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NUCLEAR INNOVATION AND RESEARCH ADVISORY BOARD

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Achieving Net Zero: The role of Nuclear Energy in Decarbonisation

A Report for the Department for Business, Energy and Industrial Strategy (BEIS)

NIRAB-244-1

Contents

Foreword from the Chair

Mike Tynan
NIRAB Chair

It has been a privilege to Chair the Nuclear Innovation and Research Advisory Board (NIRAB) over the 2 years between 2018 and 2020, and I am pleased to present this report, which is the culmination of the Board's work over that period. This report is published at a crucial time for the nuclear industry. A time when society is increasingly aware of the need to reduce carbon emissions, and the UK Government has made specific commitments to achieve net zero carbon emissions by 2050. This is an ambitious target and one that will require step-change approaches to energy generation, transmission, and usage in the UK. This is a time for innovation, creativity, and positive change in the way we meet our energy needs now, in the medium, and long term. As a nation, we have harnessed the power of the atom; fission, to generate electricity for over 60 years, and we are a world leader in the development of fusion technology. I believe it incumbent on us as leaders in the nuclear industry to ensure that civil nuclear power plays a significant role in the delivery of a low-carbon economy that meets carbon emission goals, creates economic value for the UK, and provides clean energy for the 21st century and beyond.

The mainstay of our civil nuclear power generating capacity in the UK has been the gas-cooled reactor, the first generation of which, the Magnox stations, recently came to the end of their working life. The second generation of UK nuclear reactors; the Advanced Gas Cooled Reactors (AGR's) operated for over 40 years. Their closure, anticipated to be within the next decade, will bring to an end a successful, safe, and reliable source of low-carbon electricity generation from gas-cooled nuclear reactors.

To replace these out-going reactors we require the development and delivery of new commercial nuclear power stations on a fleet scale. We have one new nuclear power station, a third generation Pressurised Water Reactor (PWR), under construction at Hinkley Point C in Somerset that will complement the UK's existing PWR at Sizewell B in Suffolk. However, this will only partially replace the generating capacity we will have lost by 2030. We need to ensure that research and innovation helps deliver a new civil nuclear programme that continues to meet the highest safety standards and delivers low-cost power for the UK. It might be that some of these stations are smaller than the Gigawatt scale units we had assumed would replace existing capacity. This has paved the way for the development of a Small Modular Reactor and the beginning of a programme for Advanced Modular Reactors that will see significant development of new applications for fission and fusion technology.

Over the last two years the Government has implemented a successful Nuclear Innovation Programme (NIP), which is consistent with recommendations from the inaugural NIRAB. It is vital that we build on the existing NIP, to augment and develop it to help ensure that nuclear power has an exciting and economically attractive role to play in our energy future. This report proposes a new NIP, identifies the technology themes that we should support, provides the logic to support those proposals, and makes recommendations to bring such a programme into delivery.

Now is the time for decisions that will bring step-change in capability and capacity into our energy systems. There is an imperative for industry and Government to work together on nuclear technology to secure a vibrant nuclear industry that cost effectively deals with the clean-up of legacy nuclear facilities, sustains current nuclear plant operation, and develops a next generation of low-carbon nuclear power. Industry and Government collaboration must span sector and international boundaries, it must encourage innovation, sharing of learning, and application of innovative technology already deployed in other industries. The nuclear regulators have already recognised the role of innovation in securing a safe and reliable nuclear industry and their early involvement in future programmes will add to the likelihood of their successful implementation.

The work of NIRAB and the Nuclear Innovation Research Office (NIRO) directly supports the UK Governments ambition for net zero carbon emissions by 2050 and brings together industry and academia to give independent and robust advice on the future of civil nuclear technology. I would like to thank all of those involved with NIRAB and NIRO over the last two years who have provided opinion, challenge, creativity, expertise, and hard work. This report is the fruition of that effort and I hope it gives impetus to the programme of investment needed to overcome the challenges we face in realising our goals for a low-carbon future.

Mike Tynan
Chair, NIRAB

Executive Summary

Climate change is a global issue and one of the greatest challenges faced by society. Urgent action is required to mitigate these unfavourable changes and as such, the UK Government has committed to achieving net zero carbon emissions by 2050. In order to achieve this target, it will be necessary to meet a significantly increased demand for electricity, and to decarbonise a wide range of other energy uses such as, but not limited to, domestic heating, heavy goods transport and industrial processes. However, delivering a sustainable, robust and cost-effective energy network to meet net zero UK commitments will be incredibly challenging. This report aims to support Government in meeting this challenge by identifying the role that an innovative civil nuclear power programme should play in such an energy system and the action needed by Government, with the support of industry, to realise that potential.

Achieving a net zero target by 2050 is likely to require all the available and capable low-carbon technologies to be deployed at scale and at the earliest opportunity; including nuclear, renewables and gas combined with Carbon Capture and Storage (CCS).

Nuclear, as well as being a source of cost competitive electricity, can contribute to the production of heat and hydrogen to decarbonise other energy vectors.

Of these, nuclear is the only 24/7 low-carbon technology to have been demonstrated at scale and has provided clean, safe and secure electricity to the grid since 1956. Therefore, in terms of energy security, cost to the economy and the ability to meet the net zero target, planning a future net zero energy system without significant nuclear energy would be extremely high risk.

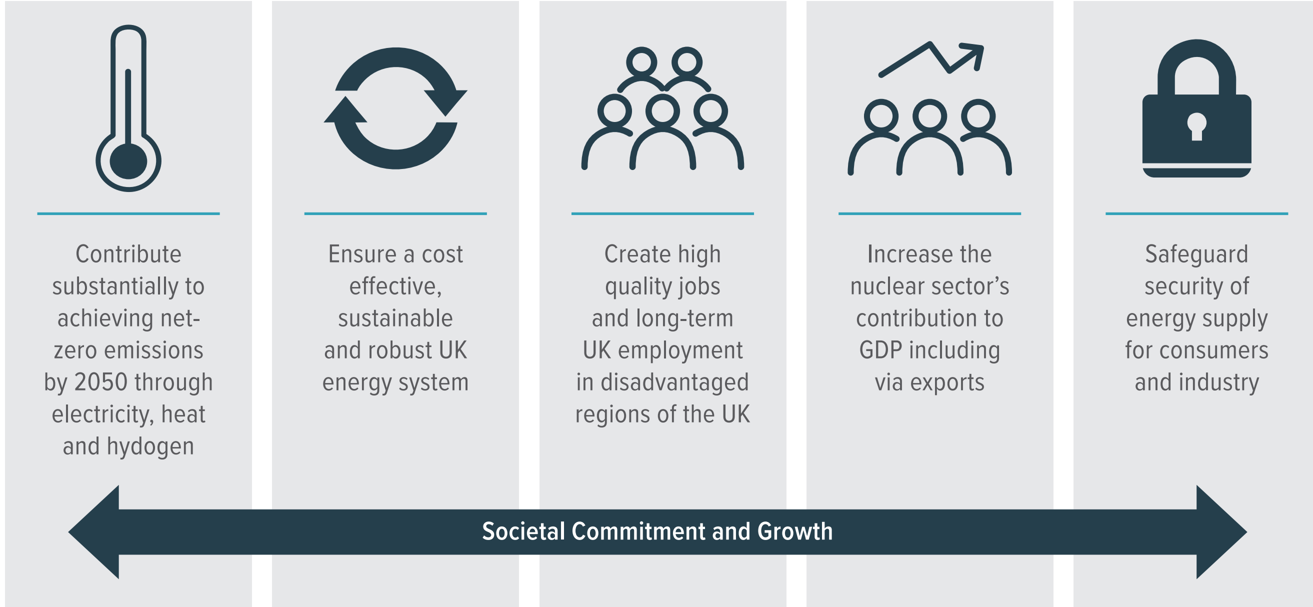
The Nuclear Innovation Research and Advisory Board (NIRAB) is convinced that new cost-competitive nuclear power must make a significant contribution to meeting the increased demand for low-carbon electricity. It would be prudent to plan for nuclear energy to provide at least half of the firm low-carbon electricity not provided by renewables. NIRAB is also convinced that nuclear power has the potential to contribute to the decarbonisation of other energy vectors, playing an increased role in a connected future clean energy system. Further work is required to quantify how nuclear can best support cogeneration; to use a high temperature process to generate hydrogen or synthetic fuels, together with the ability to switch over to delivery of mid-merit electricity, when required.

Planning a future net zero energy system without significant nuclear energy would be extremely high risk.

Nuclear may be required to make a larger contribution to the energy mix should, for example, very high capture rates (>99%) prove more challenging than anticipated and residual carbon emissions from CCS cannot be accommodated. NIRAB proposes that three streams of nuclear product development and deployment should be progressed to supply the energy needs of the population and support economic prosperity without impacting on climate change or air quality:

- Large scale Light Water Reactors (LWR), which are currently available and suitable for baseload electricity generation;
- Small Modular Reactors (SMR), which are based on the same proven technology and can offer additional flexibility to meet local energy needs;
- Advanced Modular Reactors (AMR), which typically have a higher temperature output, consequently enabling them to contribute to decarbonisation through heat and hydrogen production, as well as generate electricity at competitive costs.

These products have different characteristics and together could deliver the following benefits:



Over 80% of the UK's nuclear generating capacity will reach or exceed its design life and is scheduled to be lost within a decade, along with its direct employment and its operational supply chain. Consequently, there is an urgency to establish and implement a nuclear energy strategy cemented in enduring Government policy, with increased rollout of large-scale reactors and investment in Small and Advanced Modular Reactors.

Recommendation 1

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

As part of this, Government should continue to support:

- Advanced digital design;
- The deployment of advanced manufacturing methods and the UK supply chain capability in this area;
- The development of an improved methodology for developing codes and standards for new manufacturing methods, aligned to SMR programme needs.

Recommendation 2

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

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

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

AMR development should focus on systems that can be commercially deployed in time to make a significant contribution to meeting the net zero 2050 target. Technology down selection will need to take into account a number of factors including, but not limited to:

- The availability of evidence from the operation of reactor systems which provide a direct line of sight to the proposed design;
- The availability of a global or domestic infrastructure to draw upon for the supply of components, materials and fuel;
- Synergies with UK technical capability and experience.

High Temperature Gas Reactor (HTGR) systems score well against these criteria and are also being progressed in international programmes. NIRAB considers this technology is the most likely to be developed in the timescale required, given the above requirements.

Recommendation 3

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

A detailed techno-economic evaluation of the available technologies should be performed as soon as possible against functional requirements of the energy system (e.g. synergies with renewables, competitively priced electricity, heat, hydrogen generation or synthetic fuel production). The programme should facilitate the integration of the reactor system with the broader energy system, addressing other energy needs in addition to electricity generation. Following technology selection, sufficient resources should be allocated to alternative reactor concepts, to enable the UK to remain a credible international partner in their longer-term development.

The Nuclear Innovation Programme (NIP), funded by BEIS should support the technical and commercial cases required to underpin commercial deployment. Elements of the programme covering longer timescale technologies should continue but should form a smaller percentage of future publicly funded civil nuclear research. An effective, structured programme management regime should be applied to the NIP.

Recommendation 4

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

Where necessary, the programme should also seek to optimise UK owned / controlled intellectual property to create supply chain opportunities and to maintain core skills and capability in civil nuclear.

Taking a programmatic approach will place a greater emphasis on topics such as the development of advanced fuels and technologies for using nuclear heat to generate hydrogen. It will also include topics relevant to multiple reactor systems, including those that could be deployed on a longer timescale. Such topics include digital design, nuclear safety and security and advanced manufacturing methods for materials.

The recommended budget for public investment in a continued NIP for the 5-year period starting in April 2021 is £400M for research and development and £600M for advanced reactor demonstration, exclusive of any potential investment in a UK SMR. To achieve demonstration of an advanced reactor technology in the period 2030 to 2035 a high level of pubic investment is needed from April 2021 to ignite private sector investment and raise investor interest and confidence.

The reactor systems, fuels, disposal route and energy conversion plant associated with a UK based demonstration will require ten years to develop and construct.

NIRAB highlights the crucial importance of international engagement in the development and demonstration of nuclear technology. Accessing international expertise, critical R&D infrastructure and leveraging research, development and demonstration programmes will reduce risks, enable SMR and AMR technologies to be developed and commercialised in a cost-effective, timely manner. Indeed, international collaboration may be the only practicable route to commercialise AMRs on the timescale required to make a significant contribution to meeting the net zero target. The Generation IV International Forum (GIF), Euratom nuclear fission research programme and bilateral engagement with countries where synergies exist, all offer opportunities for such collaboration.

Recommendation 5

UK investment in nuclear fission should be leveraged effectively through international R&D programmes, that will enable successful commercialisation of technology to accelerate timeframes, making best use of resources, expertise and nuclear infrastructure.

A number of synergies exist between the needs and the challenges of AMRs systems and fusion, especially in relation to the fact that both will generate a high temperature output which may need translating into other energy vectors. The R&D programmes and associated infrastructure requirements surrounding advanced materials, computational simulations, and robotics & artificial intelligence will benefit both GIF fission technologies and fusion systems.

Recommendation 6

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

Cost effectively delivering net zero in the UK, whilst minimising the impact on society, is an enormous challenge that we all need to face. NIRAB firmly believes that addressing these six recommendations presents the best opportunity to deliver nuclear into the UK energy system for all the decarbonisation benefit it provides.

NIRAB trusts that its recommendations will provide Government with the guidance it requires to set future priorities and welcomes the opportunity to discuss any aspect.

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

1. Introduction

The Nuclear Innovation Research Advisory Board (NIRAB) exists to provide independent expert advice to Government on the publicly-funded civil nuclear research and innovation programme required to underpin energy policy and industrial strategy, and to foster cooperation and coordination across the sector.

This report provides a summary of the activity of NIRAB since April 2018. It reflects the progress made by NIRAB in formulating advice to Government on the future role of new nuclear energy as a means to achieve net zero by 2050 and in doing so create positive economic impact and jobs. A number of recommendations for action are made accordingly.

1.1. NIRAB Remit

NIRAB has been convened to provide independent expert advice to Government. Government tasked the Nuclear Innovation and Research Office (NIRO) with convening a reconstituted and restructured NIRAB able to draw on a wide range of expertise. The re-convened NIRAB first met on 4th April 2018.

The role of NIRAB is set out in its terms of reference (Appendix 1). Government has asked that NIRAB:

- Monitor the delivery and impact of the BEIS Nuclear Innovation Programme (NIP) and recommend any amendments that may be necessary in the light of outputs from the programme and developments in the nuclear landscape;
- Advise where innovation could drive down costs across the whole nuclear cycle;
- Identify opportunities for greater collaboration with industry and international partners;
- Support the development of recommendations for new research and innovation programmes required to underpin policy priorities including energy policy and industrial policy;
- Oversee a regular review of the nuclear research and innovation landscape which may include facilities, capability, portfolio and capacity in the UK;
- Foster greater cooperation and coordination across the whole of the UK's nuclear research and innovation capability, portfolio and capacity.

Ministers, Government Departments and Agencies seek advice from NIRAB on issues related to civil nuclear research and innovation in the UK. NIRAB member profiles are provided on the NIRAB web site [1]. Details of the role the NIRO undertakes in supporting the operation of NIRAB are included in Appendix 2. NIRAB does not have responsibility for managing or delivering research and innovation programmes or for directing or managing budgets, ensuring advice is appropriately independent.

NIRAB, supported by NIRO, has primarily operated through smaller working groups, holding workshops to consider specific areas of focus. These working groups have been restructured and consolidated since the publication of NIRAB's previous report [2]. The current working group structure is detailed in Appendix 3.

1.2. Structure of Report

In April 2019 NIRAB published a report [2] highlighting the urgent need to take action to enable nuclear power to make a significant contribution to meeting a target of an 80% reduction in emissions. Since then Government has adopted a much more challenging net zero emissions target. NIRAB has focused on understanding the role that nuclear energy can play in meeting this target, whilst underpinning Government policy and industrial strategy. In Chapter 2 of this report the current and emerging energy landscape is described. Chapter 3 summarises the role that nuclear should play in meeting a net zero target by 2050. The net zero target emphasises the need to go beyond decarbonisation of electricity and to make significant inroads into, amongst other areas, decarbonising heat and the production of hydrogen and synthetic fuels. Chapter 3 also covers cost reduction considerations enabling nuclear energy to be cost competitive and play a significant role in meeting future energy needs. NIRAB is convinced that this can be achieved.

Finally, Chapter 4 considers current and future research and development needs as well as future R&D Infrastructure requirements to support achieving Government strategic ambitions.

2. The UK Energy Landscape

This chapter describes the context within which NIRAB's advice and recommendations have been developed. It summarises the broader clean energy challenge and discusses the evolving landscape.

2.1. The Emerging Energy Market and the Clean Growth Challenge

Climate change is a global issue and one of the greatest challenges faced by society. UK leadership in combatting climate change by reducing greenhouse gas emissions is vital in addressing this challenge. A number of non-nuclear international bodies (including the International Energy Agency (IEA), Organization for Economic Cooperation and Development and European Union) have indicated that without a significant increase in the deployment of nuclear power, it will be difficult for the world to secure sufficient energy to achieve sustainable development and to mitigate climate change. The IEA further notes that an 80% increase in global nuclear power production is needed to meet international climate goals [3]. The same report makes a number of enabling policy recommendations further demonstrating the significant challenge of decarbonising without nuclear energy.

In the ten years to 2019, the UK set a series of carbon budgets aimed at reducing emissions by 80% from 1990 levels by 2050. The first two carbon budgets have been achieved with the UK being on target for third budget. However, Government has already identified [4] projected shortfalls against the fourth and fifth carbon budgets. The UK net zero commitment significantly increases this challenge.

In 2019, the Committee on Climate Change (CCC) published its recommendations to limit emissions of greenhouse gases over the next 30 years with a target of net zero emissions by 2050 [5]. Whilst net zero is significantly more ambitious than previous targets, upon reviewing the latest scientific evidence on climate change, the CCC concluded that net zero is necessary, feasible and cost-effective. Government accepted the main conclusions of the CCC report and the UK adopted a net zero emissions target for 2050 through the Climate Change Act 2008 [6], the first country to do so. Since the CCC report a number of further studies have been conducted. This report considers the evidence from the CCC and such studies.

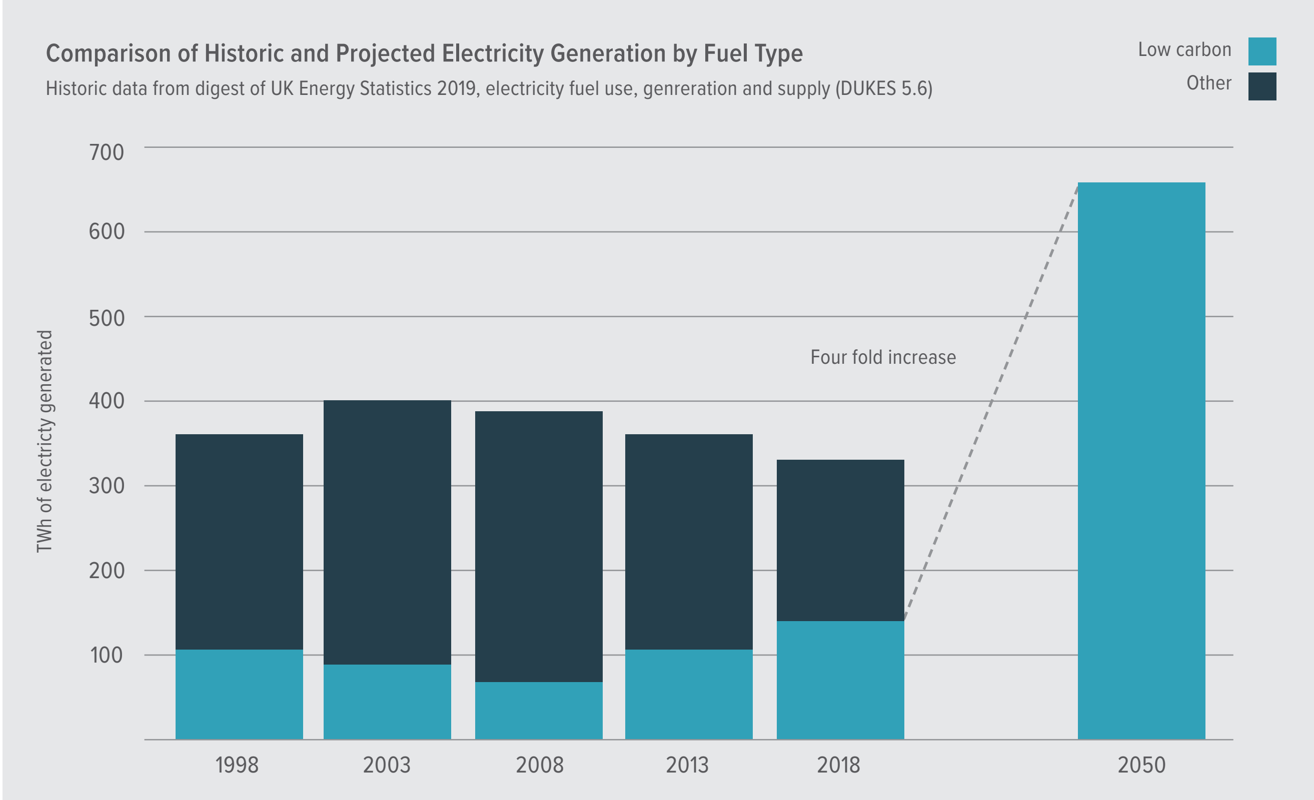


Figure 1 Comparison of historic and future electricity generation [20]

Over and above decarbonising electricity generation the UK must decarbonise housing and domestic heat, industrial emissions, transport, agriculture, aviation and shipping to meet the net zero commitment. Of course, the costs of implementation of these activities are considerable, though the last decade shows that electricity generation costs can fall when a concerted effort is applied through Government and Industry actions. Continued effort is now required to enable nuclear to achieve the same and deliver on wider energy demands.

Several non-nuclear international bodies (including the International Energy Agency, OECD and EU) have indicated that without a significant increase in the deployment of nuclear power, it will be difficult for the world to secure sufficient energy to achieve sustainable development and to mitigate climate change.

2.1.1. Future Electricity Demand

Future energy scenarios have been published by a range of organisations, including the CCC [7], the National Grid [8], Energy Systems Catapult [9], BP [10], the Energy Technologies Institute [11], Imperial College [12], Ofgem [13,14,15,16] and the Royal Society [17]. Each offers a different perspective on the details of future energy supply and demand. However, they are consistent in reflecting a considerable increase in demand for electricity and the need to decarbonise other elements of energy use to meet the net zero target.

This report uses the terminology employed in the CCC report:

- 'Firm' power – production that can be scheduled with confidence well in advance;
- 'Mid-merit' power – provided by power stations that can flexibly adjust their output over short periods of time (under an hour).

Meeting the additional demand for electricity arising from electric vehicles and heat pumps, and fully decarbonising electricity supply will require an increase in the share of low-carbon and renewables generation to around 95% in 2050. When combined with the increased demand, low-carbon electricity generation could need to be as much as four times today's levels (see Figure 1). This will require an increased and sustained infrastructure build programme for new generation. The increased renewable component will need to be complemented by low-carbon firm power options such as nuclear and gas / biofuels in conjunction with Carbon Capture and Storage (CCS).

To meet the growth in low-carbon electricity demand the CCC identified the need to construct 5 to 8 GWe of firm (baseload) renewable generating capacity and 1 to 2 GWe of other low-carbon generating capacity every year between now and 2050 (a total of 150 to 240 GW and 30 to 60 GW respectively). The CCC assumed that the non-renewable low-carbon generating capacity would be delivered by a combination of nuclear and gas fired stations operated in conjunction with CCS. However, CCS has yet to be demonstrated to achieve the necessary removal rate at an industrial scale.

2.1.2. Other Future Energy Demand

Government statistics show that in 2018 electricity generation accounted for less than 20% of UK CO_2 emissions, as illustrated in Figure 2 [18]. Substantially more effort will therefore be required to decarbonise other elements of energy use which include:

- Transport including cars and heavy goods vehicles;
- Space heating in both domestic and business premises;
- High temperature heat used in industrial processes;
- Shipping;
- Aviation;
- Agriculture.

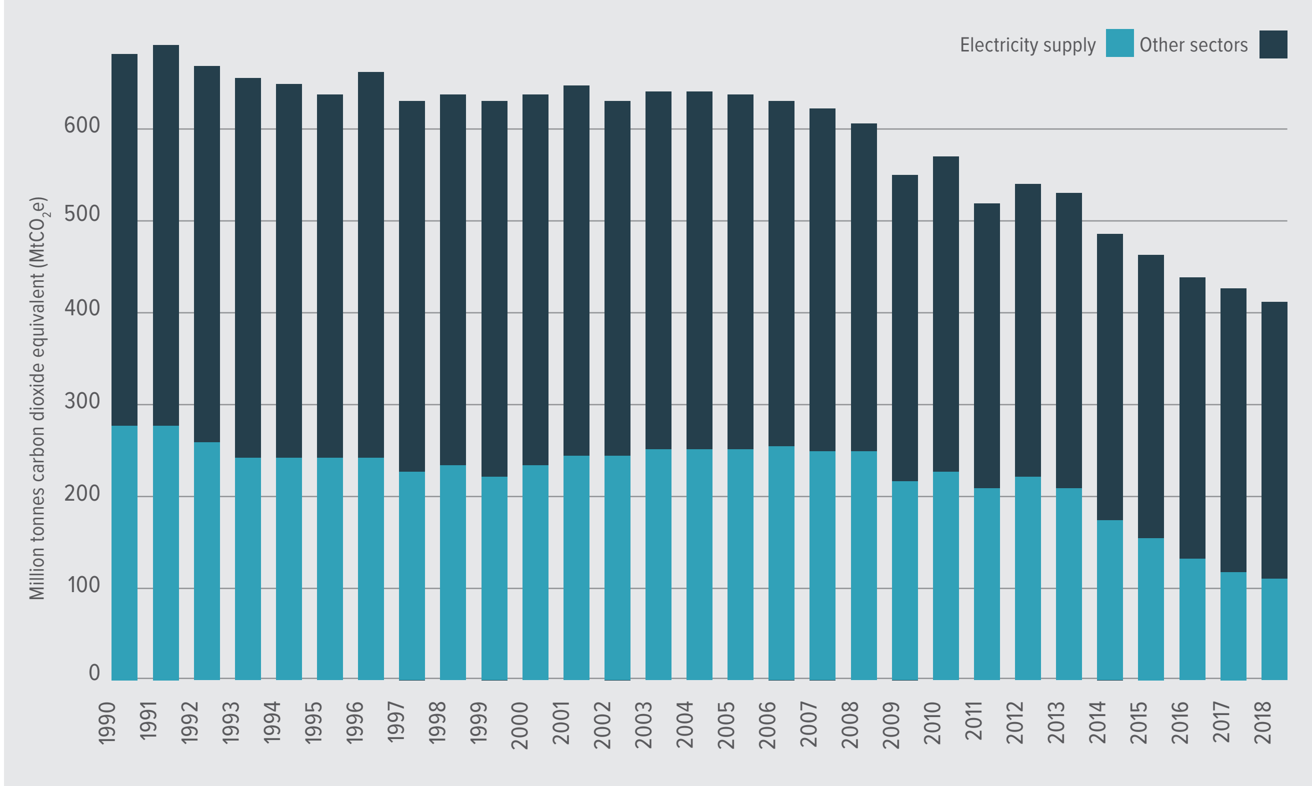


Figure 2 CO_2 emissions from electricity generation compared to other CO_2 emissions, 1990 – 2018 ($MtCO_2$) [18]

In 2018, transport emissions accounted for more than 30% of CO_2 emissions in the UK [18], and therefore meeting the 2050 target will require decarbonisation of the transport sector by phasing out traditional petrol and diesel cars [13]. Almost half of the UK's energy consumption relates to the heat needed for homes, businesses and industry. There are several possible ways to decarbonise space heating displacing natural gas, though only options that prove affordable and commercially viable will be deployed. The CCC [5] assumes that electrically driven heat pumps will be the primary means of decarbonising domestic heat. Another option is district heating utilising a low-carbon heat source as the preferred option for heat networks in densely populated areas. A further approach which would have synergies with the decarbonisation of other elements of the energy system would be to replace hydrocarbon gases for heat generation with hydrogen. The economic practicability of these options remains to be demonstrated.

Hydrogen is also a key feedstock for producing synthetic carbon-free fuels and has been suggested to be used in hydrogen fuel cells to power heavy goods vehicles. In future scenarios, hydrogen is assumed to play a major role in transport and domestic heating. The CCC has identified three main technology options for hydrogen generation, namely gas-reforming with CCS; bio-gasification with CCS; and electrolysis (further increasing the demand for low-carbon electricity generation). Steam reforming and gasification are currently the primary large-scale hydrogen production routes, but both processes consume fossil fuels and result in significant CO_2 emissions. Electrolysis is an option, but it is inefficient. Thermochemical water splitting processes are clean and more efficient but further development is required prior to commercially deployment.

The Royal Society has reported on methods of hydrogen generation, though nuclear was only seen as a potential source of electricity for electrolysis [17]. However, the International Atomic Energy Agency (IAEA) has published a technical report on hydrogen production using nuclear energy, including thermochemical water splitting processes driven by high temperature nuclear heat [19]. This technology is seen as a potential option to contribute to the UK's hydrogen demand. To meet the requirements of potential future hydrogen demands the CCC note that annual hydrogen production will need to increase ten-fold by 2050 with its expanded uses in industrial combustion, heavy goods transport, buildings heat and power production. Furthermore, hydrogen has the potential to be utilised as a feedstock for synthetic fuels to support aviation, shipping, diesel engines etc, and NIRAB believes that the IAEA is correct to highlight the potential role for nuclear in thermochemical hydrogen generation.

2.2. The Current Energy Position

2.2.1. Electricity Demand

Current electricity demand (about 300TWh/year) is met by a mix of low-carbon and unabated fossil fuel technologies. The UK has made significant progress in decarbonising electricity generation. In 2018, more than 50% of the UK electricity was supplied by low-carbon sources [20], up from 30% in 1998. The trend over time is illustrated in Figure 3.

In 2018 the contribution of low carbon sources to total electricity generation was as follows:

- 20% of electricity generation was from nuclear power;
- 21% was from variable renewables sources such as wind and solar power;
- 12% was supplied by bioenergy (10%) and hydro power (2%).

The balance was supplied primarily by fossil-fuelled power generation (40% gas & 5% coal). Current trends in electricity generation show renewables growing significantly, coal declining rapidly, and unabated gas continuing to be significant.

Nuclear has provided safe and secure low-carbon baseload generation since 1956. However, the 38% nuclear contribution to low-carbon electricity is increasingly vulnerable due to the ageing of the Advanced Gas-cooled Reactor (AGR) power station fleet. Having been built in the 1970's and 1980's, the majority of the UK's 9 GW of nuclear power plants are set to retire by 2030 (Sizewell B remaining), even including the currently planned life extensions. This means that over 80% of the UK's nuclear low-carbon generating capacity will be lost in the next decade.

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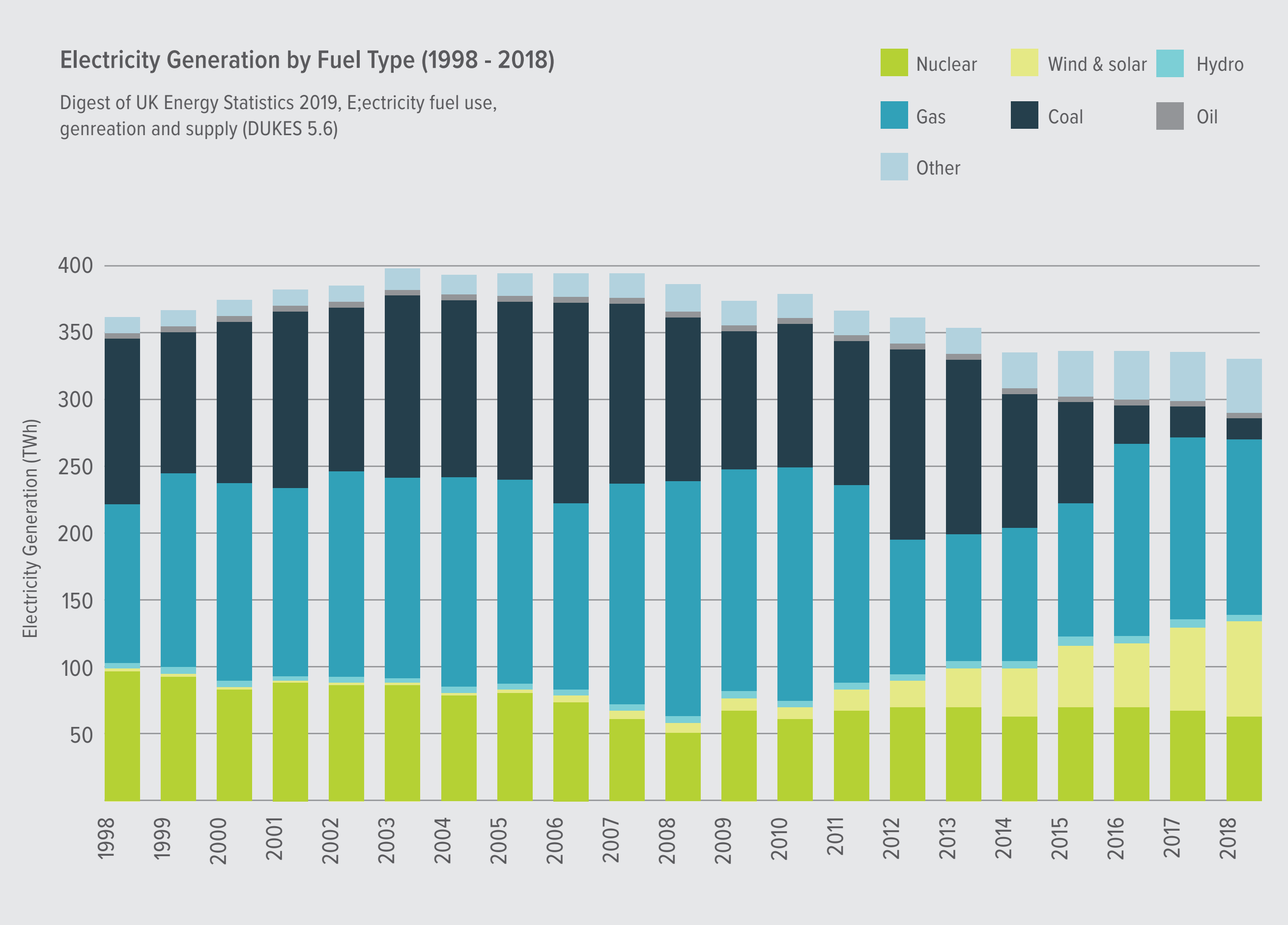

Figure 3 UK electricity generation by fuel type (1998 – 2018) [20]

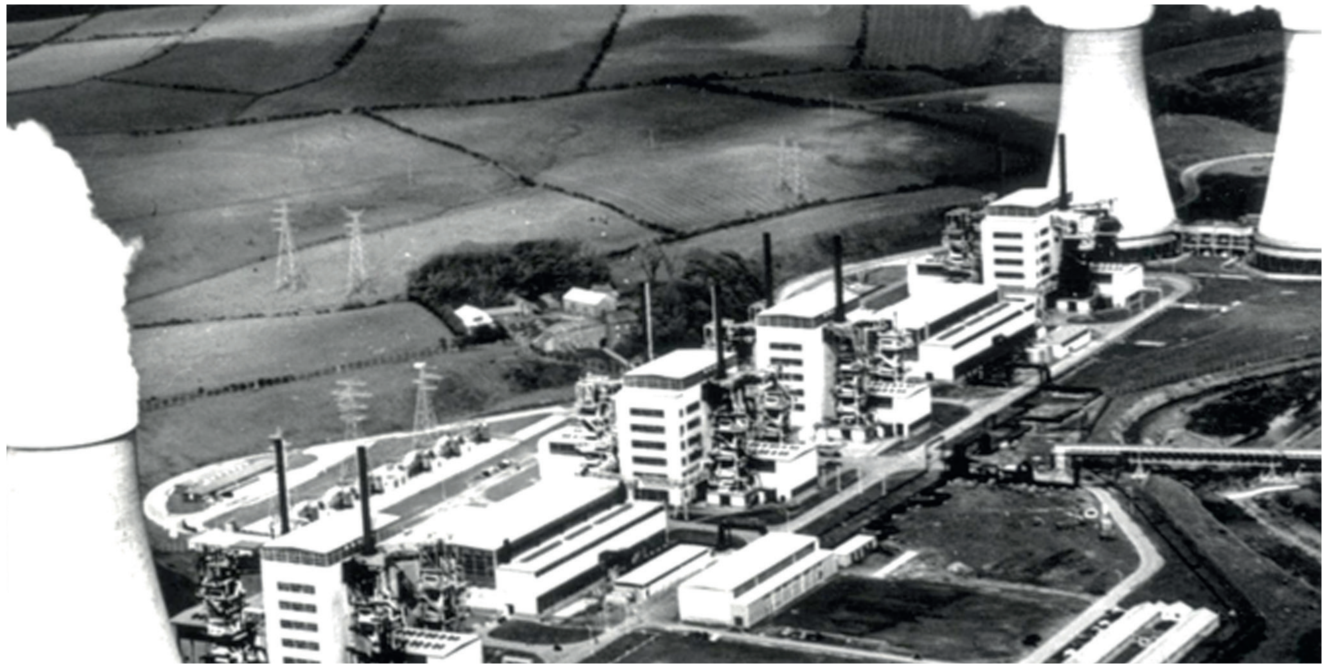

Figure 4 The world's first nuclear power station - Calder Hall, 1956

For nuclear power to just maintain its current contribution to the UK's electricity needs, the new build programme must be sustained: with Hinkley Point C and two further power plants of similar scale being built and commissioned by 2030.

2.2.2. Other Energy Demand

The energy required for transport and heat is currently met through carbon-generating technology options including petroleum products and natural gas. Whilst hydrogen is seen as the low-carbon energy vector of choice for many future non-electricity needs, UK production is currently low (0.7 Mt/year equivalent to 27 TWh, <10% of the total electricity production of more than 330 TWh). It is produced via steam methane reforming or partial oil oxidation, both of which also produce carbon dioxide. Currently hydrogen is used primarily in chemical and agricultural industries, but not for combustion for energy / heat.

2.3. Summary

Meeting the net zero emissions target will be a significant undertaking, galvanising the energy sector to meet this extremely demanding challenge. All current and emerging low-carbon energy technologies will need to be deployed, at scale, to have confidence that the target will be met. This includes nuclear, renewables, storage and gas technologies coupled with CCS.

NIRAB notes that the CCC [5] has highlighted that CCS will not be 100% efficient and will entail a degree of residual CO_2 emissions. Until the efficiency of a capture process has been demonstrated and the feasibility of establishing the transport & storage infrastructure have been established, it would be premature to rely on CCS to the exclusion of other options.

NIRAB supports the Government approach of funding a broad technology development portfolio, which will bring forward a range of options to meet the challenge. NIRAB notes that nuclear is the only low-carbon, proven technology that has been delivering low-carbon electricity to the grid for more than two generations. Such dependability is vital when coupled with other sources without such certainty.

Today's actions, which shape the emerging energy system, need to be cooperative such that synergies between firm and mid-merit energy technologies (including storage and transmission) can be exploited to build a robust (reliable and secure) and cost-effective net zero energy system for 2050.

Nuclear is the only proven technology that has been delivering low-carbon electricity to the grid for more than two generations. Such certainty is vital to mitigate other energy sources without such certainty.

3. The Role of Nuclear in Energy System Decarbonisation

The full decarbonisation of the economy is the largest challenge to be faced by our generation and to achieve it we must think radically about the whole energy system. With only 1550 weeks from the date of publication of this report until 1st January 2050 there is an urgency to make decisions and the rate of carbon abatement must increase [22]. Of the time available, 2% has passed since the net zero target was set and every 4 months another 1% of this time passes.

With only 1550 weeks until 1st January 2050 there is an urgency to make decisions and the rate of carbon abatement must increase.

Meeting net zero will involve large scale deployment of all the tools available to us along with a fundamental shift in the way in which existing and new energy technology is developed and deployed. Short and medium-term decisions taken by Government will determine decarbonisation success, or otherwise. Urgent decisions are needed on the development and deployment of new nuclear projects to replace current reactors that are due to close and on interventions on nuclear research and innovation to enable the next generation of clean, safe, flexible nuclear technologies.

Nuclear is widely accepted to have a role in a 2050 energy system [11, 5, 8, 3, 9] and alongside renewables is a valuable and low risk decarbonisation tool. The most recent modelling [9] shows a role for nuclear to provide 50% of electricity (equivalent to around 35 GW electricity generating capacity) in 2050 for a cost optimised energy system. Furthermore, nuclear power remains the only mature low-carbon option that currently meets the requirements of the UK energy system to complement the widespread deployment of renewable technologies and their associated intermittency.

At the same time, recent literature highlights the significance of residual emissions from CCS when deployed in the power sector and highlights the fact that achieving net zero with high quantities of CCS could be dependent on achieving very high (99%) capture rates [9,7]. Consequently, NIRAB consider that the current 2050 energy system thinking should seek to complement renewables and CCS with a significant nuclear contribution. NIRAB asserts that maximising the role of nuclear to supply energy in multiple forms and to a wide range of sectors is key to deep decarbonisation and that this is not adequately considered in the current climate change discussion.

It is vital to recognise the importance of diverse options to net zero and the value of the cleanest[1], proven technologies that can be deployed in the short time available.

NIRAB believes that when nuclear is considered fully, with stakeholders having all the available evidence at their disposal, the net zero challenge will be far more achievable than currently perceived. Current and further emerging evidence will be a valuable reference to inform net zero discussion amongst commentators and advisors.

NIRAB discusses here the role of current and future nuclear technologies to support the three energy vectors of electricity, hydrogen (including synthetic fuels) and heat. It outlines the energy efficient pathways to decarbonise electricity, buildings, transport, industry, agriculture, aviation and shipping (see Figure 5). It describes how nuclear could have a greatly expanded role as a reliable enabler for the UK to meet its legislative and international commitments. As part of this, NIRAB highlights the opportunity presented by nuclear technologies to contribute to urgent and widescale decarbonisation of the electricity system, followed by further major roll out of generating capacity to meet future energy system demands on heat and hydrogen.

NIRAB is convinced that maximising the role of nuclear across the three energy vectors of electricity, heat and hydrogen is key to deep decarbonisation and is under-represented in current thinking.

[1] The most optimistic prediction for emissions from CCS is in the region of 160 grams of CO_2 equivalent per kWh of energy (gCO_2e/kWh) compared to 12 gCO_2e/kWh for nuclear. gCO_2e/kWh is a measure of the combined climate impact of the Green House Gas emissions from a technology expressed in grams of CO_2 per KWh of energy produced.

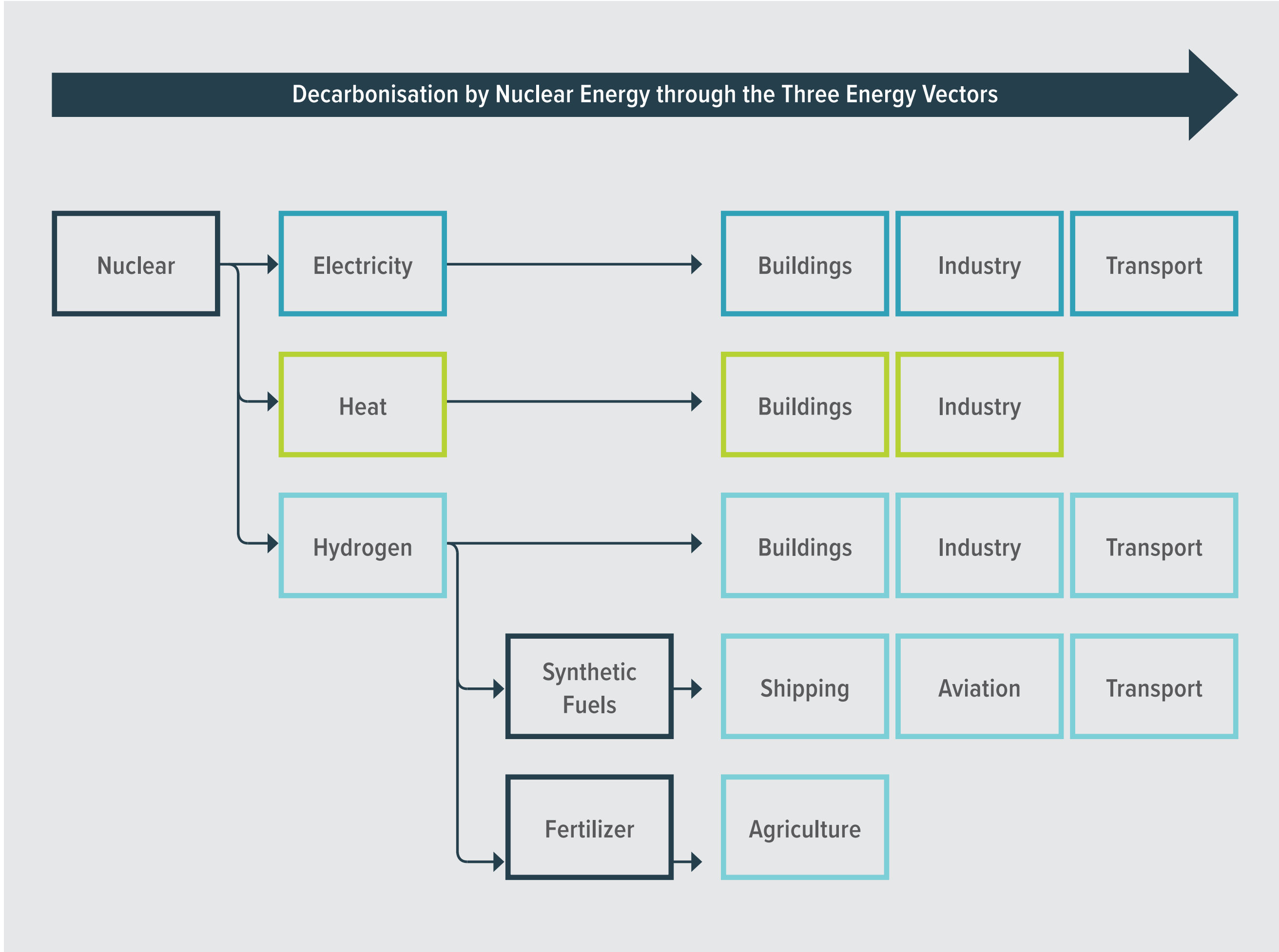

Figure 5 The role of nuclear in the deep decarbonisation of electricity, heat and hydrogen

3.1. Energy from Nuclear Fission

Electricity from nuclear has been powering homes and businesses since 1956 and is an accepted and essential part of the UK energy system. Internationally, countries that have a significant growth in demand for energy are investing in the development and deployment of nuclear technologies alongside renewable resources to meet their needs. It provides safe, mature, proven and reliable low-carbon electricity with carbon emissions that are equivalent to wind power [23] and lower than any other energy source. In 2018 nuclear generation prevented 20 million tonnes of UK CO_2 emissions entering the atmosphere; the equivalent of 9.3million cars [24]. Nuclear is a secure and established part of the energy system that, irrespective of weather can be relied upon to deliver low-carbon energy day and night. It has a fundamentally important role to play in providing electricity, heat, hydrogen and synthetic fuels to any future net zero energy system alongside other technologies such as wind, solar and gas coupled with carbon capture and storage, assuming this can be deployed at scale.

The International Energy Agency has concluded that solving climate change will be much more difficult and more expensive if the global nuclear fleet is not maintained, replaced and expanded.

The IEA has concluded that solving climate change will be much more difficult and more expensive if the global nuclear fleet is not maintained, replaced and expanded [3].

The majority of the UK's 9 GWe of nuclear power plants will reach or exceed its design life and is scheduled to be shut down by 2030, highlighting the importance of nuclear new build to replace and grow this contribution. If this is replaced by unabated gas or coal plants, then the additional carbon dioxide emissions would be 24.8 $MtCO_2e$ per year[1] in 2030 [25]. However, the current projected nuclear build programme is insufficient to replace, let alone grow, the UK's low-carbon baseload capacity in a growing energy market. Therefore, NIRAB believes that the UK should continue with the roll out of nuclear energy as an enabler to decarbonise the current energy system and support the future demands.

With appropriate support, the nuclear sector can bring further nuclear technologies (e.g. SMRs and AMRs) from demonstration stage to full commercialisation and offer diverse solutions to deep decarbonisation of multiple sectors.

In the net zero narrative, all the possible energy contributions from nuclear to decarbonisation are rarely considered and NIRAB do not consider costs to be compared on a like for like basis with other technologies. The result is that the extent and breadth to which nuclear can contribute is often underestimated by commentators, policy makers, environmental groups and analysts. NIRAB advises that these shortcomings must be addressed if Government, technology developers and investors are to make the best short and long-term decisions on behalf of the public.

Until recently, even the most detailed energy systems modelling, including that used by the CCC, did not consider the full range of services that energy from nuclear has been demonstrated to offer, nor all the product markets (e.g. hydrogen, synthetic fuels and fertilisers) into which it can provide low cost clean energy to support decarbonisation. The outcome has been that energy system futures were identified based on evidence that only partially represent the available low-carbon technologies. A recent publication [9] has addressed this shortcoming and has modelled a range of energy futures. This work identifies several potential roles for nuclear including electricity generation and the provision of combined heat and power. Future work is to be undertaken to model the role that nuclear energy can play in producing hydrogen at scale.

With appropriate support, the nuclear sector can bring forward nuclear technologies (e.g. SMR and AMR) from demonstration stage to full commercialisation and offer diverse solutions to deep decarbonisation of multiple sectors. SMRs and AMRs offer a range of energy services that will prove vital for heat and hydrogen production. The technologies that support both have already operated in the UK and are being developed around the world:

- SMR: These are proposed as near to market and based on the same basic technology as the current Sizewell B nuclear power station (i.e. LWR). The UK SMR is one of a number of examples;
- AMR: High Temperature Gas Reactor and Sodium-cooled Fast Reactor demonstrator test reactors have operated in the UK (i.e. the Dragon reactor, Dounreay Fast Reactor and the Prototype Fast Reactor). AMRs are under development around the world.

For these reasons, studies and analysis on energy system futures that help inform policy must consider all potential options for how energy from nuclear will contribute to meeting the net zero target. This requires a robust evidence base. Where knowledge gaps currently exist (e.g. on the economic case for hydrogen generation directly from nuclear heat) NIRAB's advice is that Government should facilitate the compilation and development of complete information to underpin policy and intervention decisions.

Figure 6 details the available routes and timelines to open multiple energy vector opportunities.

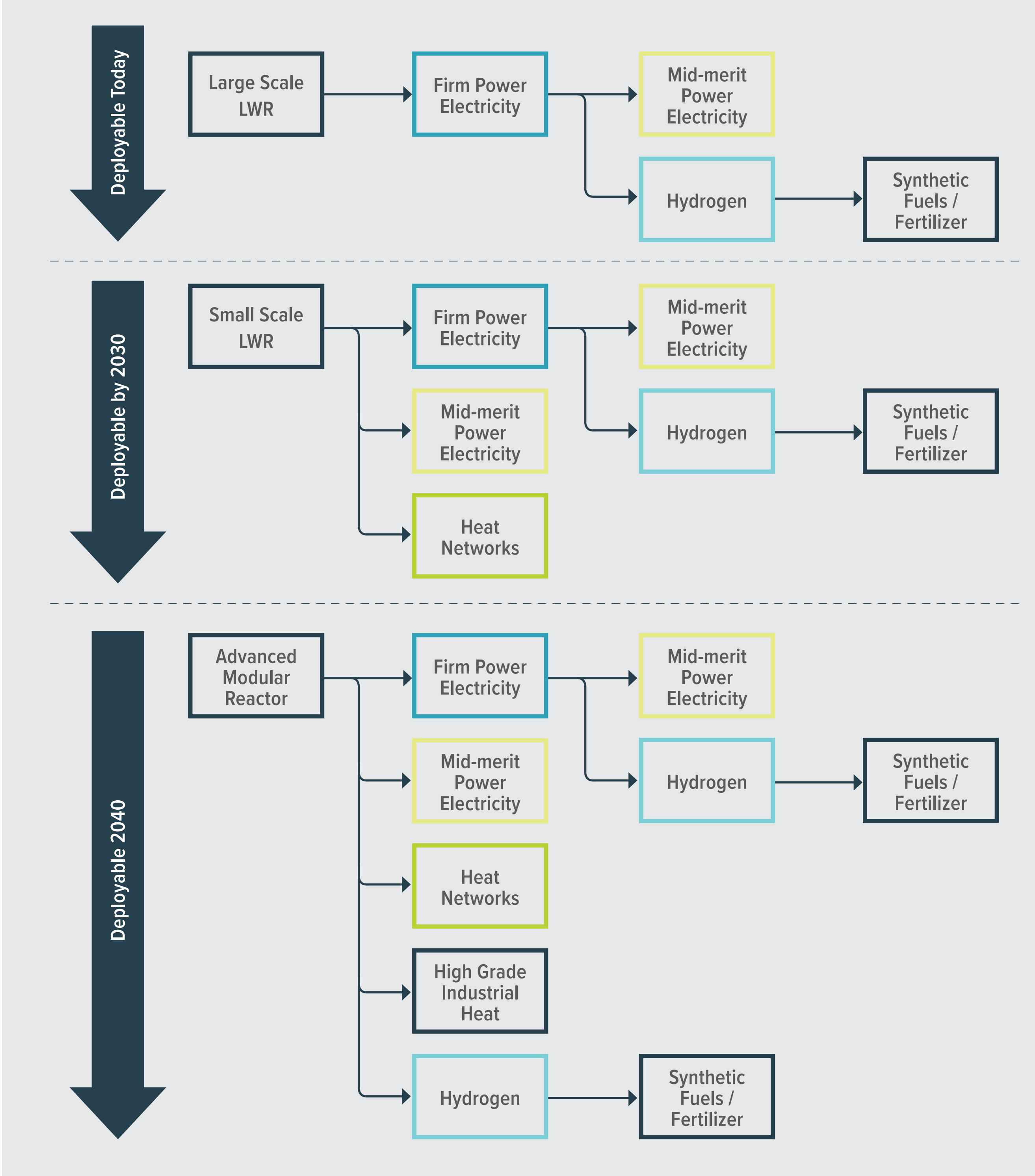

Figure 6 The electricity, heat and hydrogen energy vectors for decarbonisation of carbon intensive sectors

3.2. Cost Competitiveness of Energy from Nuclear

There is strong evidence that the cost of energy from nuclear can be highly competitive when compared on a like-for-like basis with other technologies [26,27], and significantly cheaper when the cost of capital is low [28]. Studies repeatedly highlight the importance of having an intentional nuclear new build programme that encompasses a programmatic approach of repeated and sustained building of new stations. In this environment the developer, supply chain and regulator will all become skilled in the build and commissioning process and component manufacturers will drive nth-of-a-kind learning and economies of scale.

Studies clearly find that when the intentional build programme is based on the same reactor design then the engineering design costs associated with, for example, original design effort and initial training of personnel are reduced and subsequent builds will be cheaper [29, 30].

Therefore, the first reactor of each specific design to be built in a country will be the most expensive, as shown in Figure 7.

However, despite First of a Kind (FOAK) in country initial costs applying to Hinkley Point C, the Government Value for Money Assessment found that the current strike price is comparable with other sources of energy when compared on a like-for-like basis [31]. It could, however, offer improved value to the taxpayer with alternative funding mechanisms [32].

Despite FOAK initial costs applying for Hinkley Point C, the Government Value for Money Assessment found that the current strike price is comparable with other sources of energy when compared on a like for like basis.

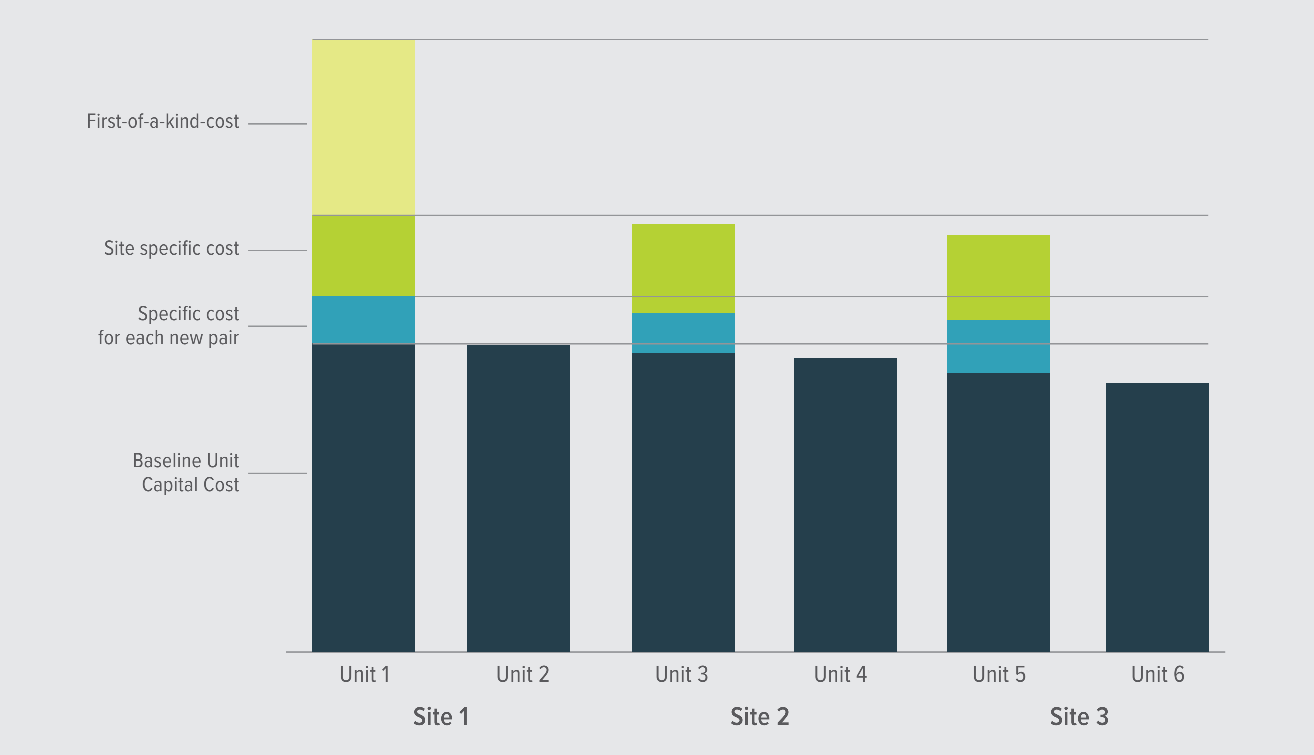

Figure 7 Cost reduction due to series and site effects [30]

Comparing different technologies economically and environmentally on a like-for-like basis is crucial [3], particularly when the structure of the future energy system is uncertain and Government intervention priorities need to be set. NIRAB firmly believe that to make robust decisions, the comparison of costs for different technologies should account for the whole system and whole lifecycle costs. This includes the costs of:

- Compensating for intermittency that requires either standby generating capacity or storage capacity to be added to the grid;
- Decommissioning and disposal of assets at the end of life;
- Transmission and distribution. The costs of this may be higher where the energy installation is in a remote location, for example far out to sea, whereas nuclear power stations can be placed in locations already connected to the grid.

Contracts for Difference for the various low-carbon technologies do not necessarily fully or consistently include all these costs due to contractual and regulatory differences, which can provide a distorted perception of the cost of energy. NIRAB advises that this should be addressed.

Furthermore, where the cost of Greenhouse Gas (GHG) emissions needs to be factored in, this should include the emissions associated with the whole lifecycle of a process. For example, the fugitive up-stream methane emissions associated with natural gas extraction should be accounted for against the production of hydrogen by steam methane reformation.

NIRAB believes that it is essential for nuclear energy projects, nuclear reactor technologies, and the underpinning R&D to be supported by Governments and private investors based on evidence of market need. Developing the evidence base on which decisions can be made must start from the economic target of the end product and also consider:

- Energy system requirements;
- Performance targets;
- Decarbonisation credentials;
- Market need.

To inform such decision-making, NIRAB advises Government to facilitate generation of appropriate economic data and wider evidence to ensure targeted R&D and commercially successful development programmes.

Economics of Energy from Nuclear

The high capital cost of nuclear projects makes them very sensitive to both the cost of finance and the construction time [25,28,29]. Financial models that reduce the cost of finance would immediately reduce the cost of nuclear energy by a greater amount than other energy sources, as shown in Figure 8. Governments are typically able to finance infrastructure projects at a much lower rate than the private sector [32]. The Regulated Asset Base (RAB) model consultation [33] is a welcome example of Government investigating nuclear financing options through appropriate allocation of risk to investors, Government and consumers.

The debt incurred to finance the capital cost also has an impact on the balance sheet of the developer/investor, which can create a challenge to Government and private organisations alike. NIRAB believes that as a matter of urgency, financing mechanisms are required that unlock the ability to commission new nuclear power stations in the UK and enable consumers to access the clear cost competitiveness of energy from nuclear and the decarbonisation benefits it provides. The need to create attractive financing frameworks is supported by the IEA [3].

As a matter of urgency, finance mechanisms are required that unlock the ability to bring new nuclear power stations to the UK.

Figure 8 The impact of increasing discount rates on the Levelised Cost of Electricity (LCOE) for technologies with different capital costs [30]

Nuclear Sector Deal Cost Reduction

Through the Nuclear Sector Deal (NSD) [34], industry has undertaken to deliver a 30% reduction in the cost of nuclear by 2030. This will be achieved through a broad range of innovation, including technical, commercial, process and cultural programmes. NIRAB is aware of the framework being developed through the NSD New Build Cost Reduction Working Group and supports the concept of an independent assessment of a project to confirm that all possible cost reduction measures have been employed before passing the Final Investment Decision.

NIRAB also believes that risk reduction and cost reduction are essential if nuclear is to compete with other clean technologies and find a place in a net zero energy system. NIRAB believes that the 2030 Nuclear Sector Deal target should be followed by further risk and cost reduction if the role of nuclear as described in this report is to be realised.

Enhanced Investability and Affordability for Small and Modular Reactor Technologies

The number of private sector funded projects for SMR and AMR has grown from 54 to 64 between 2019 and 2020 in North America alone [35]. The total number of projects across the world is much greater. Many of these technologies are said to be deployable well before 2050 and offer some clear and undeniable opportunities to further improve the investability and affordability of projects [25]. It is, however, essential that the UK has methodologies and capability in place to examine the range of reactor systems to assess the likelihood that the projected advantages and deployment dates claimed for these technologies are credible.

The step change opportunity is in the design of projects developed specifically to meet both the market need and hit a target price.

The step-change opportunity is in the design of projects to meet the market and customer needs and hit a target price for the end consumer product. The end consumer product is currently electricity, but in future is likely to include electricity, heat, hydrogen, synthetic fuels and fertiliser. Markets already exist for these products, thus nuclear projects must be designed to offer cost competitive or cheaper alternatives. Doing so would unlock the potential of energy from nuclear, decarbonise multiple sectors and could add significant economic value to the UK with reduced societal change. Figure 9 details advantages to the affordability and investability of Advance Nuclear Technologies (ANTs).

To achieve this, the reactor technology must be demonstrated in the scenario that it is set to be deployed, with cost reduction measures and innovative deployment approaches validated as part of the demonstration programme. This should include testing the role of nuclear in wider energy system decarbonisation using energy from nuclear across the three energy vectors of electricity, heat and hydrogen. The demonstration programme should show how a nuclear project can meet the needs of flexibility in a modern energy system and how standardised interfaces between the primary systems, for example between systems such as the nuclear reactor, balance of nuclear island, turbine island and the energy conversion system can reduce cost and provide project developers, reactor designers and supply chain organisations with common design parameters. Section 4.4 further outlines the broad role that a demonstrator can play.

The financing of small nuclear (up to 600 MWth) has been explored by the Expert Finance Working Group [36], which made a range of recommendations to Government on how small reactors with overnight capital costs of up to £2.5Bn could be made investable and affordable. It concluded that significant Government facilitation would be required, in particular to overcome the costs and risks associated with FOAK in country.

An example is the UK SMR consortium, which has recently been awarded a match funded grant of £18M through the Industrial Strategy Challenge Fund (ISCF) [37]. The project is targeting a FOAK reactor by 2030 and an electricity cost of £60 /MWh [38] at Nth of a Kind (NOAK).

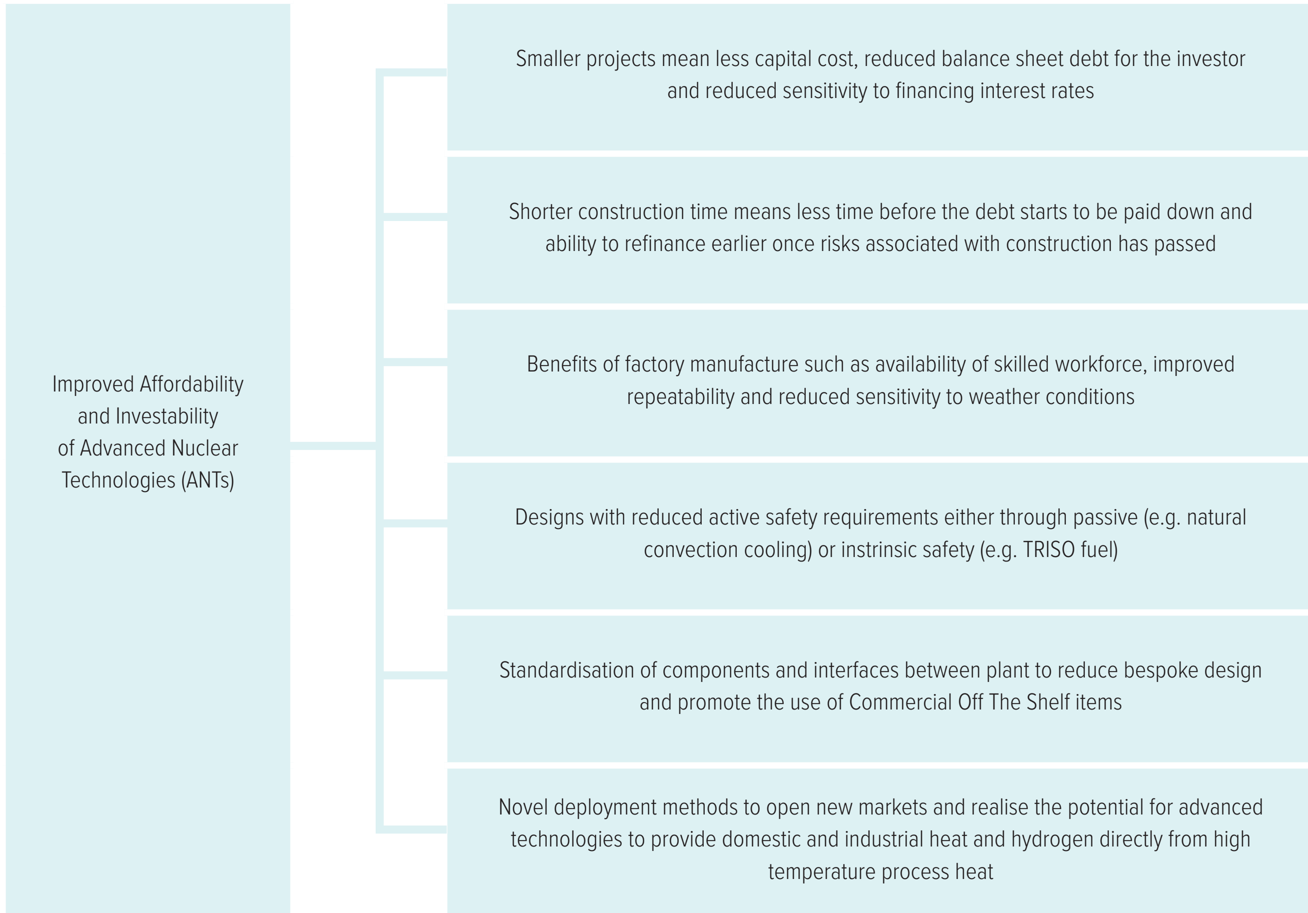

Figure 9 Improved affordability and investability of Small and Advanced Modular Reactors

3.3.Energy from Nuclear to Support Decarbonisation of Electricity

The future electricity demand in the UK is set to increase. NIRAB's view is that the UK should make plans for a large contribution from nuclear to support achieving net zero and that not doing so would be extremely high risk.

NIRAB's view is that planning a future net zero energy system without significant nuclear power would be extremely high risk, both in terms of energy security and meeting net zero.

On the pathway to achieving a decarbonised 2050 electricity generating capacity, a natural first step would be to urgently address GHG emissions resulting from the current electricity generation. The intermittency of renewables and uncertainties of other available technologies means the quickest and lowest risk pathway to achieving this is the deployment of multiple nuclear plants as well as renewables, and to locate them initially on existing nuclear licensed sites [39].

For this to be at the lowest cost they should, as far as possible, be the same design in order to maximise cost reduction opportunities including, where possible, factory build. Repeat build of a fleet of the same design should also maximise opportunities for the UK supply chain. Deploying several First of a Kind reactors each of a different design will not result in the lowest price for consumers. The opportunity for nuclear to contribute in this way could be realised by facilitating further development of the proposed large-scale build projects and early bringing to market of SMR technologies such as the UK SMR. This would initially enable energy from nuclear to support combined electricity and heat production and act as a springboard to gear up nuclear technologies that are technically and commercially viable for further deployment at scale to meet the future energy demands. In addition to the economic attraction of SMRs noted above, there are other practical and deployment benefits such as:

- The potential to deploy a series of reactors on a single site and of the same design to maximise supply chain efficiency;
- The ability to construct reactors at regional sites not suitable for large reactors (potentially including existing fossil fuel sites);
- The ability to support off-grid applications.

Recommendation 1

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

In support of this recommendation Government should continue to support:

- Advanced digital design;
- The deployment of advanced manufacturing methods and the UK supply chain capability in this area;
- The development of an improved methodology for developing codes and standards for new manufacturing methods, aligned to SMR programme needs.

Deploying several First of a Kind reactors in the UK will not result in the lowest price for consumers. Many studies have shown reductions in cost from fleet rather than individual reactor build.

3.3.1. Energy from Nuclear to Provide Mid-Merit Electricity

Currently, UK nuclear predominantly produces firm electricity. However, nuclear can also meet the needs of the mid-merit power market [40] when either;

- Partnered with a suitable technology that allows the nuclear plant to operate at full reactor power but regulate the amount of power supplied to the grid. Examples would be coupling a traditional nuclear plant to an electrolysis system to produce hydrogen by switching electricity between the two outlets; or, for higher temperature systems the provision of heat storage coupled with additional generation capacity; or,
- The nuclear reactor is specifically designed to vary its power directly, known as load following. This has been done in France [41] and Germany for many decades and new technologies have been and are being designed to deliver this functionality.

There are no technical barriers for nuclear to deliver mid-merit electricity, but electricity markets need to appropriately compensate energy providers in a competitive and non-discriminatory manner [3]. However, due to the high capital cost, the economics of nuclear make it more favourable to operate nuclear reactors consistently at optimum power and to partner with another technology whether the reactor can load-follow or not. Developers and operators of future projects can therefore design their schemes according to market demands: firm power electricity, mid-merit electricity and/or additional products and services (e.g. hydrogen, heat).

Opportunities for innovation exist in the design of load-following plant, the development of partner technologies and in the interface between nuclear and non-nuclear plant. Current 2050 energy system thinking does not recognise the opportunity for nuclear to provide mid-merit power electricity through cogeneration and NIRAB consider that this should be addressed.

3.4. Energy from Nuclear for Heat, Hydrogen and Synthetic Fuels

The production of electricity accounts for only a small proportion of the UK's total carbon emissions [18] and has been easier to decarbonise compared to other sectors. However, decarbonising harder-to-abate sectors will be crucial to meeting the 2050 net zero target and nuclear provides the energy density, temperatures, security, resilience and economics to do this. NIRAB advises that nuclear can play an increasingly significant role in decarbonising heating and the production of hydrogen, synthetic fuels and ammonia fertilisers either directly using heat or through electricity.

Recommendation 2

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

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

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

Such pathways have been demonstrated experimentally and could be suitable for commercialisation significantly before 2050 but are not considered in recent climate and energy system advice provided to Government. Only in the case of heat is nuclear considered a decarbonisation option in energy system modelling [9,11]. This should be remedied, and NIRAB advise that Government facilitate activities to further underpin and evidence the opportunity that energy from nuclear presents including technical and economic aspects. Figure 10 details available pathways from nuclear.

The pathways to efficient production of hydrogen and synthetic fuels from nuclear energy have been demonstrated and could be cost effectively deployed to positively impact 2050 net zero.

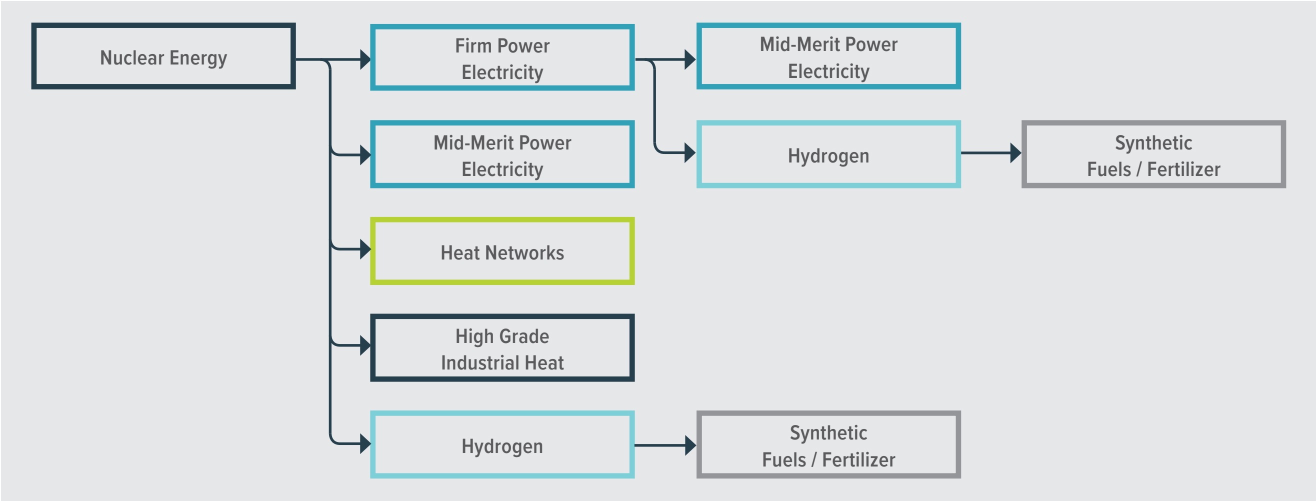

Figure 10 Pathways to the production of cost competitive heat, hydrogen and synthetic fuels from nuclear energy

3.4.1. Heat

The supply of heat directly to industrial process and space heating as part of district heating networks from nuclear provides decarbonisation pathways that can make a significant contribution to achieving net zero [12,29]. Evidence shows that low grade heat from nuclear power stations has opportunity to access heat networks in the UK [39] and additionally could provide up to 80% of the non-electric industrial heat [42]. This is equivalent to around 20% of the UK's total current GHG emissions.

Although large scale nuclear power stations could effectively supply heat to networks across the UK, the greater opportunity is related to ANTs, which can be designed to specifically meet the needs of the market and can be sited at a broader range of locations [43]. Accessing this decarbonisation opportunity through establishment and expansion of heat networks requires close coordination and facilitation by central Government, local Government and a wide range of other stakeholders.

NIRAB is confident that decarbonising heat using energy from nuclear alongside other forms of energy efficiency and electric resistive heating is a major opportunity and that the development of district heating networks supplied by nuclear energy should be a significant consideration as part of decarbonisation options for the UK.

3.4.2. Hydrogen

The hydrogen economy is predicted to be a major part of a net zero energy system, with the potential to decarbonise transportation, heating, industry, aviation and agriculture. There are multiple routes to the production of hydrogen from nuclear energy, from which synthetic fuels and ammonia for fertiliser can also be manufactured. Recent studies have shown that clean hydrogen from nuclear energy could be produced for \$2.5/kg-H_2 [39]. The cost of production from natural gas with CCS is in the region of \$2.3/kg-H_2 in Europe [44].

There is strong evidence that thermochemical processes driven by heat directly from nuclear energy and electrolysis from electricity from nuclear energy can produce cost effective hydrogen.

Current thinking relies on producing large quantities of hydrogen through the Steam Methane Reformation or electrolysis where that is not available [7, 45, 46]. The former has a high reliance on imported gas supplies equivalent to greater than the current UK electricity demand [5] and on residual emissions from CCS being tolerable in a net zero world.

Given the urgency of establishing a clean hydrogen economy Government should intervene to support collaborations between nuclear and hydrogen stakeholders. Similarly, further technical and economic evidence should be generated to support down-selection and at-scale demonstration of preferred technologies for production of hydrogen from nuclear energy.

Research and innovation should focus on both the reactor technologies themselves and their effective interaction with the development of a hydrogen network.

Hydrogen from Thermochemical Water Splitting Processes

Thermochemical processes produce hydrogen directly using high grade heat from nuclear energy with a number of options for the chemical cycles being researched [47,48]. These currently at the experimental stage, they potentially provide a credible, highly cost competitive [43, 49] and diverse route to produce large quantities of hydrogen. This approach to hydrogen production could reduce costs, would relieve the predicted reliance on other production routes (e.g. reformation of methane with CCS or electrolysis) and would reduce the risks associated with residual emissions.

Government should facilitate actions to ensure that nuclear energy is fully recognised and underpinned as a credible and cost competitive route to the production of clean hydrogen.

There are several established hydrogen generation processes [48] that can be driven by heat within the range of temperatures available from AMRs. These processes would likely be more energy efficient than electrolysis. Combined nuclear-hydrogen systems designed specifically for hydrogen production alone would have lower capital cost due to the lack of need for a turbine and generator. The versatility of such systems could offer at scale deployment of nuclear-hydrogen systems for the sole production of hydrogen at a refinery scale leading to export potential for carbon-neutral hydrocarbon products.

There are several AMR technologies that can provide the temperatures needed for the thermochemical production of hydrogen and Government should facilitate further work to understand the most suitable through a robust down-selection process. However, of those that would be suitable (VHTR, HTGR, LFR, SFR and MSR), the HTGR is currently the most developed and widely demonstrated technology that has the greatest potential to support achieving net zero targets by 2050. Decades of indigenous technological operational and regulatory experience for gas-cooled reactors are available in the UK.

Further work should be facilitated to better understand the economics and ideal deployment model that would lead to the most investable and affordable projects. In addition to AMRs, SMRs and Large-Scale reactors offer routes to hydrogen through heat and electricity, and these should be considered as part of further assessment.

Hydrogen from Electrolysis

Electrolysis systems attached to nuclear power plants and heat from the reactor could support the efficient electrolysis of water to produce hydrogen [47]. In theory, any power station could use this principle to moderate the electricity sent to the grid thereby offering variable amounts of dispatchable electricity to the grid by switching between roles. This is being demonstrated by Exelon in the United States where they are retrofitting a hydrogen electrolysis unit to a conventional non-load following plant [50]. A similar arrangement has been mooted for a demonstration associated with 2 AGR power reactors and the energy requirements of the Lancaster and Morecambe district. Economics for doing this may be favourable as it allows plant operators to sell electricity in more flexible ways while operating their reactor at full power.

The CCC [45] found that in a low gas scenario, nuclear would be required to provide 35 GW of electricity generating capacity to meet the anticipated demand for hydrogen in 2050. However, this does not consider the efficiency opportunity that thermochemical hydrogen production could offer before 2050.

Government should ensure that future nuclear energy demonstrations and projects can be designed to support the dual purpose of electricity and hydrogen generation.

The CCC found that, in a low gas scenario, nuclear would be required to provide 35 GW of electricity generating capacity to support hydrogen production.

3.4.3. Synthetic Fuels and Fertiliser Production

Both synthetic fuels and ammonia-based fertilisers require hydrogen as a feedstock, so decarbonising their current and future production route is related to the ability to access clean hydrogen. Their potential to offer decarbonisation to the UK is large but further research is needed to evaluate their clean manufacture in greater depth. Energy from nuclear is a highly credible option for synthetic fuel production but is not currently part of the narrative on clean hydrocarbons. This should be remedied.

Government should facilitate a deeper and broader understanding of the role for synthetic fuels from nuclear energy as an enabler for decarbonisation of hard-to-abate sectors.

Synthetic fuels can replace today's hydrocarbon fuels and have the potential to enable decarbonisation of sectors where emissions occur from decentralised sources in the medium to long term (5 to 10+ years) [46]. Consumers would be able to continue using carbon-based fuels for transportation, with minimal infrastructure upgrade, but with zero net emissions. These fuels are otherwise known as 'drop-in' fuels.

The CCC notes that the demand for synthetic fuels could be very large for deep decarbonisation of transport, aviation and shipping [5]. At present the scale of production is limited by the availability of affordable, clean hydrogen rather than technical readiness [46] although in the current environment, specific policies would be required to reduce the cost gap between synthetic hydrocarbons and fossil fuels [45].

Subject to the right economics and realising the cost reduction opportunities for nuclear power, NIRAB consider synthetic fuels from nuclear to be a potentially credible option in providing dramatic, rapid and widespread decarbonisation, while minimising societal impact or infrastructure upgrades.

Synthetic fuels from nuclear could provide dramatic, rapid and widespread decarbonisation, while minimising societal impact or infrastructure upgrades.

In light of this work, Government should facilitate the right collaborations and knowledge transfer methods such that both nuclear and synthetic fuels stakeholders can make informed decisions towards collaborative decarbonisation goals.

3.5. Energy from Nuclear Fusion

At present fusion technology is unlikely to make a significant contribution to meeting 2050 net zero targets due to remaining technological hurdles. However, nuclear fusion could contribute to meeting UK energy needs in the future. The prospects for fusion are also highlighted through the international and European funded ITER project and a number of privately funded projects that are gaining momentum. UK companies are benefitting from involvement in both, building knowledge and capability as a foundation for further development of the technology.

NIRAB welcomes the continued commitment to fusion by Government and recent announcement of the first activities towards a UK nuclear fusion demonstrator, Spherical Tokamak for Energy Production (STEP) and believes that nuclear fusion has the potential to provide zero carbon energy for UK consumers beyond 2050. Areas of the research funded through the nuclear fusion programme should also be leveraged for application in fission and vice versa. In this way, technology transfer between the nuclear fusion and fission research and demonstration programmes can be maximised to ensure best value for money and commercialisation of technology on the shortest possible timescales. As an example of the opportunity, both fusion reactors and AMRs are likely to have some similar materials research needs due to the high temperature outputs of both technologies.

4. Research and Development Priorities

The landscape of nuclear fission research, innovation and commercialisation is changing. In 2016, the priorities for the NIP were to protect crucial capability that was at risk of being lost, to develop capacity to support the roll-out of a future nuclear power programme and to support cost reduction. The current NIP has made substantial progress in maintaining and developing both capability and capacity and is also supporting some aspects of cost reduction. However, the landscape has changed radically with the adoption of a net zero emissions target.

The objective should now be far more ambitious. The aim should be the deployment of that capability and capacity to support a nuclear energy programme that will make a major contribution to the effort of meeting the net zero target. Key aspects of this development will be to support the cost-effective deployment of SMRs and AMRs.

To achieve this a concentrated effort is required to research, develop and commercialise civil nuclear technology that can make a significant impact in decarbonising our economy by 2050. NIRAB proposes a programmatic approach to the development of these solutions and associated Government support, be it funded through the NIP, ISCF or other sources.

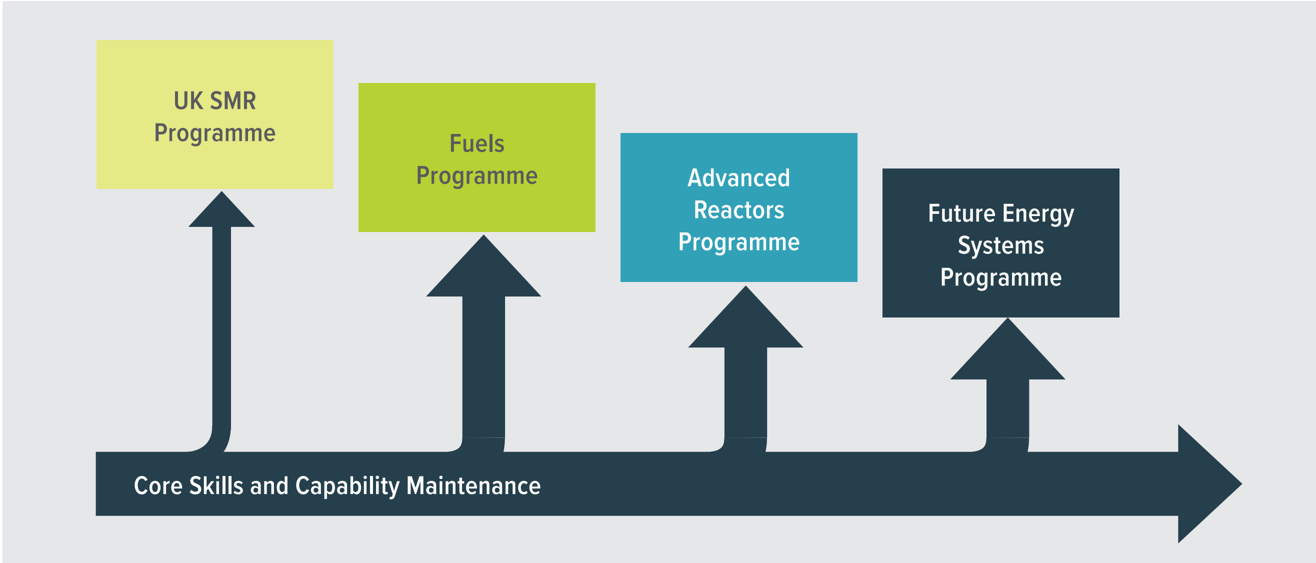

Figure 11 A Programme approach to Civil Nuclear Deployment

The intent of a programmatic approach is to empower development of the technology branches needed to deliver commercialised solutions in the 2030-35 period. These programmes will build on and flow out of work undertaken in the NIP, both to date and in the future. As technology moves towards full commercialisation, the development needs become more bespoke. NIRAB recognises this challenge and the impact this has on forecasting the facilities required to deploy a reactor system.

This section contains NIRAB advice including a review of the current NIP, future facility requirements and the need for an AMR demonstrator. It is recognised that the NIP provides an important element of the future deployment civil nuclear programme but is only one strand of a wider strategy.

4.1. The Present NIP and Key Outcomes

Work under the NIP commenced in 2017 and is a £180m commitment by Government. The NIP was established with input from the original NIRAB and NIRO and a framework for projects was established which covered a wide spectrum of activities (Figure 12).

NIRAB has reviewed the current research areas within the NIP and found them to be delivering against the initial objectives. It has delivered a foundation from which the UK can pursue a range of nuclear technologies, maintaining options and the domestic capability needed to deploy future reactor systems, advanced fuels and fuel cycles which could contribute significantly to delivering a net zero energy system by 2050. A number of defined successes have been achieved since the commencement of the programme, including but not limited to:

- Enhancing the value of UK knowledge on the international stage to leverage international research and development budgets by capturing and maintaining historical test reactor data that is unique to the UK;
- Development of tools to make the nuclear industry more efficient and reduce costs, such as strategic assessment tools, new technologies for waste & decommissioning, integration of fuel cycle codes and nuclear plant digital twin;
- Securing at risk skills, supporting jobs and developing the capability and capacity to export expertise in advanced fuels;
- Creating value to the UK by leveraging over £127 million on the public investment in an Advanced Fuel Cycle Programme (AFCP) alone, of which over £110 million is from international programmes. Also, successfully attracting £10's millions of industrial investment in advanced manufacturing to support efficient modular delivery;
- Rediscovering the UK's spirit of innovation and developing the next generation of nuclear power engaging over 40 academic institutions and commercial companies in civil nuclear R&D, signalling the first major investment in fission R&D since the 1980's;
- Development of new facilities such as: Centrifugal contactors and photo reactors; centralised Test Facility for control and instrumentation electric relay testing; UTGard Laboratory Phase 2 opened; fuel rig for test production of Uranium silicide; scale up from the laboratory to full test rig for coated particle fuels crucial for HTGR development;
- Managed and developed UK capability and capacity by supporting over 35,000 hours research (equivalent to around 25 full time employees) in advanced fuel and fuel cycle (across over 200 individuals); maintaining and developing key skills to underpin future UK nuclear capability;
- Bolstering the UK as a leading nuclear nation on the international stage. The NIP is core to the UK international engagement programmes. Successes include UK engagement in the GIF and UK engagement in a number of IAEA committees.

Digital Nuclear Reactor Design	Advanced Nuclear Manufacturing and Materials
Nuclear Safety and Security Engineering	Nuclear Facilities and Strategic Toolkit
AMR Feasibility and Development Study	Advanced Fuel Cycle Programme

Figure 12 Nuclear Innovation Programme research areas

4.2. Future Drivers

Nuclear in the Drive to Net zero

The future drive changes from capability maintenance and capacity development to deployment of that capability to support demonstration in the period 2030 to 2035 with commercial deployment in the early 2040's. Efforts should be focused primarily on a system or systems that can make a significant contribution to meeting the net zero 2050 target. This will require research and develop needs to be both appropriately sized and rebalanced against those technologies most likely to deliver zero carbon energy options on this timescale.

NIRAB believes the programmes (including the NIP) should contain a component consistent with vigorously pursuing the opportunity for nuclear to support decarbonisation through heat and hydrogen in addition to the traditional supply of electricity (both baseload and flexible). There is a short-term need for technology down selection to inform the direction for the relevant areas of the NIP and Demonstration Programme. This will need to take into account a number of factors including, but not limited to:

- Experience from reactor systems that have previously been demonstrated or operated commercially and which provide a direct line of sight to the proposed design;
- The availability of a global or domestic infrastructure to draw upon for the supply of components, materials and fuel;
- Synergies with UK technical capability and experience.

NIRAB believes the reactor technology most likely to meet these requirements is a HTGR, though a more detailed analysis is required to underpin the necessary investment. Different reactor systems give differing outputs and alignment with downstream energy conversion systems will need further work, in turn influencing the technology selection. This analysis should centre on desired outcomes, international collaboration potential and parallel opportunities. A brief overview of the applicability of the current research themes to a range of reactor technologies is given in Appendix 4.

Efforts should be focused on systems that make a significant contribution to meeting the net zero 2050 target.

Recommendation 3

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

As soon as possible a detailed techno-commercial technology evaluation against functional requirements of the energy system (e.g. synergies with renewables, competitively priced electricity, heat, hydrogen generation or synthetic fuel production) should be performed leading to demonstration (see Section 4.4). The programme should demonstrate integration of the reactor system with the broader energy system, addressing other energy needs in addition to electricity generation.

Following technology selection, sufficient resources should also be devoted to alternative reactor concepts with a clear view of their suitability for the developing marketplace and their ability to meet the timescales required. This will enable the UK to remain a credible international partner in their longer-term development.

Innovation supported by Government intervention has the potential to bring forward SMR and AMR delivery times and promote economic growth through early access to a global market. NIRAB believes that civil nuclear research and innovation activities should be structured in order to:

- Manage the NIP as a strategic exercise with a consolidated long-term view and commercial deployment objective;
- Focus on the development of technologies that enable net zero by 2050 and scale back areas which do not meet this aim;
- Establish programmes that focus on commercial deployment and lead to the exploitation of nuclear as a flexible, versatile technology capable of providing a range of energy outputs and integrated into the wider energy system.

Recommendation 4

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

Figure 13 Prototype Fast Reactor located in the foreground to the left of the image, with the Dounreay Fast Reactor (the spherical building) in the background.

The Need for Demonstration

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

Demonstration in this sense could be of an indigenous design, built and operated in the UK, or it could draw on data from historical or international demonstrators to provide the evidence required to move into commercialisation.

The UK has developed engineering tools for design and safety demonstration through the previous Fast Reactor programme and, importantly, through the decades of commercial operation and regulation of the AGR fleet.

Figure 13 highlights two test reactors that successfully operated in the UK for extended periods; the sodium-cooled Dounreay Fast Reactor and the Prototype Fast Reactor. The latter operated for 19 years providing 250 MW of electricity into the National Grid, enough to supply a city the size of Aberdeen. Additionally, The Dragon HTGR test reactor was built at Winfrith and supplied electricity to the grid between 1965 and 1976. The UK also hosted the facilities and R&D infrastructure that supported all these reactors.

Technology demonstration will prove advanced reactor technologies and their flexible role in a balanced energy system.

The Government's AMR competition is designed to support research for reactor concepts or designs to confirm their feasibility. It is not a down selection of a preferred UK technology for deployment, indeed there are other systems that may also be suitable for consideration as a demonstrator reactor. Whilst a technology demonstration in the UK would be preferable to develop UK capability and supply chains, opportunities exist for international cooperation where advantages in terms of decreased timescales and a reduced funding from UK public sources are likely to be realised.

4.3. A Programmatic Approach

To focus activities towards commercialisation, NIRAB advises that specific elements of the work scope should become programmes with their own development and commercialisation goals (Figure 11). These programmes should be product focussed and have developed their own commercial business cases against which delivery is measured.

The intent of this approach is to enable each of these programmes to define their roadmaps to commercialisation and the accompanying facility and investment requirements they will need to get there. The funding for the programmes at lower technical maturity should come from the NIP, migrating to other sources as they develop towards commercialisation.

From a Government perspective it is important is to recognise the holistic programme and its role in energy security, decarbonisation and economic growth.

The relationship between the proposed workstreams will require crossover between the programmes. For example, it is expected that while a core materials programme would be maintained, the technology specific elements of that programme will migrate to the technology development programme (e.g. AMR) relevant to that work-scope.

4.4. Advanced Reactor Demonstration Programme

Recommendation 3 advises that an Advanced Reactor Demonstration Programme be initiated that develops a down-selected AMR technology towards commercial deployment. Figure 14 sets out an indicative timeline for a UK based demonstrator, highlighting the need for urgent action now to deliver on the necessary timescales.

Importantly, the key technology elements for some AMR systems have been proven in trials or operating reactors and the intent of a future demonstration should be to validate design philosophies and construction practices such that multiple strands of a future commercial plant are brought together to leverage the same funds. For example, in addition to validating reactor technology, demonstration should:

- Provide fuel irradiation data contributing to qualification of new fuels and enabling the UK to be a major future exporter of fuel;
- Be a test bed for the systems that will enable energy from nuclear to provide decarbonisation to the energy system across multiple energy vectors. For example, the demonstrator could be a platform for testing new turbines, hydrogen production systems and heat supply for industrial and space heating applications;
- Show how having standardised components and system interfaces can reduce cost by applying open-architecture principles to the design of the reactor and balance of plant systems. [36] Expert Finance Working Group Report;
- Show the art of the possible in modular construction and factory build;
- Test novel commissioning approaches such as commissioning of major systems in the factory before transporting of modules to site.

The recommended allocation of finances for a demonstration programme is outlined in Section 4.6, and the opportunities for international collaboration described in Section 4.7.

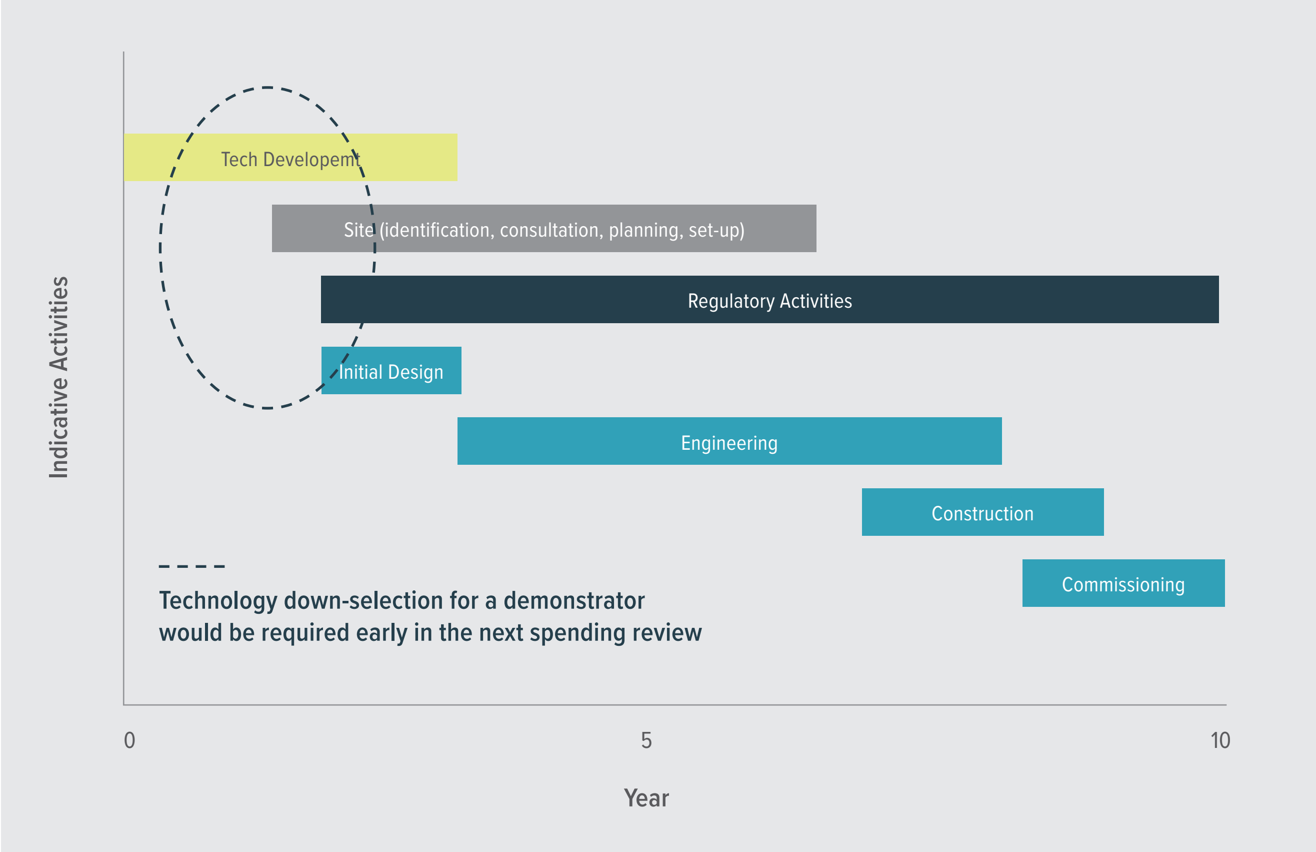

Figure 14 Indicative timeline to demonstrator

NIRAB advise that the first step towards a demonstration programme should be the creation of a small team within the NIP to create the foundations for a demonstrator. This team would be charged with technology down-selection and establishing the early stage infrastructure, for example site allocation, services and build provision etc. Once the demonstrator has a confirmed business case and funding, only then would a Demonstrator become a stand-alone activity, separated in a programme sense from the core NIP.

4.5. Future Nuclear Innovation Programme

Bringing forward innovative thinking from a base in research and development through to commercialisation and deployment will be crucial to unlocking the true potential of nuclear energy. The challenges and opportunities vary for different technology groups, which are each at varying levels of maturity.

For large scale nuclear, where the base LWR technologies are very mature there is no requirement for research prior to further deployment. However, there is opportunity for research and innovation to contribute to reduced cost through:

- Smoother regulatory approvals through improved underpinning of reactor systems;
- Modularisation and off-site fabrication of an existing design;
- Project delivery excellence;
- Bringing modern construction approaches from other sectors;
- Reducing the construction time of a plant.

Similarly, the deployment of SMRs, which employ mature LWR technologies in a novel configuration, is not contingent upon further research, though innovation offers a greater opportunity for cost reduction.

Furthermore, for both SMR and AMR the opportunity is to undertake research to design future reactors that meet a target cost and realise the benefits of factory manufacture, economies of multiples and technological advancement.

AMR technologies typically produce a higher temperature output that brings additional opportunities for the decarbonisation of hydrogen production directly from heat and the supply of high-grade heat to industry. They also offer further optimisations through intrinsically safe design and operation.

For these applications, innovation investment has a fundamental role to play in bringing forward advanced reactor technologies. Funding should therefore be prioritised towards technology that can supply a current or future market need in a cost competitive manner.

Innovation through Government intervention has the potential to bring forward advanced nuclear technology deployment and promote economic growth, through early access to a growing global market.

To achieve this, research, innovation, verification and validation needs should drive the programme to ensure that specific outcomes can be achieved, i.e. the Government programme should focus on driving forward specific reactor systems into a demonstration phase. Identifying and managing the critical path items will be key to ensuring these recommendations converge on the 2050 goal.

Therefore, the future NIP should concentrate on a programme of technology development and innovation leading to stand-alone programmes for commercial deployment before 2050 and demonstration of technologies to meet a market need. Wherever possible, these programmes should also seek to optimise UK owned / controlled intellectual property and the development of a competitive UK supply chain. In parallel, it should be recognised that there are skills and capabilities that require investment to maintain capability for strategic and national security purposes. Both requirements could be managed via the future NIP, as shown in Figure 15.

The UKSMR is an example of a stand-alone commercial deployment programme that is already benefiting from earlier work on the NIP. NIRAB advice on how demonstration and fuels areas should be managed as programmes in their own right and be appropriately focussed and prioritised is provided in the following sections.

The future Nuclear Innovation Programme should concentrate on technology development and innovation to underpin AMR deployment.

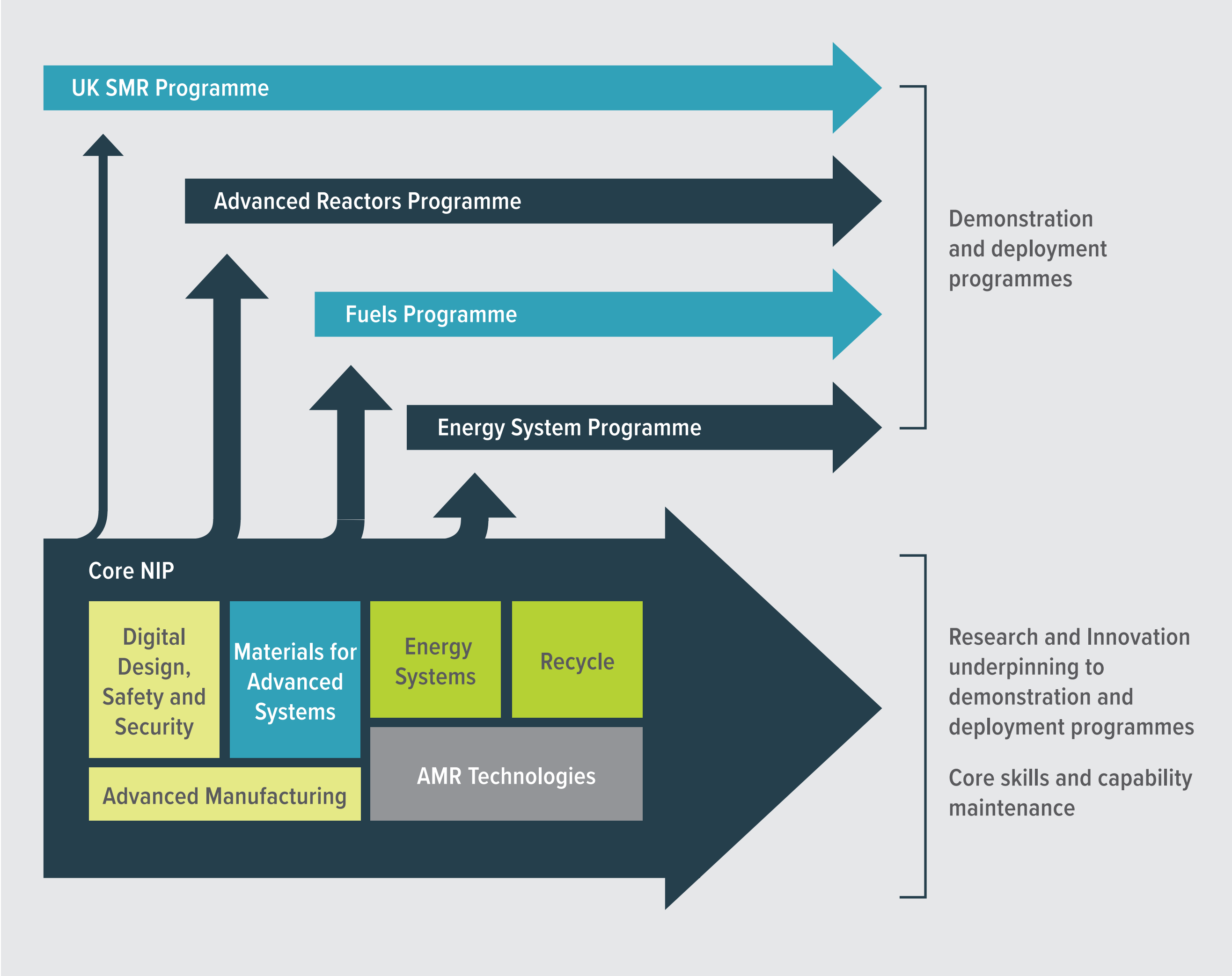

Figure 15 The Nuclear Innovation Programme funding delivers a wide range of industry needs and acts as a launch pad for commercialisation, demonstration and deployment programmes

4.5.1. Future Research and Innovation Focus

NIRAB believes that by working in partnership with industry and other sectors to help reinforce the role of the civil nuclear sector as part of the wider solution, net zero carbon commitments can be met. NIRAB advises that priority research areas to support acceleration of deployment of advanced reactor systems include:

- **Fuels** – The advanced fuels work is being coordinated by National Nuclear Laboratory under the current AFCP, and the Nuclear Fuels Centre of Excellence. The programme should have an increased focus on fuel fabrication, performance and post irradiation behaviour in storage environments for preferred SMR and AMR being assessed against 2050 commitments. In particular, this should include continued investment in coated particle technology and Accident Tolerant Fuels which could have near and long-term safety and export benefits for the UK. Within an overall increase there will be a reduced need to carry out research on fast reactor fuels.Consideration should be given to the near-to-market and advanced reactor fuel elements of the project concerning when they should become programmes with a dedicated focus on commercialisation. It is expected that this would be a near term activity;
- **AMR Technologies** – A sustained and underpinned series of activities focussed on realising the benefits that AMRs provide including a feasibility and development study (in progress) and a technology down-select to further focus the required research and innovation. Activities in this area should be aligned with both maintaining key knowledge on a range of reactor types, and on the overall intention to demonstrate the technologies required for commercialisation of an AMR in the UK. The latter should develop into an Advanced Reactor Demonstration Programme;

- **Digital Design, Safety & Security** – The NIP digital engineering output is more advanced than work in other sectors. It is recommended that the NIP should work across sectors to provide the secure through life digital development environment into which bespoke civil nuclear codes and standards can be embedded, e.g. for reactor physics modelling. The challenge of deploying Artificial Intelligence and advanced control systems within safety critical and/or secure environments is a challenge shared with the defence, aviation and oil and gas sectors. It is recommended that cross sector development of secure digital systems is explored;

- **Materials for AMR systems** – AMR systems, particularly those operating at high temperatures, present materials challenges. Work is required to ensure any current material limitations are technically understood prior to significant investment in reactor demonstrations. Specifically, understanding the impact of neutrons on materials is critical to eventual utilisation in reactors. Consequently, access to neutron sources is important for this programme;

- **Energy Systems** – NIRAB believes that the role of nuclear should not be limited to electricity generation. In order to realise the full potential of nuclear, research should be commissioned to assess, develop and demonstrate how direct heat from nuclear can provide heat and hydrogen (and subsequent hydrogen uses such as the manufacture of synthetic fuels) to support decarbonisation in multiple carbon intensive sectors. In addition, this assessment should consider how reactor systems interact with the hydrogen and heat networks. This area should be closely linked to the Demonstration Programme and, dependant on the industrial interest or alternative funding routes available, serious consideration should be given to this work stream being a separate programme outside the NIP;

- **Advanced Manufacturing (including non-metals)** – Advanced manufacturing and the development of codes and standards necessary for deployment are not limited to metals. Composites, ceramics and electronics could all be deployed in advanced civil nuclear systems. Work is required to develop these products and the appropriate standards for civil nuclear deployment. This work should be co-ordinated with and build on existing work in other sectors.

4.5.2. Long-Term Skills and Capability Maintenance

While it is important to focus research and innovation on systems that can contribute to decarbonisation prior to 2050, this should not be to the exclusion of research relevant to reactor systems which could be deployed in the longer-term. Research relevant to systems that offer opportunities post 2050 should receive funding, but at a level commensurate to their Technology Readiness Levels (TRLs) and ability to deploy commercially before 2050. For example, molten salt technology as well as molten salt reactors could deliver benefits such as heat storage to facilitate mid-merit electricity generation. They also offer a potential route to recover energy from fusion. Appropriate investment in this area would have long term cross sector benefits and would position the UK for domestic and export opportunities.

Finally, there are areas of investment required to retain capability, irrespective of the need to support an advanced reactor demonstration programme. Whilst continued investment is required it is proposed that the UK cut back investment, as a proportion of total spend, for:

- **Recycling** – It is thought unlikely that fast reactor technology and the associated fuel recycle capability will be deployed at scale to offer substantial decarbonisation in the near term. However, a global expansion of nuclear energy could place an increasing strain on uranium supply and spent fuel storage / disposal facilities. This could result in a much greater emphasis on energy security and sustainability and the consequent closure of at least part of the fuel cycle. The level of funding required is likely to be less than the peak funding scheduled in the period 2019 to 2021 but may need to be maintained at a level close to the average of the level of spend between 2017 and 2021. Careful consideration needs to be given to the knowledge capture associated with the UKs world-leading recycle and reprocessing capability.

In recommending funding, it is recognised that as the geo-political landscape changes with respect to energy security there may be a need (for political or energy security reasons) to revisit these investments.

The recommendations within this document will result in some changes to the current programme; some areas will need to grow, and some will not. The proposed funding changes to the NIP to deliver on the role for nuclear in a decarbonised economy are shown in Table 1.

Work Area	Description	Increase / Decrease
Fuels	Almost all future reactor types require new fuels which need enrichment to high assay low enriched uranium levels. None of these fuels are manufactured commercially today. This provides an opportunity to invest in the R&D required to develop the core competence across the range of fuels and manufacturing techniques most likely to be required for near-to-market reactors.	Increase
AMR Technologies	There is a clear driver for down selection of advanced reactor systems leading to reactor demonstration. Such advanced systems need to tie into the broader energy system in the UK and opportunities are seen in the use of such systems to contribute to heating, hydrogen and synthetic fuels in the medium term.	Increase
Digital Design, Safety & Security	Design of future reactors systems will require a significant upskilling of the nuclear community in the utilisation of advanced tools and techniques. Areas such as virtual engineering, security and modelling / simulations have been identified as important areas.	No Change
Materials for AMR Systems and Advanced Manufacturing	If, as expected, advanced reactor systems are pursued which operate at high temperatures it will be essential to ensure appropriate underpinning of materials performance. A key area of interest for the NIP should be defining the codes and standards and establishing pragmatic protocols for implementation.	No Change
Energy Systems	One of the main drivers for investment in advanced nuclear systems is the breadth of potential alternative outputs a nuclear heat source could potentially drive; from thermo-chemical hydrogen production to synthetic aircraft fuels.	Increase
Recycle	The UK has world-leading expertise in this area. It is likely that advanced reactor systems that could contribute to meeting the net zero target by 2050 will operate an open fuel cycle with no requirement for fuel recycle. However, in the longer term a global growth in nuclear energy and the need for energy sustainability may drive towards some parts of the energy system needing to adopt a closed fuel cycle. Under these circumstances it will be essential to maintain a competence in recycle technology.	No Change from average, but reduction from peak

Table 1 Proposed relative funding adjustments to the NIP

4.5.3. Infrastructure and Equipment Investment

Successful delivery of an innovation programme will rely upon access to an appropriate infrastructure. Government investment in recent years means that in many areas the necessary infrastructure is already available. Examples of recent investment include £90m in the National Nuclear User Facility (Phase 1 and 2), £10m in the Nuclear Fuel Centre of Excellence, £30m in the Henry Royce Institute for nuclear materials and over £250m in fusion facilities, including STEP. This has provided a strong baseline for future nuclear development however, some gaps remain. Future investment should develop the facilities required to undertake the validation and verification of nuclear technologies, tailored to their technical requirements.

In line with a need to consolidate investment in programmes, which can support civil nuclear deployment to meet net zero carbon commitments, NIRAB has identified seven potential areas of investment in infrastructure and equipment as outlined in Table 2.

	Area of the NIP Supported	Description	Rationale	Wider Interest
Reactor Demonstration	Demonstration Programme Energy Systems AMR Technologies	Facilities (i.e. digital, thermal hydraulics, materials development, fuels, etc) should predominantly support near to market technologies which can impact the 2050 net zero carbon agenda.	Several advanced technologies have the potential for deployment prior to 2050, e.g. HTGR and SFR. The benefits of these technologies need proving to allow technology deployment, ideally with combined energy outputs (e.g. electricity plus hydrogen).	Technology demonstration would have advantages to UK R&D and potentially access to neutrons for materials development.
Access to Neutrons	Demonstration Programme Fuels Programme	Developers will require access to neutrons to allow materials testing and validation against conditions which simulate proposed operating conditions.	Validation and verification procedures for civil nuclear components require testing of materials to specific conditions to prove operational suitability. Reactor condition are simulated through exposure in test reactors to identified neutron conditions.	Different reactor designs could require access to different characteristics of neutron production/test reactors. Access could be via a variety of different options from UK facility build to international collaboration and procured access.
Advanced Fuels	Fuels Programme	Equipment to support development and commercialization of the next generation of fuels including TRISO, ATF and other fuels with higher fissile content.	All major civil nuclear nations have a fuels manufacturing facility to ensure security of supply and technical competence plus economic benefit. The UK has a strong pedigree in fuel manufacture employing approximately 1000 people at Springfields today. Fuels are a long lead development item which all developers require.	All new fuel reactor systems proposed will require fuels which are not currently manufactured on a commercial scale anywhere in the globe. The initial market may be limited.
Coolant, Fuels and Materials	Demonstration Programme AMR Technologies Materials for AMR systems	The UK should maintain research in molten salt and metal-cooled reactors. This includes facilities for exploring thermal hydraulics, salt / coolant chemistry and potential reactor materials. Funding levels should be continuously reviewed against developing markets and technologies.	Longer-term technology, e.g. Molten Salt, has the potential for significant benefits (operational, safety and economic). However, due to material challenges, deployment timescales are longer. It is suggested that, in the current environment, maintaining an interest in these technologies is recommended.	Molten salts are important to wider thermal storage and fusion technology. Funding could possibly be leveraged via these technologies.
Digital workspace	Digital Design Safety & Security Demonstration Programme	A facility for the design, development, validation and verification of digital systems, e.g. control, maintenance or virtual training systems, for use in secure environments, including nuclear.	The NIP has proven the UK is advanced in its development of digital platforms. C&I systems are important elements of future plants with respect to control systems, remote maintenance and data analytics as the Internet of Things and automation becomes mainstream. Efficient regulation of such systems with secure environments is now required.	This is not a uniquely nuclear issue, although there will be elements which are nuclear specific. It is suggested that such a facility is focused on security and safeguards and links to other sectors.
Advanced Manufacturing	AMR Technologies Demonstration Programme Fuels Programme	Non-metallic material and manufacturing techniques should be developed including ceramics, composites, fabrics and plastic deployments in harsh environments as well as industrial shake tables to support seismic qualification.	Innovation in non-metal manufacturing could provide significant efficiencies to civil nuclear costs and efficiencies. Facilities to support such materials development could enhance deployment of advanced sensors, robotics and other remote applications.	Non-metallic material deployments in harsh environments have wide applications in robotics and other sectors including space, oil and gas.
Energy Systems Integration	Demonstration Programme Energy Systems	Facilities to develop and demonstrate the alternative energy outputs with appropriate civil nuclear reactor(s). Examples include hydrogen production, synthetic fuels, district and industrial heat and high temperature energy storage.	Civil nuclear technology has the potential to provide a range of alternative outputs (heat, hydrogen etc.) which could positively impact the UKs net zero requirements for 2050. Government should invest in facilities to support development and demonstration of these processes as well as appropriate reactor technology.	Government support is anticipated through the early identification of a site and appropriate infrastructure. Developer support is anticipated once the technology is confirmed

Table 2 Infrastructure and equipment investment

Table 2 Infrastructure and equipment investment

The work areas are intended to support the embedding of civil nuclear solutions as part of an integrated clean energy network. An example of such R&D Infrastructure is for digital deployment in secure environments. NIRAB acknowledge that there are other initiatives in this area, e.g. the Artificial Intelligence Sector Deal identifies a £69m investment in robotics for extreme environments. Given limitations both in funding and the technical skills to develop such systems, it is proposed that BEIS should explore and encourage cross sector development of secure, resilient and advanced digital environments for through life deployment of energy assets.

Government should explore cross sector initiatives to drive economic efficiencies.

Access to Neutrons

To develop and commercialise future nuclear assets, civil nuclear solution developers will require access to neutrons for reactor materials and fuel substantiation. There is no research reactor or other source of neutrons available in the UK for this purpose. Developers must therefore access international facilities, where possible. However, the spectra required vary between technology sources. Research reactors are generally tailored for a given output and there is currently no single research reactor which meets the requirements of all future technology types. The closure of the Halden Research Reactor has diminished UK access to international irradiation facilities. The Versatile Test Reactor is under development in the USA and the Jules Horowitz Reactor is under construction in France, but neither is expected to be operational for at least 5 years meaning a significant delay before fuel irradiation testing can be carried out. NIRAB acknowledges the foresight of BEIS in investing in a 2% stake in the French Jules Horowitz reactor. This should provide certainty on future access, but it is unlikely to satisfy all UK needs, therefore, further work is required to better understand such requirements. Bilateral agreements with other facilities, e.g. with Belgian, Dutch or US operators, may offer value for money on a case by case basis.

The case for building a UK-based research reactor has not been made yet, however the Welsh Government Office for Science is proposing to carry out an optioneering study to review all options capable of securing a supply of medical isotopes in the UK. One option would be the construction of a research reactor. If a business case can be made for the construction of a research reactor it will need to clearly set out the functionality required. This could include a range of functions including not only the production of medical isotopes, but also the irradiation of materials to underpin reactor safety cases. The latter requirement would require that the reactor should be capable of producing neutrons with an energy spectrum relevant to near-to-market advanced reactor technologies.

4.5.4. Cross Sector Research

Integration across the UK civil nuclear sector should be considered where possible, to increase value for money and decrease deployment timescales.

Synergies with Decommissioning

NIRAB recognises the contributions being made in robotics for extreme environments and nuclear battery technologies. Recent competitions in robotics in the decommissioning arena (e.g. the Nuclear Decommissioning Authority (NDA) Robotics Competition), remote decommissioning in ponds using adapted oil and gas technology and the use of Unmanned Aerial Vehicles for mapping on nuclear licensed sites all demonstrate the potential for innovation to deliver profound benefits. Therefore, the principle of outcome-based innovation should be deployed on the new build programme.

It is noted that increased collaboration across the areas of civil nuclear research and development including the NDA, and the NIP, will maximise innovation transfer and commercialisation opportunities.

Fusion Synergies

A number of synergies also exist between the needs and the challenges of advanced nuclear fission systems and fusion, especially in relation to the fact that both will generate a high temperature output which may need translating into other energy vectors. In particular, the R&D programmes and associated infrastructure requirements surrounding advanced materials, computational simulations, and robotics & artificial intelligence will benefit both Generation IV fission technologies and fusion systems.

Recommendation 6

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

Figure 16 Recommended funding allocation for future Government investment in civil nuclear fission research and innovation

4.6. Funding Requirement

For the future UK energy system to benefit from the versatility and flexibility that nuclear offers to decarbonisation, significant Government intervention is required alongside private investment and cost reduction. For nuclear to play the role outlined in this document, NIRAB considers it is essential to allocate £1Bn over the period 2021-26 as shown in Figure 16.

The recommended intervention related to the Demonstration Programme detailed in Section 4.4 and that related to the NIP in Section 4.5.

The funding strategy should involve both fully-funded and part-funded elements of the programme. Government investment should continue to fully fund the strategic capability maintenance elements of the NIP. Those elements that relate to industrial development and commercial deployment should also be facilitated by Government through significant up-front investment to leverage private sector investment. This funding strategy is outlined in Figure 17 and a number of key principles are proposed:

- The underpinning R&D programme is substantially funded from Government sources;
- As the programme progresses to reactor demonstration, Government seeks partners both in terms of programme funding but also routes to technology deployment;
- Subsequent phases of reactor deployment should be fully funded by appropriate reactor investors;
- Infrastructure requirements are not separated from R&D programme requirements, as these will be identified as part overall R&D funding activities.

For demonstration of an AMR in the period 2030 to 2035 a high level of public investment is needed from 2021 to ignite private sector investment and raise investor interest and confidence with spending increasing thereafter. Reactor systems, fuels, disposal route and energy conversion plant associated with a UK based demonstration will require ten years to develop and construct.

Funding requirements for the current UK SMR programme supported through the industrial strategy fund are not included in the above figures.

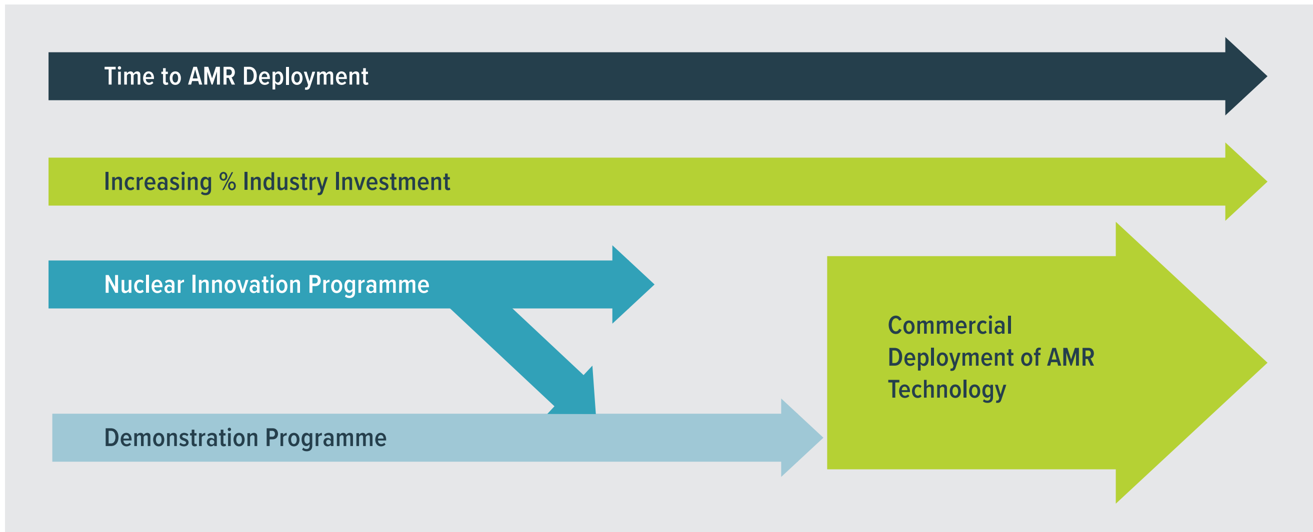

Figure 17 Proposed funding strategy for activities leading to commercial deployment (strategic capability development considered separately)

4.7. International Collaboration

Increased international engagement offers huge opportunities in cost sharing, acceleration of commercial deployment and the creation of export potential. Dependent on opportunities, the UK should consider working internationally to support AMR demonstration and deployment. This could involve:

- Working internationally to leverage the current UK and collaborator programmes, with a view to demonstration of a single technology in the UK;
- Investing in a partner's programme with a view to demonstration elsewhere prior to deployment in the UK;
- Participation in more than one demonstrator through international collaboration, thereby keeping the global deployment options flexible, de-risking the technical development and enabling access to key skills.

Accessing international expertise, critical R&D infrastructure and leveraging research, development and demonstration programmes will better enable SMR and AMR technologies to be developed in a cost-effective manner. International collaboration and appropriate sharing of resources will also accelerate commercialisation. The GIF, Euratom nuclear fission research and the Sustainable Nuclear Energy Technology Plan Strategic Research and Innovation Agenda [51] all offer opportunities to leverage UK investment and the UK should continue engaging with these programmes.

Recommendation 5

UK investment in nuclear fission should be leveraged effectively through international R&D programmes, that will enable successful commercialisation of technology to accelerate timeframes, making best use of resources, expertise and nuclear infrastructure.

Bi-lateral collaborations also bring immense potential and the UK should continue engage and collaborate where synergies exist. For example, though the United States Department of Energy / UK BEIS Nuclear Fission R&D Action Plan and similar arrangement with Natural Resources Canada. Another example where collaboration could lead to accelerated AMR deployment is the Japanese Atomic Energy Agency, which has been operating the High Temperature Test Reactor at Oarai since 1999 including research to exploit the high temperature output to produce hydrogen. The data and experience gained in Japan from this programme could reduce risks, shorten timescales and reduce the costs of demonstration and commercial deployment of HTGRs in the UK.

4.8. Managing the Programme

In order to meet net zero commitments, research and development activities need to be managed to deliver the objective of reactor development and commercial operations by the 2040's.

A change from the skills and capability maintenance within the NIP to a programme-led campaign will require an effective strategy, detailing required outcomes, appropriate government / industry funding and supply chain collaboration.

The proposed programmes (Figure 15) are all linked as they represent waves of technology development which can be deployed in the short, medium and long term, albeit supported by the development of the necessary cross-cutting skills and support technologies (e.g. fuel cycle). Further, it is noted that for the UK to effectively progress long-term technology development programmes, including required financial support, Government require a means to provide an effective long-term vision and management of these programmes, which includes a declared strategy for civil nuclear technology development. Figure 18 illustrates the proposed programme concept.

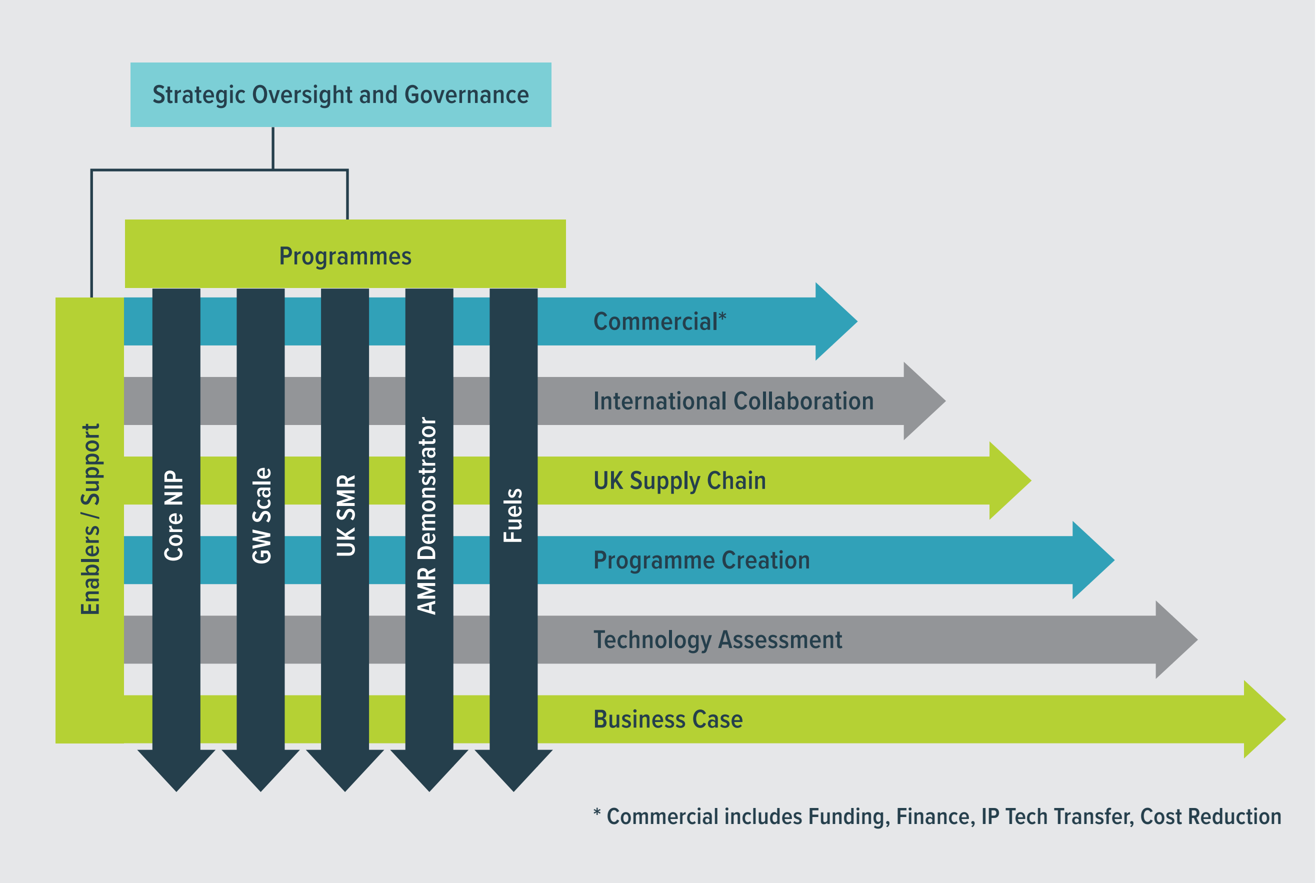

Figure 18 Programme concept

The management of programmes must be effectively coordinated. Programmes need to be strategically planned and funded against long-term schedules that recognise the risks associated with technology development and the long-term value they bring. Effective programme management will be required to achieve the anticipated benefits. It is important that in delivering programmes, techno-economic considerations are actively managed against the business case and associated benefits and it is also important that the strategic direction of the programmes remains within Government control or a non-commercial guiding entity such as the NIRAB, specifically structured for such a purpose.

Appendix 1. NIRAB Terms of Reference

Nuclear Innovation and Research Advisory Board Terms of Reference and Ways of Working

This Appendix sets out the terms of reference and ways of working for the nuclear research and innovation advisory framework comprising a combination of the Nuclear Innovation and Research Advisory Board (NIRAB) and the Nuclear Innovation and Research Office (NIRO).

Context

NIRAB was originally convened in January 2014 and provided advice on nuclear research and innovation to Government for a period of 3 years until it was disbanded in December 2016. Throughout this time NIRO acted as expert secretariat to NIRAB to convene meetings, gather and analyse data and draft reports.

Government found the advice valuable, along with other inputs, to inform the decision to invest in an ambitious Nuclear Innovation Programme and revitalise the nuclear research landscape in the UK. Government wishes to retain access to independent expert advice as the Nuclear Innovation Programme evolves and has tasked NIRO with convening a reconstituted and restructured NIRAB able to draw on a wide range of expertise.

Terms of Reference

NIRAB's Role

To work in partnership with NIRO to advise Ministers, Government Departments and Agencies on issues related to nuclear research and innovation in the UK. In particular to:

- Monitor the delivery and impact of the BEIS Nuclear Innovation Programme and recommend any amendments that may be necessary in the light of outputs from the programme and developments in the nuclear landscape;
- Advise where innovation could drive down costs across the whole nuclear cycle;
- Identify opportunities for greater collaboration with industry and international partners;
- To support the development of recommendations for new research and innovation programmes required to underpin priority policies including energy policy and industrial policy;
- To oversee a regular review of the nuclear research and innovation landscape which may include facilities, capability, portfolio and capacity in the UK;
- To foster greater cooperation and coordination across the whole of the UK's nuclear research and innovation capability, portfolio and capacity.

NIRAB does not have responsibility for managing or delivering R&D programmes or for directing or managing R&D budgets.

The Chair

The role of Chair of NIRAB is independent of Government. In addition to chairing the main meetings of NIRAB the Chair may be called upon to represent the Board in discussions with other key stakeholder such as Ministers, Parliamentary select committees and attending meetings of the Nuclear Industry Council to discuss R&D issues.

Membership of NIRAB

NIRAB will need to be able to draw on a wide range of expertise to be able to offer informed advice on the range of issues that may need to be addressed in the coming years. NIRAB will therefore comprise a pool of up to 40 members with attendance at meetings being determined by the expertise needed to address specific issues on the agenda.

Members will be invited to join NIRAB, for an initial period of two years with membership to be reviewed periodically beyond this point. With the exception of the Chair, appointments will be unfunded, other than the reimbursement of reasonable travel and subsistence costs.

Membership will encompass a wide range of subject expertise, and Members will be individuals with the credibility and position to best represent their fields. Members will be appointed as individuals and be expected to represent the interests of their field rather than their employer.

Observers and Supporting Staff

Meetings may include Observers such as Government and Departmental Chief Scientific Advisors, officials and representatives of public funding organisations including Research Councils, NDA and Innovate UK, as appropriate.

By agreement with the NIRAB Chair, other participants may be invited to attend meetings as observers to provide support and information.

Ways of Working

Meetings

It is anticipated that NIRAB meetings will take place up to four times per year, with attendance at each meeting dependent on the subjects to be covered at the meeting; not all Members will therefore be called upon for every meeting. As far as is reasonably possible Members will not deputise attendance.

Sub Groups

NIRAB may convene sub-groups to carry out specific workstreams as necessary, with participation not limited to NIRAB members.

Relationship to NIRO

NIRO is a full-time team and will comprise a part of the advisory framework. NIRO will:

- Provide secretariat support for NIRAB meetings and any sub-groups that may be convened;
- Provide the analytical capacity required to provide advice to officials;
- Draft annual reports and other reports, as required, for review by NIRAB;
- Carry out gap analysis in order to inform advice to Government on R&D programme priorities;
- Facilitate coordination of nuclear innovation and R&D activity and communications within and between Government and industry;
- Support Government's production of the business cases required to underpin nuclear research and innovation programmes.

Appendix 2. Nuclear Innovation and Research Office

The Nuclear Innovation and Research Office (NIRO) is a small full-time group of nuclear specialists working under contract to the Department for Business, Energy and Industrial Strategy. The role of NIRO is to provide independent technical and strategic advice and support to Government that will de-risk investment, inform policy and enable Government to achieve maximum value for money to the UK taxpayer. NIRO therefore comprises a part of the advisory framework. Its role in relation to NIRAB is described in the Terms of Reference set out in Appendix 1. In summary NIRO will:

- Provide secretariat support for NIRAB meetings and any sub-groups that may be convened;
- Provide the analytical capacity required to provide advice to officials;
- Draft annual reports and other reports, as required, for review by NIRAB;
- Carry out gap analysis in order to inform advice to Government on R&D programme priorities;
- Facilitate coordination of nuclear innovation and R&D activity and communications within and between Government and industry.

The NIRO Executive Director sits on NIRAB. Much of the work of NIRAB is carried out through working groups. More information of the working groups that have operated over the period covered by this report is provided in Appendix 3. Members of the NIRO team support the Chairs of these working groups by taking the role of Vice-Chair. Where possible the Vice-Chairs attend meetings of other working groups to ensure that information is shared between the groups and a consistent approach is adopted.

Appendix 3.NIRAB Working Groups

Most of the work required to shape the recommendations made by NIRAB has been carried out in a series of working groups which report their findings to the main Board for endorsement or amendment. The working groups have been consolidated since the publication of the previous report.

Membership and leadership of working groups

All of the NIRAB working groups are made up of NIRAB members and are chaired by a NIRAB member. In each case a member of the NIRO team acts as vice-chair and takes responsibility for organising meetings, compiling information and drafting reports for consideration by the working group. All of the NIRAB members belong to at least one of the working groups.

During the first year of NIRAB's existence a series of 6 working groups operated. These subsequently consolidated in to three groups. Each addresses some aspect of the exam question posed by Government. The purpose and scope of each group is outlined below.

Working Group 1 Nuclear Futures

Purpose

The purpose of working group 1 is to clearly articulate the potential scale of nuclear energy deployment that may be required to enable a net zero emissions target to be met. The group needs to consider near, medium and long-term deployment.

Scope of work

The working group will draw on and, where necessary, interpret

- Existing Government policy statements (for example the Industrial Policy, the Clean Growth Strategy, the Nuclear Sector Deal and the emissions targets set out in the Climate Change Act 2008);
- The outputs from studies of energy forecasts (e.g. the "net zero" report by the Committee on Climate Change) and wide-ranging consultations (for example the Big Tech workshops facilitated by NNL).

The group will consider how nuclear energy could contribute to meeting a range of energy demands including:

- Safe, secure and affordable generation of baseload electricity (referred to as firm power by the Committee on Climate Change;
- Flexible electricity generation required to compensate for the intermittency of renewables (referred to as mid-merit power by the Committee on Climate Change;
- Contribution to decarbonising other energy needs, especially the decarbonisation of heating (either directly or through the generation of hydrogen).

The working group will not:

- Seek to independently develop objectives which it believes Government or Industry should espouse;
- Make its own forecasts of future energy needs;
- Focus simply on short term objectives.

Working Group 2 – Affordability and Investability

Purpose

The purpose of the NIRAB affordability and cost reduction working group is to advise Government and industry on where research and innovation can improve the affordability and reduce the cost of nuclear energy requirements identified by the Nuclear Futures working group (WG1).

Much work has been done recently within the UK and globally related to cost-reduction and so the working group should consider and build on a range of recently published studies in these topic areas, in addition to the expertise of the group members, to provide tangible actions for Government and/or industry which aim to achieve set of short and long-term recommendations. Scope of work

The scope of working group is to:

- Evaluate strategic initiatives that can be taken to improve affordability, reduce costs and determine in what areas, if any, Government could and should develop an enabling framework to drive change;
- To develop recommendations for specific innovation areas/programmes for NIRAB to consider where:
  - Existing Government funding may be redirected within the current Spending Review period to better meet the cost reduction ambition set out in the Nuclear Sector Deal objectives – close communication with working group 3 will be necessary;
  - New Government funding may be required as part of the next spending review period to better meet cost reduction objectives or to enhance affordability;
- Collect or develop the evidence required to underpin recommendations;
- Seek to identify opportunities for international collaboration;
- Consider how any recommendations should be prioritised, where appropriate.

In formulating its recommendations, the working group should consider and interpret:

- Outputs from other NIRAB working groups where relevant;
- Existing Government policy statements (for example the Industrial Policy, the Clean Growth Strategy, the Nuclear Sector Deal and the Climate Change Act 2008);
- Publications directly linked to Nuclear cost reduction efforts including:
  - Expert Finance Working Group report;
  - ETI Nuclear Cost Drivers Project: Summary Report;
  - Output from the Nuclear Innovation Programme;
  - Output from the series of Big Tech workshops led by NNL.

Working Group 3 – Programme and Infrastructure

Purpose

The purpose of working group 3 is to assess the completeness and efficacy of the current BEIS Nuclear Innovation Programme, and provide advice to BEIS on the structure, content and priorities for a post-2021 programme, in line with the potential need to deploy nuclear energy in the near, medium and long term.

Scope of work

The working group should use the outputs of working group 1 as describing the near, medium and long term need to deploy nuclear energy;

The working group should take into account (from the outputs of WG1)

The working group should consider:

- The appropriateness and completeness of the Nuclear Innovation Programme areas;
- Whether there are any gaps or unnecessary elements in the programme;
- Whether the currently anticipated funding for the Nuclear Innovation Programme is appropriate to facilitate the achievement the of near and long-term objectives?
- What the UK should seek to be renowned for and whether there is a need to further focus the Nuclear Innovation Programme to enable this objective to be met effectively;
- How should the programme evolve post-2021 to best achieve the objectives;
- What further facilities will be needed to support a future programme and whether all currently available facilities will continue to be needed;
- Opportunities for international collaboration which align well to UK innovation needs and offer synergies to enable more rapid progress to be made, including opportunities to access international facilities;
- How competing innovation needs should be prioritised;
- Developing the evidence required to underpin recommendations.

The working group will not:

- Undertake a detailed technical peer review of the programme areas that have already been contracted;
- Develop new detailed programme content for any gaps identified in the current programme;
- Advise on the detailed content of any post-2021 programme recommendations.

Where necessary the working group membership will be extended to include innovation specialists who are not members of NIRAB to facilitate activities relating to the Nuclear Sector Deal.

Appendix 4. R&D Technologies and Themes

Cross Cutting Theme		Current	Near Term	Future Technology						Cross Sector Collaboration	Comments
		GW Scale	RR SMR	HTGR	Sodium Fast Reactors	Lead-Cooled Fast Reactors	Molten Salts	Gas Cooled Fast Reactors	Other		
Cross Cutting Theme	Fuel Cycle (Front End)	✓	✓	✓✓✓	✓✓✓	✓	✓✓✓	✓			Essential for future energy security and the UK is well placed to develop a fuels for all technologies
	Fuel Cycle (Recycle and storage)				✓✓✓	✓✓✓	✓✓	✓✓✓	✓		Skills retention and proliferation is a greater issue with respect to the recycle and storage than current proposals for fast reactor designs.
	Digital Design			✓	✓	✓	✓	✓		In part	Digital design alone can be enhanced via current products. Value is realised across the product lifecycle - e.g. manufacture, ops support, training etc...
	Digital Security and Resilience	✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓	An essential area to help realise cost effective deployment and operations. Includes control systems and operations.
	Advanced Manufacture		✓✓	✓✓	✓✓	✓	✓✓	✓	✓✓	✓	Adoption of appropriate common Codes and Standards (including pragmatic V&V) is essential. Specific techniques less so.
	Energy Conversion and Use		✓✓	✓✓✓	✓✓	✓✓	✓✓✓	✓✓	✓✓✓	In part	Understanding energy conversion and uses is essential to realise the wider benefits of civil nuclear incl hydrogen, district heat, electricity generation (carnot cycle?)
	Retractor Materials	✓	✓✓	✓	✓	✓	✓✓✓	✓	✓✓	Cross over with NDA	New materials will be required for new technologies, especially for molten salt, fusion and other novel applications, e.g. space.

Glossary

AFCP	Advanced Fuel Cycle Programme
AGR	Advanced Gas-cooled reactor
AMR	Advanced Modular Reactor
BEIS	Department for Business, Energy and Industrial Strategy
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CO_2e	Carbon Dioxide Equivalent
FOAK	First of a Kind
GHG	Greenhouse Gas
GIF	Generation IV International Forum
GWe	Giga Watt electric
HTGR	High Temperature Gas Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LCoE	Levelised Cost of Electricity
LFR	Lead Cooled Fast Reactor
LWR	Light Water Reactor
MWe	Mega Watt electric
MSR	Molten Salt Reactor
NDA	Nuclear Decommissioning Authority
NIP	Nuclear Innovation Programme
NIRAB	Nuclear Innovation and Research Advisory Board
NIRO	Nuclear Innovation and Research Office
NSD	Nuclear Sector Deal
RAB	Regulated Asset Base
R&D	Research and Development
SFR	Sodium Fast Reactor
SMR	Small Modular Reactor
STEP	Spherical Tokamak for Energy Production
TWh	Tera Watt Hour

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