMRs, revives the need to critically examine this aspect. The first comprehensive examination of reactor siting by the government was in 2011 when a national policy statement defined eight sites [49, p. 33][†] as 'potentially suitable for the deployment of new nuclear power stations in England and Wales before the end of 2025'. This policy was formed in the context of several GWe-sized LWRs, which were the candidates for building new reactors at existing NDA sites. Various studies have since examined the potential for siting both large and small reactors, notably a study by Atkins for ETI [50]. This was reported, with commentary, in a report by the ETI [51], which, for Gen III+ reactors, concluded that a theoretical capacity of 62 GWe would be reduced by various factors, leading to the conclusion that [51, p. 9]:

> *'Large reactors are best suited for baseload electricity production – analysis indicated an upper capacity limit in England and Wales to 2050 from site availability of around 35 GWe. Actual deployment will be influenced by a number of factors and could be lower'.*

For SMRs [52, p. 19]:

> *'…an indicative theoretical capacity was found to be 67 GWe. An upper limit was not found as part of the Power Plant Siting Study and further work would be expected to identify additional SMR site capacity'.*

The overall conclusions are that, depending on the size of the reactors and the individual site limits, overall capacities of up to the highest levels so far examined (75 GWe) could be possible. This would, to some extent, depend on the thermal efficiency of the reactors concerned, with the 75 GWe in LWRs equating to ~208 GWth.

There are several new variants that will require study.

1. The siting of SMRs closer to centres of population to enable district heating to be a realistic option.
2. The siting of high-temperature-heat reactors adjacent to hydrogen manufacturing plants or other chemical uses.
3. The limitations of the numbers of small reactors that can be co-sited – and indeed the overall thermal limit likely for the range of sites to be considered.

This final point is relevant if anything like the ten Gigafactory level of rollout were to be contemplated (see §3.3) as these levels of site capacity are assumed to be at least a factor of five higher than has been previously contemplated.

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[*] *The detailed GFA assessments are available from The University of Manchester.*

[†] *The eight sites were Bradwell, Hartlepool, Heysham, Hinkley Point, Oldbury, Sizewell, Sellafield and Wylfa.*

As well as the regulatory aspects of siting, stakeholder opinion, particularly for small reactors near communities, will be very important. It is therefore timely that BEIS initiated a public dialogue on modular nuclear technologies in early 2021, the result of which is awaited.

Overall, the siting studies must be consolidated to cover all the currently feasible scenarios and work undertaken to ensure that only feasible siting scenarios, or ones that can be made feasible by further study, are carried forward. Having defined the range of feasible siting arrangements, the economics of the different arrangements will become important, as the regulatory requirements (including security) will vary the 'annual site cost per TWh'.

The siting of the rest of the fuel cycle can also be important, especially in the case of closed cycle reactor systems. Many of these early stage proposals are apt to assume co-siting of reprocessing and reactor(s) – often attributing this to 'minimising transport'. Such schemes will require stringent economic examination, as simple modelling may tend to find that – in common with current LWR reprocessing schemes – closed fuel cycle systems might expect to be heavily dependent on fleet size for the economic benefits of centralised recycling.

Finally, as the reactor manufacture is presumed to be highly modularised, the transport of modules from the reactor factory may also be critical, and might well favour coastal and/or existing shipbuilding sites.

4

International developments

4.1 **Review of international activities**

There is currently a lot of interest in advanced reactor systems that offer the advantage of higher temperatures to provide a wider range of cogeneration and particularly H_2 production as part of the strategy to achieve net zero. The latest International Atomic Energy Agency (IAEA) 'SMR Book' [53][*] lists 72 development projects, 41 of which are not based on water reactor technology. There are additional projects that are not listed in the book, with the total number of advanced systems closer to 50. The majority of these will never be built so it is worth being selective both in terms of project feasibility and their relevance.

The US, Canada and the UK are three countries with projects to support development of advanced reactor designs; Table 4 lists their recent funding of advanced reactor projects.

The USDOE are funding development work on the ARC-20 (Advanced Reactor Concepts-20), which provided shared-cost funding to complete design work; and the Advanced Reactor Demonstration Program (ARDP) with shared-cost funding to build a demonstration reactor [54] and complete development work before construction. The Canadian SMR programme has continued and expanded with two demonstration sites offered [35, 55]. The UK AMR competition funded feasibility studies on Phase 1 [30] and some development work on Phase 2 [56].

While detailed explanation of each of the systems in Table 4 is unnecessary, some of the less familiar new reactors and those with tertiary salt loops warrant a brief description.

1. The Fast Modular Reactor is a scaled-down version of the General Atomics EM2 design for an all ceramic-fuelled, helium-cooled reactor.
2. The Natrium reactor is essentially a PRISM reactor with a molten salt tertiary circuit with 2.75 GWh of thermal storage, enabling it to deliver 500 MWe for 5.5 hours from its stored capacity.
3. The Stable Salt Reactor-300 Wasteburner (SSR-300W), MMR and IMSR also include molten thermal salt loops which provide added flexibility for high temperature reactors. It should be noted that if solar salts[†] are used in these loops, the temperature is limited to <600°C.

All of the reactors in Table 4 have the potential to contribute to higher temperature hydrogen production technologies, but HTGRs are required for the highest temperature applications and to meet the thermal requirements for the most demanding industrial processes, such as steel making. The microreactors are generally aimed at specific markets either to service isolated settlements (such as in northern Canada) or activities (such as military bases). When placed in a larger capacity marketplace they have limitations because of higher levelised power costs of lower uranium utilisation (which also increases the carbon footprint). For these reasons, this paper focuses on HTGRs with powers >100 MWth from this point on.

There are two streams of HTGR development, both of which utilise TRISO fuel. Firstly, prismatic reactors, where the TRISO fuel is arranged in the form of hexagonal graphite stringers containing cylindrical compacts of TRISO particles dispersed in a graphite matrix. This line of development was based on the two reactors built by General Atomics (specifically Peach Bottom 1 and Fort St Vrain). Development was continued with an international collaboration started in 1995: The Gas Turbine Modular High Temperature Reactor (GT-MHR), between Russia, US, Japan and the EU (i.e. France), to specify a 600 MWth VHTR design that could be applied to electricity generation using a gas turbine cycle; or could be reconfigured to provide high-quality heat [57]. This work crystallised into a range of vendor designs, with many similarities, backed up by work in national laboratories, see Table 5.

The second stream consists of pebble-bed reactors, where the TRISO particles are dispersed in graphite compacts in the form of spheres (the 'pebbles'). The pebbles pass through the reactor core and are assayed for burn-up before either being returned to the core or sentenced as spent fuel. This stream was demonstrated in Germany with the AVR and THTR-300 reactors, with limited success. In the late 1990s, South Africa and China started to develop the technology. The South African project was quite well developed with input from NUKEM Technologies and Westinghouse, but failed to get final funding. China was more successful with a small experimental reactor, HTR-10, followed by the construction of twin 250 MWth HTR-PM reactors, which are currently being commissioned.

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[*] It should be noted that BEIS has adopted the nomenclature that 'SMR' refers to Small Modular Light Water Reactors (without a specific maximum power output), with all other systems being referred to as 'Advanced Modular Reactors' (AMRs). These reactors have advanced engineered features, are deployable either as a single or multi-module plant, and are designed to be built in factories and shipped to utilities for installation as demand arises.

[†] Solar salts are molten salts used in solar power plants as a temporary energy storage medium [81].

Table 4. Reactor development projects that have received funding from UK, Canada and US advanced reactor programmes.

Reactor (type)	Developer (country)	Power MWth (MWe net)	Primary outlet T (°C)	Recent funding
Microreactors (<50 MWe or <100 MWth)*				
MMR (Prismatic HTGR)	Ultra Safe Nuclear (US)	15 (5)	725	UK AMR Competition Phase one (<£300k) Entered Stage three of the CNL partnership to construct a demonstration reactor
StarCore (Pebble-bed HTGR)	StarCore Nuclear (Canada)	50 (20)	750	Completed Phase one of the CNL partnership to construct a demonstration reactor
U-Battery (Prismatic HTGR)	Urenco (UK)	10 (4)	750	UK AMR Competition Phase two (£10M) Completed Phase one of the CNL partnership to construct a demonstration reactor
Larger SMRs (>50MWe or >100MWth)				
ARC-100 (SFR)	Advanced Reactor Concepts (US)	260 (100)	515	UK AMR Competition Phase one (<£300k) New Brunswick Province matching funding CA$20M and site in New Brunswick USDOE ARC-20 $27.5M as part costs to complete design work
Fast Modular Reactor (GFR)	General Atomics & Framatome (US)	~100 (50)	>700	USDOE ARC-20 $24.8M as part costs to complete design work
Natrium Reactor (SFR)	TerraPower & GE Hitachi (US)	~860 (345)	~530	The USDOE ARDP has awarded shared funding with $80M development costs
IMSR (MSR)	Terrestrial Energy (US, Canada)	400 (190)	700	Completed Phase one of the CNL partnership to construct a demonstration reactor
SSR-300W (MSR)	Moltex Energy (UK)	750 (300)	650	UK AMR Competition Phase one (<£300k) Canadian government SMR funding CA$50.5M and site in New Brunswick
Westinghouse LFR LFR)	Westinghouse (US)	1,050 (400)	550	UK AMR Competition Phase two (£10M)
Xe-100 (Pebble-bed HTGR)	X Energy (US)	200 (80)	750	The USDOE ARDP has awarded shared funding with $80M development costs, with eventual funding of $1,230M as 50% of construction costs, with a site at INL

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* *The main use of microreactors is off-grid to replace diesel power.*

Table 5. Main lines of current HTGR development.

Reactor	Status	Developer (country)	Power conversion	Power MWth (MWe net)	Primary outlet T (°C)	Notes
Prismatic designs based on Gas Turbine Modular High Temperature Reactor (GT-MHR) project						
GTHTR300	Design developed, pre-licensing	JAEA & Industrial consortium (Japan)	Direct Brayton cycle	600 (100-300)	850-900	Most developed VHTR design with option for H_2 prod; status uncertain
GT-MHR	Preliminary design, components testing underway	Afrikantov OKBM (Russia)	Direct Brayton cycle	600 (288)	850	No progress since 2014
MHR-T 4	Conceptual design	Afrikantov OKBM (Russia)	Direct Brayton cycle	600 (205)	950	Cogeneration for steam reforming of methane for H_2 production
MHR-100	Conceptual design	Afrikantov OKBM (Russia)	Direct Brayton cycle	215 (25-87)	795-950	Cogeneration reactor aimed at oil/gas industry
SC-HTGR HTGR	Conceptual design	Framatome (US)	2 loop Rankine cycle	600 (272)	750	
Pebble-bed designs						
PBMR-400	Preliminary design	PBMR SOC Ltd (S Africa)	Direct Brayton cycle	165	900	Since 2010: Care and maintenance
A-HTR-100	Conceptual design	Eskom Holdings SOC Ltd. (South Africa)	Brayton, with molten salt heat storage circuit with cogeneration Rankine cycle.	100 (50)	1200	On hold from 2019, looking for funding. Based on the THTR-300 design with concrete RPV
HTMR-100	Conceptual design	STL Pty Ltd (South Africa)	Rankine cycle	100 (35)	750	Looking to demonstrate Th high conversion
Xe-100	Basic design, pre-licensing	X-Energy LLC (US)	Rankine cycle	200 (82.5)	750	Funding from US ARDP
Shidao Bay 1 HTR-PM	Undergoing commission	CNEC (China)	Rankine cycle	2x250 (total 211)	750	Twin station began commissioning 2020; more intended

So far no HTGR has been built with a Brayton cycle*; though the AVR reactor was operated with primary outlet temperatures ~950°C. The Japanese 30 MWth HTTR experimental reactor has demonstrated extraction of heat >950°C and is a useful testbed for developing both HTGRs and also their wider applications. HTTR has been shut down since the Fukushima Dai-ichi accident but is planned to restart its research campaign in the near future [58]. Perhaps the most relevant line of current development is with the Japanese GTHTR300 reactor concept. Combined with access to HTTR as a development tool, there is a very powerful route for making an early demonstration. Discussion is needed with JAEA to establish the current position and if there is interest in collaboration, particularly in the context of a UK demonstration site; recent debates in the House of Lords identify engagement with the Japan Atomic Energy Authority (JAEA) [59], and existing collaborations between NNL and the JAEA are being expanded to include HTGR technology [60].

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* *The Brayton cycle (also referred to as the Joule cycle) is a thermodynamic cycle which represents the operation of a gas turbine heat engine.*

The US might be an obvious potential partner but the venture-funded projects may not be backed up by sufficient experience in the technologies concerned. The main opportunities would be with companies like General Atomics, Framatome US, BWXT (who have announced a new HTGR initiative) and with the national labs ORNL and INL.

Russia has several designs, mostly aimed at supporting the oil and gas industry (see Table 5), but has too many lines of nuclear development and no experience, even if collaboration were to prove acceptable to both sides.

The Chinese development of pebble bed reactors has been very successful, but at the moment the HTR-PM programme is looking to build a sequence of blocks of six reactors for power production; replacing large numbers of coal stations is a priority in China.

The current government in South Korea has a policy of completing current nuclear projects and continuing operation of nuclear power stations for their original operating lives but not constructing any further nuclear plant. Despite this, South Korea is continuing to do work on a 300 MWe HTGR design for hydrogen production. Ultra Safe Nuclear has recently agreed with Hyundai Engineering and the Korean Atomic Energy Research Institute (KAERI) to develop technologies for the MMR reactor and associated hydrogen production.

4.2 **Teaming**

Starting a UK-alone 'High Temperature Nuclear Heat' project from scratch to meet net zero would not be achievable on the timescales available before 2050. Though the basic knowledge of the HTGR systems is still available, and fuel cycle R&D is being undertaken, the UK will require a reactor technology that has been tested to some extent, with a design that can be adapted to the UK's requirements within two to three years. This confirms that only the HTGR option could allow a demonstration reactor to be built. Other systems may be of future interest to the UK and adoption of an HTGR programme could be a stepping stone towards a route with a closed fuel cycle.

The best route for collaboration needs to be identified and the start of this process must be preceded by the setting up of a UK organisation which can lead the process down the demanding critical path. Technically, the UK has skills in graphite and structural integrity at high temperatures, and much ground-breaking work is being done by the Nuclear Advanced Manufacturing Research Centre (NAMRC) and associated networks on design, virtual reality, inspection, joining and manufacturing development. It would be essential to achieve appropriate engagement from UK industry and the UK would offer a site for the demonstrator.

One early debate will need to cover the consideration of co-siting a hydrogen generation plant with the reactor demonstrator. This must be preceded by a decision on the main development route for nuclear hydrogen production. Hydrogen produced only from electricity can use the same technologies as envisioned for renewables; but for the thermochemical processes envisaged to team with an HTGR, projects to develop technologies to a scale suitable for demonstration must be carried out. It must be determined if that can be done with UK resources or, as is the case with the reactor, should be done in collaboration with another country or countries.

The renewed active membership of the Gen IV International Forum and participation in the SFR and HTGR sections will be important in building connections and information exchange. The main challenge of building a demonstration reactor in the UK will be how to rapidly put in place a viable project structure which will involve both funding and organisational innovation.

5

Levelling the playing field

5.1 UK project structure

Regarding the target AMR Demonstrator (presumed to be an HTGR), the broader question of how to judge future short and long-term options for UK zero carbon energy scenarios is complicated by the current lack of clarity on how such options will be evaluated and pursued. The tendency for some debates to focus on single options and concentrate on individual aspects of the future scene rather than taking overall views is not helpful.

It is also not easy to judge how the government (particularly BEIS), structures its deliberations. Exploration of BEIS organograms [61] yields the names of many subject organisations, some of which are tabulated in Table 6.

This gives an idea of the scope of the organisation, but nothing on the level of integration and goal-sharing between these component entities which would be necessary to foster the level playing field decision making that is needed. It must surely be true that net zero by 2050 is the most significant and difficult concept ever required to reach a satisfactory and holistically optimal solution.

Overall, this lack of visibility makes it unclear how the various factors that have been commented on in the preceding sections would or could be weighed and turned into balanced recommendations for policy. It would be tempting to think of Table 6 as a representation of a highly linked and integrated structure bringing the multiple facets of the various future scenarios into a set of weighted and reasoned recommendations. It could, however, equally easily represent a series of siloed directorates, with a few isolated sections setting out future policy. Fortunately, recent evidence is encouraging in that the April 2020 NIRAB Annual Report [33] was well reflected in the subsequent *Ten Point Plan* [17] and energy white paper [15].

In other areas however, the evidence is less heartening, with the choice of projects for the two phases of the Advanced Modular Reactor competition not appearing to reflect any consistency with the sort of policies outlined in either the NIRAB advice or the subsequent BEIS publications.

There is a considerable level of nuclear expertise within the Nuclear Innovation and Research Office (NIRO), one of whose roles is to provide backup for NIRAB. From the NIRO website [62]:

> *'NIRO is a full-time diverse team of approximate 12 nuclear professionals from a cross section of the industry which, with guidance from NIRAB, advises BEIS on nuclear research and innovation. NIRO is hosted by the National Nuclear Laboratory (NNL).'*

Its three main activities are listed as [62]:

- supporting BEIS in the management of the Nuclear Innovation Programme;
- working with NIRAB to formulate advice to HMG on advanced nuclear systems;
- supporting BEIS on technical aspects of nuclear policy.

How this office interfaces with the sections in Table 6 is unclear, but certainly the NIRAB advice role has recently inevitably been minimal, as NIRAB has not met since January 2020. This has been unfortunate as there are many areas (several explored in this paper) where NIRAB would have been ideally placed to make studies and recommendations.

***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.**

Table 6. Selected directorates relevant to energy within BEIS as at September 2020 [61].

Clean Growth	**Energy Transformation DG Office**
Clean Heat	**Industrial Energy**
Clean Power Strategy and Deployment	**International Climate Change**
Climate and Energy – Trade and Europe	**International Energy and Climate Finance**
Energy and Security DG Office	**Nuclear**
Energy Development and Resilience	**Science and Innovation**
Energy Efficiency and Local	**Science and Research**
Energy Security, Networks and Markets	**Smart Metering Implementation**

It must be essential that the organisation of BEIS and its interfaces with other ministries should provide a platform for properties and possibilities of all the contributing vectors to be openly discussed and methods of weighting them at least discussed, if not agreed. It could be hoped that some clarity will emerge when the government's net zero strategy is published, and it could also be hoped that some of the requirements and concerns raised in this paper will be addressed.

The position is complicated by the wide range of scenarios being studied by various organisations. This has been discussed in §3.1, but other low-carbon energy options show similar spreads. In particular, it might be expected that the CCC would have a central role in indicating a balance of zero carbon cases. The data shown in Table 1 however suggest that the CCC's position on nuclear energy is not in alignment with ambitions to champion a 'middle road' balanced strategy. Also, its analyses are unique, with little or no comparison with other computations and scenarios that might come to different conclusions. In particular, by assuming a fixed £85/MWh for nuclear and only assuming large reactors for electricity generation, the CCC has not considered the wider role that nuclear could have (a role which has been reflected in the energy white paper [15]). Given the ambitions of the energy white paper (and the growing proximity of COP26), it might now be the time for the CCC to work closely with NIRAB and others to ensure that the role of nuclear is considered fully.

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

At present, the organisation with the most promising 'balanced zero carbon mission' would seem to be the ESC [63]:

> *'Energy Systems Catapult was set up to accelerate the transformation of the UK's energy system and ensure UK businesses and consumers capture the opportunities of clean growth. The Catapult is an independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia and research. We take a whole-systems view of the energy sector, helping us to identify and address innovation priorities and market barriers, in order to decarbonise the energy system at the lowest cost.'*

However, the definition of ESC's challenge paints a picture which seems more concerned with proving the individual tools than optimising the toolkit [63]:

> *'The UK has ambitious targets to reduce its greenhouse gas emissions to Net Zero by 2050. Achieving those targets while improving consumer experiences, will require a significant increase in the amount of innovation in the energy sector. Yet many businesses struggle to test and commercialise new innovations under current market conditions; policymakers face a challenge to understand the risks and opportunities in designing new market arrangements; investors grapple with evaluating returns on assets and innovation, without knowing how future markets will operate; while regulators may struggle to design rules to protect consumers if they don't know which solutions are viable and will get traction.'*

The ESC has extensive expertise in the area of whole-system energy modelling using its peer-reviewed ESME system. This has the ability to combine a number of energy sources with assumed economic and environmental properties and give an estimate of the optimum available. This gives the promise that, given agreement on the plausible properties of the range of energy options, the system will deliver an optimum. However, it relies on the estimates being of equal veracity – it will not cope with being fed 'miracle cures'. Other modelling teams such as UKTIMES at UCL, the modelling of heat decarbonisation at Imperial College [64] and the BEIS DDM modelling team cover various aspects of the various scenarios. However, as evidenced by the variety of 'optima' illustrated by the favoured options in the studies summarised in Table 1, there is a clear need for a review of the various techniques and inputs, at least to understand the drivers for the different estimates.

As the ESC is set up to deliver 'independent and unbiased evidence to support policy making by government', it would appear that one of the necessary level playing field assessment mechanisms would be for ESC to carry out such a review. This should be aimed at seeking agreement on the plausible properties of the range of energy options. Given the context of the huge range of options and preferences, this will clearly not be a trivial aim. At the very least, such a study could point out what drives the differences, and point out areas of study to reduce the range of assumptions.

As an initial tranche of this work, there are major ETI papers dealing with nuclear [9, 51, 65] which set the economic parameters required for nuclear to reach the scenarios examined (see Figure 2). It would appear that an open and holistic review of these studies, together with the similar work done with ESME by the ESC on other technologies, would go a long way towards providing visibility of the range of possible net zero scenarios. This could be combined with the other modelling capacities already mentioned to set up transparent level playing field models, which could monitor economic developments, motivating improvements and detecting unrealistic optimism.

***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.**

5.2 Economics

Net zero by 2050 is too major and economically significant an aim to be pursued on any basis other than an assured optimum path for the environment, public welfare and the UK economy. This implies an economic overview function which can evaluate the various decarbonisation routes as part of the overall system. This imperative is well illustrated by the need to optimise the cost burden of intermittency – with renewables not capable of firm electricity delivery, and nuclear hugely economically disadvantaged by anything that reduces its output to the system. Both these factors decree that the system must possess a level of storage to allow supply to match demand, but who pays for it is clearly a matter for high-level study and policy decisions. As discussed, many of the modelling tools already exist to define the optima, but how the system is made to adhere to the optimum is a higher level matter which needs urgent attention.

Evaluation of the various decarbonisation routes does necessitate underpinned and objective estimates of electricity generation and storage costs and prices, and, in the wider field, needs the same parameters for energy saving, heat, hydrogen provision and energy storage. Currently (and nuclear energy is as much at fault as any other decarbonisation technology), there is an understandable tendency to first determine what the answer must be, then announce this as the result from whatever analysis is carried out. Detecting this on nuclear systems is sometimes surprisingly easy; for example reactors with closed fuel cycles which claim recycling 'on site'. While this minimises transport, it does so at the expense of including the capital cost of these additional facilities in the electricity price calculation. This might indeed work, but the number of reactors on site to make it work is rarely stated and likely to be far too large to meet any realistic site limitations.

The challenge is:

1. to set a realistic cost for a vector to 'qualify' for a place in the market (models such as ESME are good at this); and
2. for nuclear at least, define a 'top-down' methodology. Set out the major blocks of spend on reactors, fuel, O&M, waste storage and disposal, decommissioning; and then see if a credible spend can give 'the right answer' and if so – at what discount rate?

A similar approach is required for other energy vectors – particularly for those, like nuclear, potentially engaged in hydrogen generation for heat and low-carbon fuels. At present there is clearly a recognised 'required hydrogen cost', which is attained by all the methods proposed, often with little supporting evidence. These routes cry out for a 'top down' approach as mentioned above.

One of the requirements for economic viability is 'fleet build in factories', which has been a conspicuous feature of the success of offshore wind power. As has been mentioned previously, the UK nuclear build programme has studiously avoided anything like fleet build for the last 60 years (though the eight Calder Hall and Chapelcross reactors built in the 1950s were very similar), but it would appear that there has been an acceptance of the need for fleet/factory build of SMRs in its latest policy. The discussion on HTGRs in previous sections make it clear that fleet/factory build is the only method likely to succeed for nuclear in the hydrogen market. The achievement of a FOAK demonstrator would enable a viable, largely UK-based, supply chain to be developed and the inclusion of a 'hydrogen generator' in the demonstrator would widen this supply chain to an entirely 'near-zero-carbon-hydrogen-supply'.

This section gives a bare outline of how a broadly optimal energy decarbonisation programme might be derived and tested. What it does not do is indicate how to square the circle between identifying such a programme and putting the detailed elements into practice at a minimum cost for the domestic and industrial consumer. Fortunately, there is a considerable amount of time between the 'identification' and the 'enactment' phases – provided only that a start is made on the overall critical path activities without delay.

5.3 Stakeholders and information availability

All the methods which must be used to achieve net zero will have features that either appeal to or repel different bodies of stakeholders, some of which will inevitably be important in decision making. Nuclear energy has always polarised opinions, with dedicated advocates, but also fervent bodies of stakeholders with fundamental objections. Much of the feeling against nuclear is values-based with, for example, radioactive waste being viewed on a spectrum between:

- a socio-economic view of the world which supports the view of a limited amount of waste to be disposed of under stringent regulation to avoid human or environmental harm; to
- an environmental view, which interprets waste as a huge intractable problem, which cannot but offer the prospect of unacceptable harm to future generations.

These positions are often supported by literature and social media reports offering huge variations on the same potential detriment – from 'hardly worth worrying about' on one side to 'thousands will die' on the other. Fortunately, there is evidence that groups of stakeholders can, given time and expert mediation, actually reach agreement on the 'numbers', while remaining at variance on 'the importance to be attributed to the numbers'. A good example of such a mediated process took place in the BNFL National Stakeholder Dialogue [66], and is detailed in the report of the Spent Fuel Management Options Working Group [67], and summarised in the Executive Summary.

It is suggested that, as a real contributor to concentrating debate on real differences in values rather than spurious arguments on partisan versions of 'facts', that a resource (e.g. a website) could be set up to hold reviewed and mediated information on nuclear energy, with references to detailed peer-reviewed studies on the plethora of topics involved[*]. This would enable interested stakeholders to seek out information which would facilitate debate on a level playing field. This concept has been much discussed by the Dalton Nuclear Institute and would require a highly credible review function, a similarly credible hosting platform, and funding. This would complement the platform set up under recommendation three in §3.6.

This concept is here mentioned for nuclear energy, but ideally, all vectors contributing to net zero would have such a platform, which would minimise the time and effort wasted on debates over the veracity of facts and maximise the time and effort put into the more important debate on how significant the universally-accepted facts are.

***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.**

5.4 Sustainability

Of all the key concepts invoked when considering how to achieve net zero, sustainability is almost certainly the most used, and the least understood. At the scale of this paper, only the barest outline of the subject can be given, but it should be recognised that the use and misuse of sustainability can be key to the overall impressions gained by stakeholders, or even policy makers.

At the international level, the United Nations adopts seventeen 'Goals' [68]. Goal 7 is 'Ensure access to affordable, reliable, sustainable and modern energy for all', which has five sub-goals, such as [68, p. 19]:

> *'7.1 By 2030, ensure universal access to affordable, reliable and modern energy services.'*

Overall, these 17 goals have involved 244 indicators. No country in the world yet collects data on all the targets and indicators, but the UK has risen from 75% to 81% since 2019. There is an 82-page UN publication on the development of statistics for Sustainable Development Goals (SDGs) [69], and it is quite clear that this area is very far from simple, and far from accessible. As an example of this, the SDG indicators are classified into three tiers [70], based on their level of methodological development and the availability of data at the global level. In all the reporting, there is no attempt to rate or rank the importance of the various indicators [71] and this provides a stark contrast to any methods which seek to perform a Multi-Attribute Decision Analysis (MADA).

In fact, after a less than cursory examination, there is a great deal of work and outreach to be done before anything about the SDG indicators and their reporting becomes translatable into plain English on anything but the current indicator by indicator basis. As an example of this, the UK's December 2020 Sustainable Development Goals data update [72] reports that 'the UK has fully disaggregated 38% of the total SDGs with 18% partially disaggregated'. In particular, the UK has not made a start on Goal 7 (Ensure access to affordable, reliable, sustainable and modern energy for all) or Goal 13 (Take urgent action to combat climate change and its impacts). This means that the method of reporting UK Sustainable Development progress to the UK in the areas of energy and climate change have yet to be determined.

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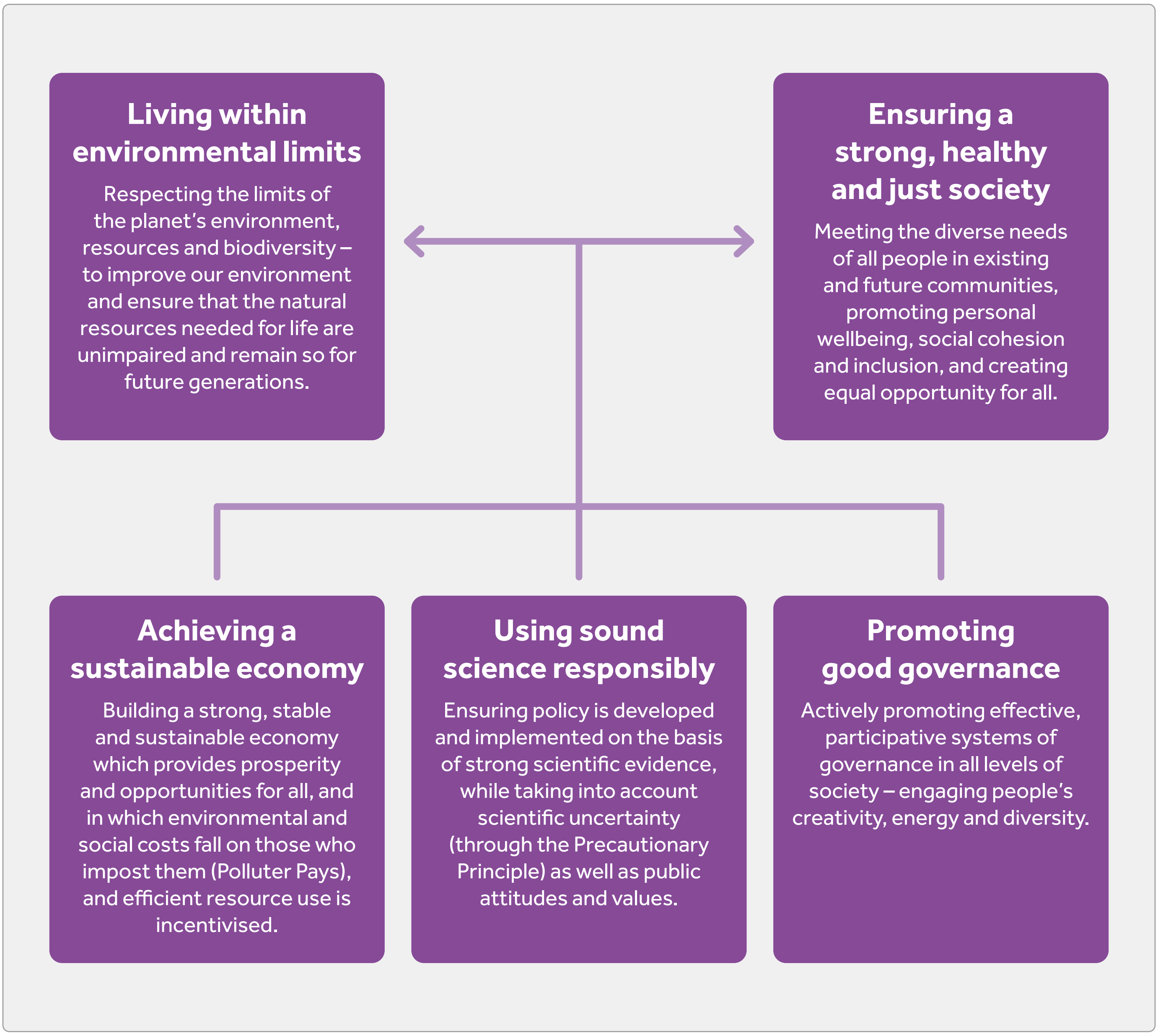
[*] *As an example of such a study, see the EC's Joint Research Centre recent technical assessment of nuclear energy* [75].

The position for UK sustainability reporting within the UK is somewhat easier to understand. The earliest useful publication from the government on sustainable development would appear to be the *Guiding Principles for Sustainable Development* published in 2014 [73]. The key diagram (Figure 4), recognises that there are three 'pillars' of sustainable development, which need to be balanced, and immediately signals that deciding the path of sustainable development will be akin to a MADA, where the 'scores' and 'weights' will need to be optimised by some process to enable 'success' and 'progress' to be judged.

The paper explicitly recognises [73]:

> *'Sustainable development recognises that the three 'pillars' – the economy; society; and the environment – are interconnected. The government has initiated a series of growth reviews to put the UK on a path to a strong, sustainable and balanced growth. Our long-term economic growth relies on protecting and enhancing the environmental resources that underpin it, and paying due regard to social needs.'*

Figure 4. Principles of sustainable development, adapted from [73].



Living within environmental limits

Respecting the limits of the planet's environment, resources and biodiversity – to improve our environment and ensure that the natural resources needed for life are unimpaired and remain so for future generations.

Ensuring a strong, healthy and just society

Meeting the diverse needs of all people in existing and future communities, promoting personal wellbeing, social cohesion and inclusion, and creating equal opportunity for all.

Achieving a sustainable economy

Building a strong, stable and sustainable economy which provides prosperity and opportunities for all, and in which environmental and social costs fall on those who impost them (Polluter Pays), and efficient resource use is incentivised.

Using sound science responsibly

Ensuring policy is developed and implemented on the basis of strong scientific evidence, while taking into account scientific uncertainty (through the Precautionary Principle) as well as public attitudes and values.

Promoting good governance

Actively promoting effective, participative systems of governance in all levels of society – engaging people's creativity, energy and diversity.

It is clear from the outset that there is unlikely to be a hard-wired measure of sustainability in either energy in general or nuclear in particular; with the level (or not) of excellence determined by the optimisation of the three 'pillars' and the two outcomes shown in the diagram. This is inconsistent with the United Nations' equal (and separate) treatment of its 17 goals.

The overall complexity involved in answering the question: what is sustainability?, can be exemplified by the debate on the classification of nuclear energy in the EU's Taxonomy, which is a tool to help investors, companies, issuers and project promoters navigate the transition to a low-carbon, resilient and resource-efficient economy [74]. This seeks to assess whether a given activity 'makes a substantive contribution to one of six environmental objectives', while 'doing no significant harm to the other five, where relevant'. These environmental objectives are:

- climate change mitigation;
- climate change adaptation;
- the sustainable use and protection of water and marine resources;
- the transition to a circular economy;
- pollution prevention and control;
- the protection and restoration of biodiversity and ecosystems.

The outcome of this assessment determines the terms on which initiatives can be financed, which is crucial for a high initial cost practice like nuclear energy.

The EU Technical Expert Group on Ethical Finance found itself unable to judge whether nuclear, while extremely good at climate change mitigation, qualified for ethical finance on the basis of 'doing no significant harm' in other areas. The matter was referred to the EC's Joint Research Centre (JRC), who have duly produced a 387-page report [75], which has provided a far-reaching and extremely detailed analysis of the extent of the downsides from nuclear energy generation, but without an agreed balancing mechanism there will still be room for huge debate. The lack of an agreed balancing methodology has permeated this report section, and underlines the ability for individual interests to claim sustainability 'miracle cures'.

The most basic sustainability measure for nuclear (fission) energy is the ability of uranium resources to support the likely worldwide nuclear energy generation for an extended period. This immediately brings 'balances' into play, as the amount of uranium available will depend on the grade of ore that is exploited, down to and including the four billion tonnes contained in sea water at 3.3 ppb*. While the lack of sustainability at this end of the spectrum has been pointed out [76], the economics of geological extraction will largely determine the overall size of the resource. However, it can be confidently stated that at currently credible uranium costs, the resource will support any conceivable once-through fuel cycle nuclear programme for at least most of this century. These open cycles use only around 1% of the energy in the mined uranium, and this can be multiplied by at least a factor of 50 by changing to a closed fuel cycle. The period until uranium exhaustion would then increase from many decades to several centuries. This change will remain available for as long as the spent fuel and the depleted uranium from enrichment remain available for recycle. Therefore the biggest sustainability-based development for nuclear energy is likely to be the decision to actually dispose of these resources, placing them beyond use.

5.5 **Decision making**

First and foremost, this paper is about helping the UK to plot and follow a credible path to net zero by 2050. It starts with the hypothesis that such a path would be more difficult and expensive to realise without a significant role for nuclear energy, and in this would seem to be supported by the majority of credible studies in this area. Many of the paper's arguments are based on the firm foundation of an analysis of the UK's failure to build on early successes in nuclear, regularly changing policies every few years (usually for reasons of political expediency) on an activity that must foster and derive value from technology development and deployment over decades.

However, by declaring a policy to completely decarbonise the UK's economy over three decades, the UK government has, hopefully irreversibly, put itself in the position of needing a 30-year action plan. This puts it on a course which can support a sensible nuclear energy deployment plan in the fields of near-zero-carbon electricity, together with high and low temperature heat.

The drivers for decarbonisation are simple: the conservation of the planet we live on, the living standards of its human inhabitants, and the continuation of all the ecosystems which also call it home. It is a goal increasingly shared, even if only in name in some cases, across the world, and the UK's position will be brought into sharp focus by the COP26 conference in Glasgow in November 2021.

Unsurprisingly, such a 30-year action plan will require a steady, long-term path, and this paper outlines the attributes of such a path for the contribution of nuclear energy. The action plan needs to be based on credible and verifiable assessments of all its component parts, and here there is the obvious need for openness to be achieved, while

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* *Parts per billion.*

allowing a sensible role for commercial competition. Many of the current decarbonisation vectors, including nuclear in some quarters, sell themselves as 'miracle cures' of various sorts. A key need at the beginning of the action plan must therefore be to find a mechanism to achieve these 'credible and verifiable assessments' without discouraging or discrediting successful innovation.

This is the key message of this study. It seeks nuclear where appropriate and advantageous, but seeks to avoid being side-lined by unsupported hyperbole. It is to be hoped that this 'best for the UK, best for the planet' message can be turned into reality.

6

Conclusions

This study has affirmed the conclusions of both NIRAB and the energy white paper that nuclear energy can, subject to proving its economics, have a significant role in enabling a pathway to the UK's target of net zero by 2050. This should include firm electricity generation by Gen III+ and SMRs, together with the evaluation of excess heat being used for district heating.

The generation of hydrogen using high temperature nuclear heat is another potential role for nuclear fission, and here the case for examining the construction of a UK-sited HTGR Demonstration Reactor is persuasive, together with the evaluation of also demonstrating the use of the high temperature heat to generate low-carbon hydrogen.

The review of the status of HTGR technology has pointed to the need for the UK to team internationally and has presented an outline review of the various possibilities. The review of the technological abilities both in the UK and overseas has indicated that a demonstration reactor could be online by 2030, but that this date is very much on the critical path. In particular, achieving this objective will require a suitable organisation to be empowered to progress and integrate the whole task from R&D in both reactor technology and hydrogen generation and international teaming through to reactor siting and build.

The progress of this new (or newly empowered) entity should be overseen by a broadly-based advisory body engaged to offer advice to government on all aspects of the forward nuclear programme. This work should be against the background of an ongoing UK view of the developments in AMR systems led by a body unconflicted by the claims and lobbying from any particular system proposer. Such a system should also be considered for all the energy sources present in the net zero path to enable government, stakeholders and potential technology providers to have a clear and unbiased view of the current net zero state of play. This system, with suitable peer review, should enable a less diverse range of views of the viable net zero paths by ensuring that only potentially viable systems are afforded support.

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.

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.

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.

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.

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.

Recommendation six

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

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.

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.

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