Nuclear Industry Association

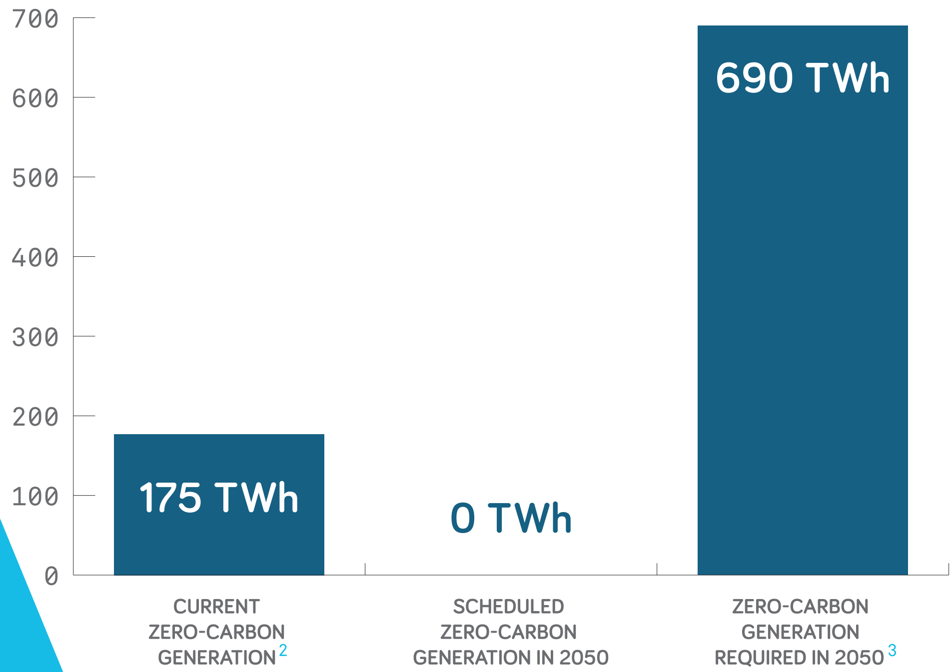
February 2021

Hydrogen Roadmap

1. NUCLEAR'S GREEN HYDROGEN POTENTIAL

Today, the UK depends on fossil fuels for more than three-quarters of its energy. Over the next thirty years, we must transition to a net zero economy. The challenge is immense. The Climate Change Committee has estimated that we need to generate four times as much clean power by 2050, as well as 225 TWh of low-carbon hydrogen to complete our decarbonisation.[1]

Figure 1 ***UK zero-carbon generation***



1] The Sixth Carbon Budget: The UK's path to Net Zero, Climate Change Committee, December 2020 www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf

2] DUKES 5.1 (includes thermal renewables such as biomass), Department for Business, Energy & Industrial Strategy (BEIS), July 2020 www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes

3] Energy White Paper: Powering Our Net Zero Future, BEIS, December 2020 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf

Faced with this task, we will need to deploy every low-carbon technology at our disposal to produce clean hydrogen, especially “green hydrogen” from zero-carbon sources. Nuclear, as a proven zero-carbon generator, should be a key part of the clean hydrogen mix:

- Current nuclear reactors and those under construction today could power cold-water electrolysis, producing emissions-free hydrogen at normal temperatures. Modular reactor technologies will also be able to power this process to produce green hydrogen.

- Low carbon heat from new nuclear reactors could power steam electrolysis, which is more efficient in producing hydrogen.

- Advanced modular reactors under development operating between 600-900°C could split water into hydrogen and oxygen without electricity, as envisaged in the Prime Minister’s Ten Point Plan.

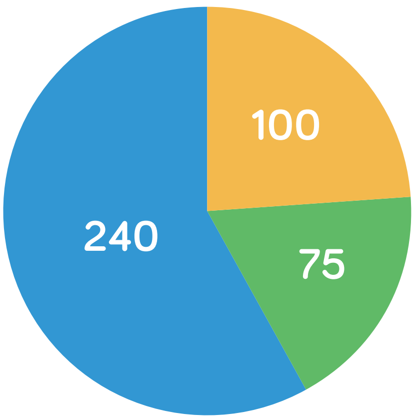
All of these processes would produce emissions-free hydrogen. Combined with the extremely low lifecycle carbon footprint of nuclear power, these options would form an invaluable part of a robust, clean hydrogen mix.

This paper therefore explains how nuclear can support the vision of the Prime Minister’s Ten Point Plan and the Government’s Energy White Paper. Building on Forty by ’50: The Nuclear Roadmap – endorsed by the joint Government and industry Nuclear Industry Council (NIC) – we set out in the paper below how nuclear can contribute to the hydrogen economy and what steps can make that happen.

Our ambition is for nuclear to produce 75 TWh of hydrogen by 2050, approximately one-third of the total requirement. This vision is predicated on the successful establishment of a nuclear financing mechanism to deliver extra capacity, and we are encouraged that the Government is actively considering several options to reduce the cost of capital.

Figure 2 *Deep decarbonisation in 2050 - beyond electricity*

415 TWh PER YEAR OF CLEAN ENERGY



TERAWATT HOURS PER YEAR

NET ZERO NUCLEAR ECONOMY

AN ADDITIONAL 18GW OF CAPACITY FOCUSED ON THE PRODUCTION OF HYDROGEN AND DISTRICT HEATING COULD FURTHER REINFORCE NUCLEAR'S CONTRIBUTION TO A NET ZERO ECONOMY

ON AVERAGE AVOIDING 186.75 MILLION TONNES OF CO_2 A YEAR—EQUIVALENT TO ANNUAL EMISSIONS OF 48 COAL-FIRED POWER PLANTS[4]

300,000 ADDITIONAL JOBS

£33BN ANNUAL GVA—GREATER THAN THE ENTIRE ELECTRICITY AND GAS INDUSTRY TODAY[5]

ELECTRICAL POWER GENERATED | POTENTIAL HYDROGEN GENERATED | POTENTIAL DISTRICT HEAT GENERATED

4] Greenhouse Gas Equivalencies Calculator, Environmental Protection Agency https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
5] Gross value added (GVA) of the United Kingdom (UK) in 2018, by sector, Statista, 27 May 2020 https://www.statista.com/statistics/285023/gross-value-added-gva-in-the-uk-by-sector

The industry recognises that this is only the beginning of the story. We therefore offer our full cooperation to the Government to help develop a robust policy framework to see through this great collective endeavour.

2. NUCLEAR AND THE HYDROGEN ECONOMY

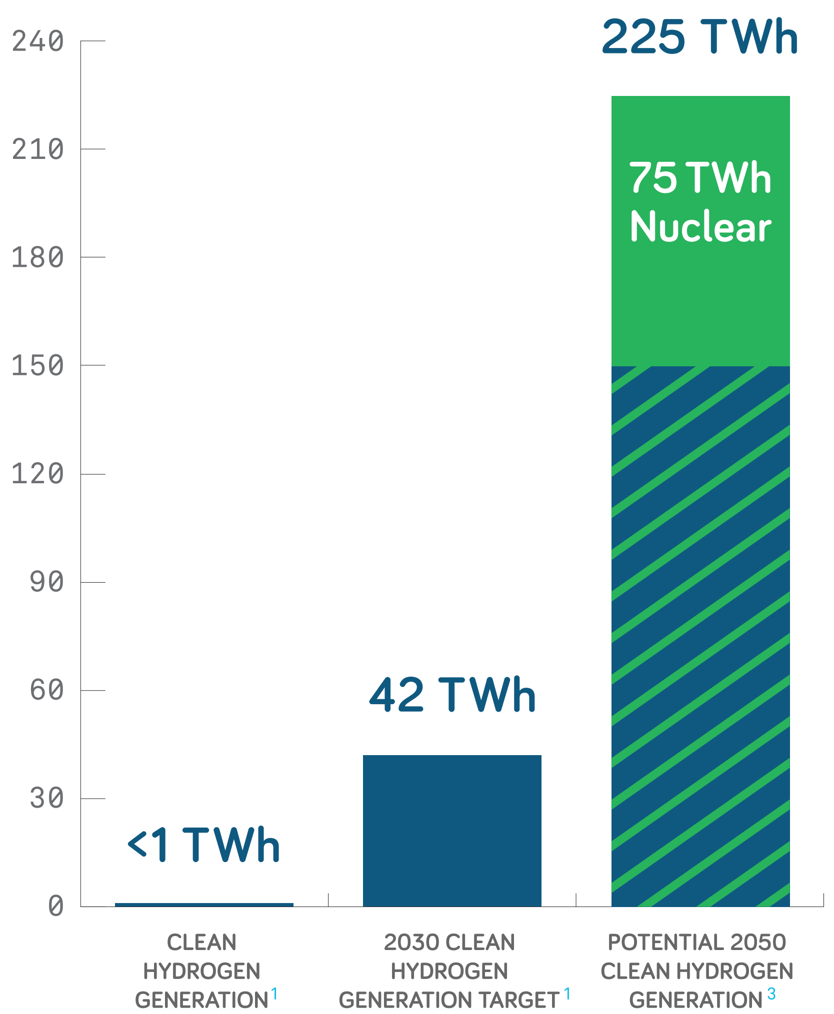
Hydrogen has been identified as a promising alternative to electrification, when the latter is not easily available, because it burns without any carbon emissions and can be produced through well-known chemical processes.

The Ten Point Plan set an initial target of 5 GW of low-carbon hydrogen production capacity by 2030, enough to produce 42 TWh, 20% of the 2050 target. Therefore, the growth rate to achieve 225 TWh of low-carbon hydrogen by 2050 will need to be significantly higher during 2030-50.

Given this vast ambition, nuclear should be a key part of the green hydrogen mix. Nuclear offers a reliable option for hydrogen today, in electrolysis driven by clean, firm power, and promising options for hydrogen tomorrow, in steam electrolysis and thermochemical water splitting. Forty by '50: The Nuclear Roadmap estimated that approximately 12-13 GW of dedicated nuclear capacity could produce 75 TWh per year of hydrogen by 2050.

In the following section, we examine how nuclear can create clean hydrogen, and what frameworks need to be put in place to encourage investment and develop a viable market.

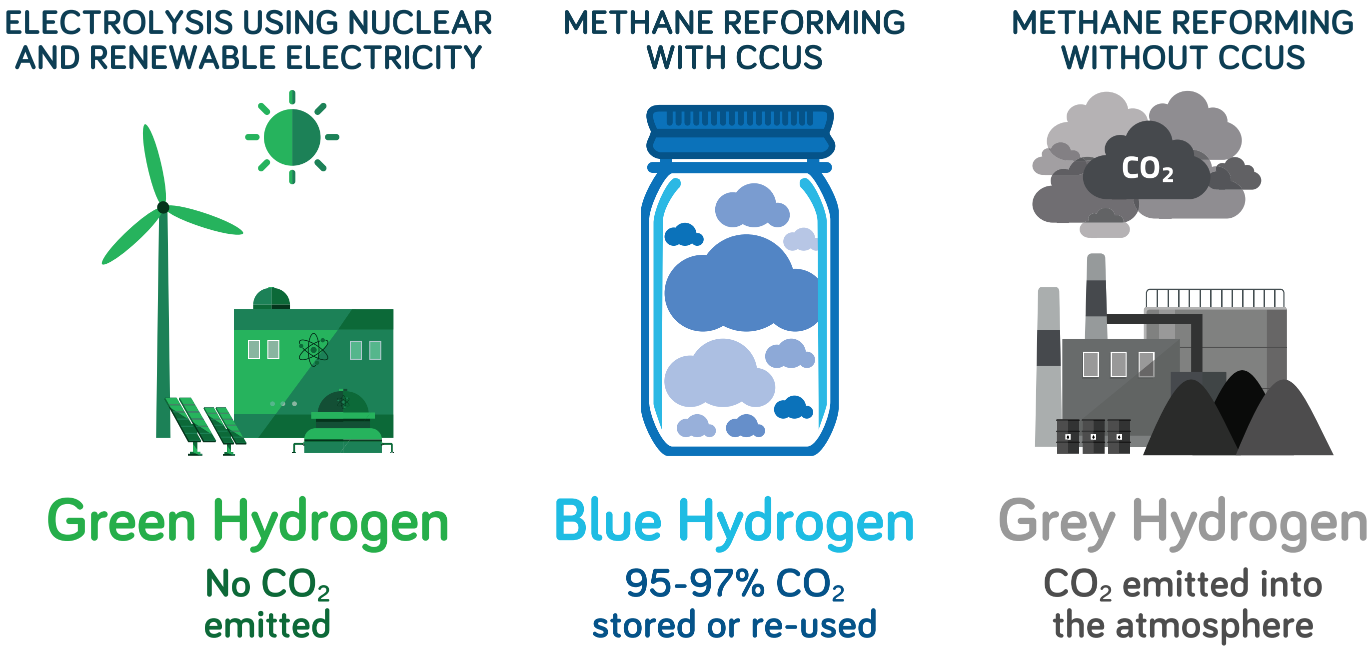
Figure 3 *Clean hydrogen production*



3. GREEN HYDROGEN PRODUCTION CAPABILITIES OF NUCLEAR POWER

Nuclear power, as noted above, can produce green hydrogen through electrolysis, one of three different ways to produce hydrogen:

Figure 4 *Hydrogen production methods*



Grey hydrogen is the most common method today, although it produces 10 kg of emissions for every 1 kg of hydrogen produced.

As technology develops, however, there will be four ways in which nuclear can produce hydrogen:[6,7]

1. **Cold water electrolysis** – electricity from a power station is used to split water into hydrogen and oxygen.
   - This requires diverting the electricity produced by the station from the grid to an electrolyser. The Hydrogen to Heysham[8] project investigated this process, which is available today and has been proven at a small-scale. The process is the cheapest currently available. It involves the cost of the electrolyser, the cost of storage, as well as the normal costs of producing the electricity.

2. **Steam electrolysis** – high-temperature steam electrolysis takes place between around 600-1000°C and requires a third less energy than cold water electrolysis and is therefore expected to be more efficient. Use of lower temperature heat can also increase the electrolysis efficiency, though not as much as in the 600-1000°C range. For instance, initial EDF analysis indicates that using low temperature heat (c. 150-200°C) from UK EPRs to support steam electrolysis will be technically feasible – via heat exchangers to achieve the required operating temperatures – and will offer efficiency benefits over cold water electrolysis. Steam electrolysis is technology available today.

6] Hydrogen Production and Uses, World Nuclear Association, Updated November 2020 www.world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx

7] Nuclear cogeneration: civil nuclear energy in a low-carbon future, The Royal Society, October 2020 https://royalsociety.org/-/media/policy/projects/nuclear-cogeneration/2020-10-7-nuclear-cogeneration-policy-briefing.pdf

8] H2H – Hydrogen to Heysham Feasibility Report, EDF Energy R&D UK Centre, October 2019 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866374/Phase_1_-_EDF_-_Hydrogen_to_Heysham.pdf

3. **Thermochemical water splitting** – heat between 600-900°C produced by an Advanced Modular Reactor (AMR) in the presence of chemical catalysts can be used to cause water to split into hydrogen and oxygen.

   - The current generation of reactors do not produce temperatures high enough for this process. The Government has, however, recognised that AMRs "could operate at over 800°C and the high-grade heat could unlock efficient production of hydrogen." AMRs could both produce clean power and clean hydrogen simultaneously.

4. **Reforming fossil fuels** – waste heat from nuclear power could provide the high temperatures for the steam reforming process instead of fossil fuels, but as carbon dioxide is released, this would need to be accompanied by carbon capture and storage.

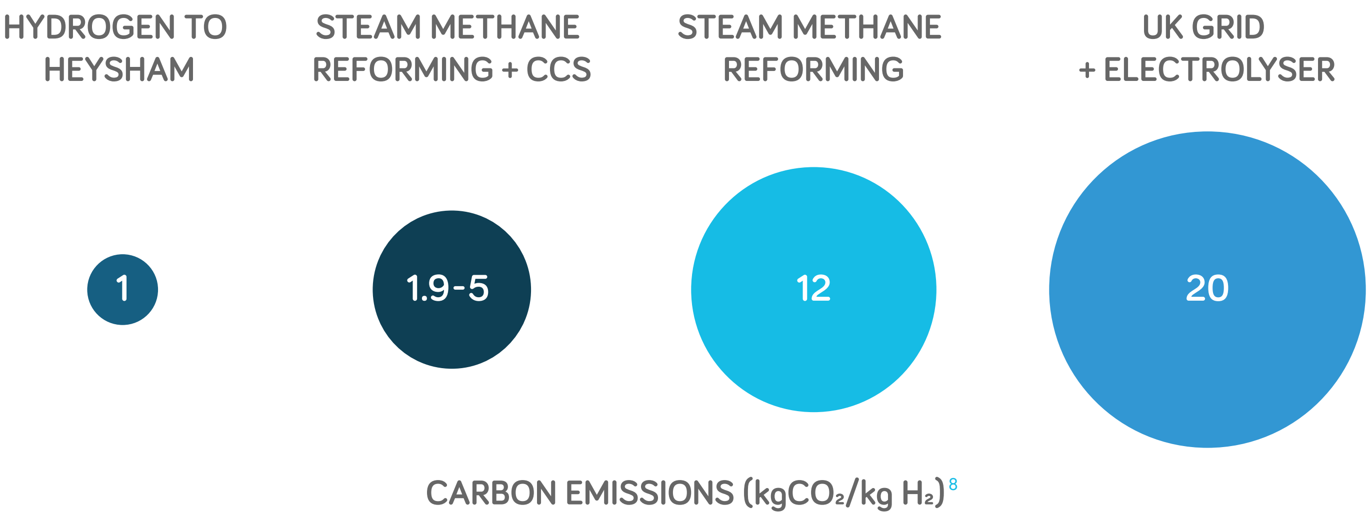
Case Study: Hydrogen to Heysham

EDF Energy's Hydrogen to Heysham (H2H) project examined the feasibility of producing hydrogen by electrolysis using electricity directly from Heysham nuclear power station, for a range of potential local applications. The feasibility study involved the development of a concept design for a 2MW electrolyser system—1MW each from a PEM and an Alkaline electrolyser—and was done in collaboration with EDF Hynamics, Lancaster University, EIFER and Atkins.

The H2H project, if realised, is calculated to have a carbon footprint of 24 $gCO_2/kWh\ H_2$, compared to 509 $gCO_2/kWh\ H_2$ for an equivalent grid-connected project—a significant difference in the level of carbon emissions.

The project also assessed the use of the by-product oxygen, for onsite use at the Heysham power stations or further applications. The study confirmed the technical feasibility of the production of hydrogen, coupled with nuclear generation for future nuclear new builds and that it met the relevant nuclear safety and industrial regulatory requirements, including health and safety and air quality. The project did not progress to demonstrator phase due to challenges in developing a successful business model without any support or incentives for end users to consume the green hydrogen produced.

Figure 5 *Nuclear-hydrogen: comparative carbon footprint*



The UK nuclear industry already has existing supply chain capability that can help facilitate the development of these hydrogen capabilities in the UK, including nuclear research facilities which have transferable skills that could be used for hydrogen chemistry and materials research.

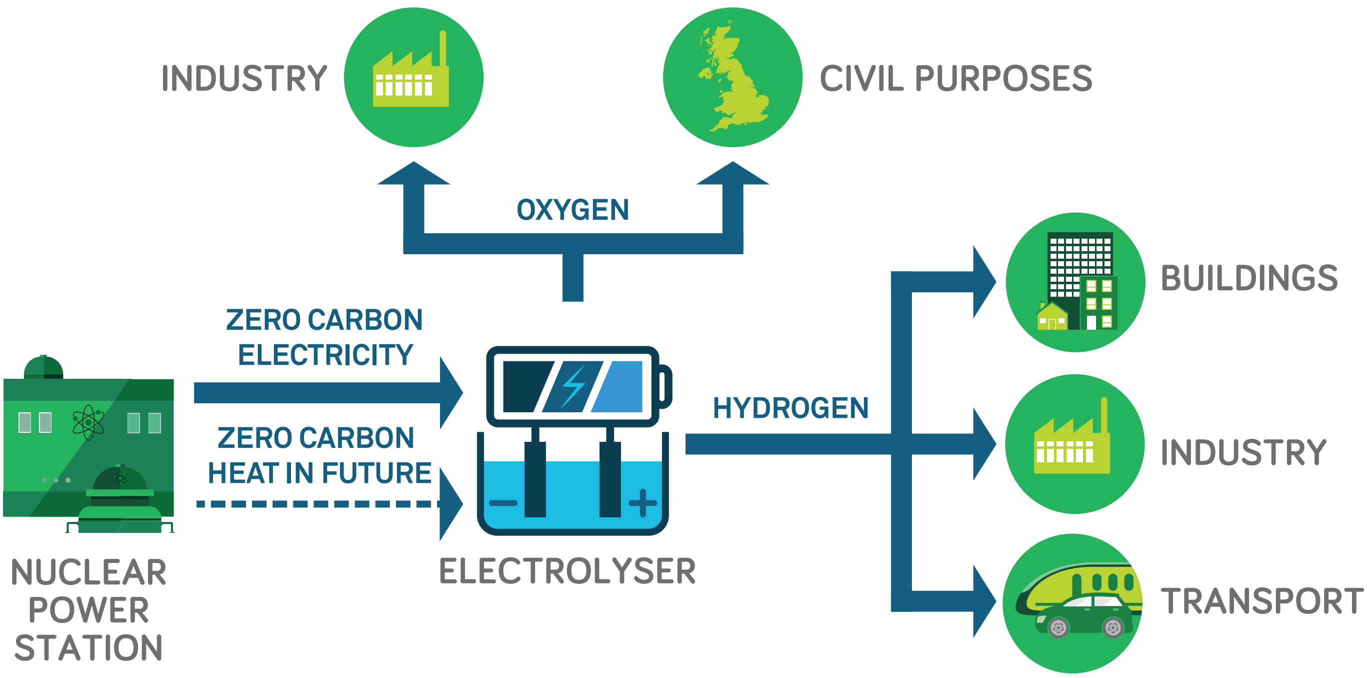
Case Study: Sizewell C

Sizewell C has the potential to make huge quantities of green hydrogen, using both electricity and heat, and to help the East of England take a lead in the new hydrogen economy. Heat assisted green hydrogen is projected to be more efficient (by around 10%) than hydrogen produced from electricity only.

To decarbonise construction at Sizewell C, the new nuclear project in Suffolk is looking to develop a demonstration electrolyser of around 2MW and around the size of a shipping container, capable of producing up to 800kg of hydrogen per day. This low-carbon hydrogen could be used in buses transporting construction workers to and from site, and to provide cleaner shipping at nearby ports, as well as providing clean heat and power to manufacturing around the facility. In the longer term a permanent larger facility supplied with low-carbon heat and power by Sizewell C could produce hydrogen at scale.

In November 2020, Sizewell C issued an Expression of Interest (EoI) seeking partners to develop its hydrogen demonstrator project, which may be powered by Sizewell B. Current steps also include an Innovate UK funded study on transitioning from a diesel to a hydrogen fleet of vehicles at Sizewell. East Suffolk Council is also involved in the study.

Figure 6 *Nuclear-hydrogen from electrolysis*



In the immediate future, Government support for nuclear projects that produce hydrogen through electrolysis, such as the demonstrator that Sizewell C wants to build, would be welcome, as it would develop the nearest term opportunity for nuclear-hydrogen.

In the longer term, SMRs and AMRs could also deliver increased efficiencies and further cost reductions. Government support for AMR research is therefore welcome and essential, and continued investment over the coming years will be a priority to make the technology commercially viable by the Government's target of a demonstrator by the early 2030s. As well as AMRs which offer the potential for heat above 600 degrees for hydrogen production, fusion would also provide high-grade heat. Government have invested £220 million in the first phase of design of a fusion prototype power plant, STEP.

Case Study: Advanced Modular Reactors

Advanced Modular Reactors (AMRs) are an increasingly popular choice for decarbonisation globally, with development programmes in some of the world's largest economies, such as Canada, the US, China, France and the UK. Their small size and associated lower costs, modularity and flexibility are seen as advantageous to not only producing electricity, but also for process heat and hydrogen. One of the key benefits to AMRs is that location is not a significantly limiting factor, which is a constraint for large scale nuclear and renewables.

A report from Lucid Catalyst found that using AMRs to transition to a hydrogen economy could be achieved through an investment of $17 trillion globally over 30 years, compared to the $25 trillion needed to maintain fossil fuels over the same period.

The UK Government has already taken steps to enable the development of AMRs in electricity generation by committing up to £385 million for the Advanced Nuclear Fund in the Government's 2020 Energy White Paper, which may include the development of a demonstrator AMR for hydrogen production. Such demonstrators are targeted to be deployed in the early 2030s.

Nuclear's potential for cogeneration, producing electricity and useful heat together, opens further possibilities for a resilient, decarbonised system. For example, when there is surplus renewable generation, using cogeneration could divert nuclear output to hydrogen production. Nuclear also has the ability to generate synthetic fuels, such as ammonia, using a hydrogen-based process, and these additional revenue streams will help drive down the costs of hybrid generation.

Reactors capable of cogeneration or dedicated to hydrogen could be built on brownfield sites, such as old fossil fuel plants and decommissioned nuclear plants, such as Trawsfynydd, that are already connected to existing energy infrastructure. AMRs are particularly suitable for placement on the sites of large manufacturing plants and factories and could also produce hydrogen to power such facilities. This would be useful for carbon-intensive industries, such as steel, which could otherwise struggle to decarbonise due to their unsuitability for electrification.

These possibilities for nuclear-hydrogen should all be explored to maximise the extent of decarbonisation.

4. ADDRESSING BARRIERS TO NUCLEAR-HYDROGEN DEPLOYMENT

The development of green hydrogen capabilities for all types of nuclear reactors would be facilitated by addressing policy and regulatory issues, alongside other steps in this report.

Production Costs and Financing

Cost is the principal barrier to green hydrogen, rather than technical capability. Grey hydrogen is currently cheaper to produce, particularly since its carbon emissions are not adequately priced. Calibrated incentives and investments can achieve the cost reductions necessary to make clean hydrogen competitive.

In order to reduce costs, we recommend that:

- A grant and subsidy scheme be set up to encourage research and development to help reduce the costs of electrolysers. This could be part of a broader scheme to offer capital grants to zero-carbon generators to install electrolysers.

- A new funding model is introduced to reduce the cost of capital associated with nuclear projects, reducing the price of electricity they produce. This could be achieved from either direct government financing or another financing model, such as a Regulated Asset Base (RAB).

- Government should work with Ofgem to explore the scope for a new scheme to replace payments to zero-carbon generators for constraining generation gradually with support for hydrogen production. For reference, constraint payments to variable renewables reached nearly £450 million in 2019.[9]

    - Under this approach, clean power could be diverted to produce hydrogen through electrolysis rather than switching off during periods of excess supply. This would convert the sunk costs of constraints into productive support for decarbonisation.
    - It is important to note that this recommendation would need further consideration and would require a gradual introduction to the system and any replacement of constraint payments could only be proportional to the practical capacity available for powering electrolysers.

- An ambitious carbon pricing system is established that reflects the full externalities of emissions and the UK's net zero target.

- The anomaly whereby nuclear-produced hydrogen, unlike renewable-powered hydrogen, does not qualify for Renewable Transport Fuel Obligation (RTFO) support should be removed.

- Nuclear-hydrogen production in a range of forms is eligible for inclusion in the recently announced Net Zero Hydrogen Production fund.

- An AMR development timeline is set out, including demonstration of hydrogen production technology, involving five-year R&D funding settlements to provide stability.

These steps would encourage investment in hydrogen, which in turn would drive down costs. As we have seen from the experience of offshore wind power, continuous investment with Government support is the best way to make low-carbon technologies more cost competitive. The same will be true for nuclear-hydrogen. This is a potential avenue for the new UK Infrastructure Bank to explore.

Japan and the US have both launched programmes to investigate the cogeneration capability of nuclear in producing green hydrogen, so the UK can have confidence that other major economies have identified the promising opportunities here.

Economic Advantages of Nuclear-hydrogen

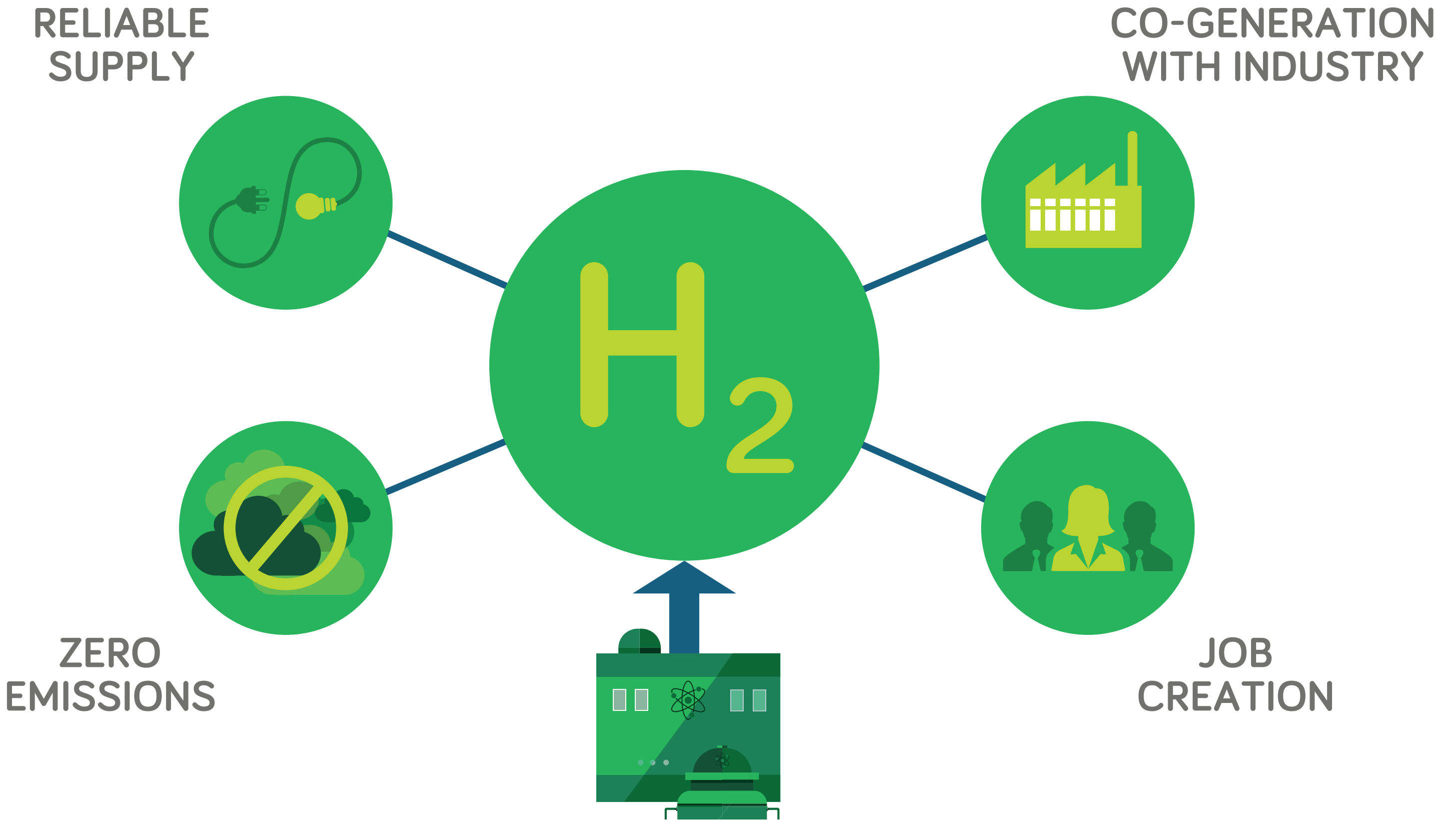
Given the capabilities explained above, and with these enabling steps taken, nuclear-hydrogen could improve the economics of hydrogen production based on the following factors:

9] Constraints – can't stop loving you, Tom Palmer, January 2020 www.cornwall-insight.com/newsroom/all-news/constraints-can-t-stop-loving-you

- Provision of reliable, firm zero-carbon power, helping to ensure electrolysers can achieve high load factors throughout the year, lowering costs of hydrogen production.
- Improvement of the efficiency of hydrogen electrolytic production through use of heat, achieving higher output at the same cost.
- Utilisation of low carbon heat as well as electricity (co-generation) from future nuclear reactors, expanding potential industrial uses.
- Use of both heat and power from nuclear energy and from the ability to switch some nuclear output between supporting hydrogen production and meeting wider national electricity demand, potentially reducing system costs.

A recent report by the Nuclear Innovation and Research Advisory Board (NIRAB)[10] states that clean hydrogen from nuclear energy could be produced for \$2.5/kg-H_2, compared to the cost of production from natural gas with CCS which is in the region of \$2.3/kg-H_2 where electrolysis is not available. This provides an early indication that, supported by the right framework, green hydrogen from nuclear could be competitive in a broader mix.

Figure 7 *Benefits of nuclear-hydrogen*



Blue and Green Hydrogen Forecasting

Green hydrogen should become the UK's preferred option in the long term, as the best way to hit net zero is to avoid emitting carbon in the first place. Hydrogen produced by either renewables or nuclear also offers a lower lifecycle carbon footprint.

10] Achieving Net Zero: The role of Nuclear Energy in Decarbonisation, Nuclear Innovation and Research Advisory Board, April 2020 www.nirab.org.uk/application/files/6315/9160/6859/NIRAB_Achieving_Net_Zero_-_The_Role_of_Nuclear_Energy_in_Decarbonisation_-_Screen_View.pdf

Blue hydrogen nonetheless has an important role in driving the transition from natural gas to hydrogen as well as stimulating a UK hydrogen market. As previously explained, the UK needs to mobilise all feasible low-carbon technologies to hit net zero.

The following parameters for hydrogen deployment in the Hydrogen Strategy would therefore create clear policy goals under which to pursue further technical innovations and cost reductions removing barriers to the deployment of green hydrogen, including nuclear-hydrogen:

- Green hydrogen, produced directly from nuclear and renewable generators, should be the preferred option where possible, producing the majority of supplies by 2050, with blue hydrogen providing support for the areas hardest to decarbonise.
- Nuclear-hydrogen should be central to green hydrogen alongside renewable hydrogen, because it offers clean, reliable power for electrolysis and the additional efficiency benefits from combining low-carbon heat and electricity from nuclear energy, including through AMR technologies
- Grey hydrogen should be phased out as practical.

5. NUCLEAR-HYDROGEN: PROSPERITY, REGIONS AND SKILLS

Nuclear-hydrogen production would support the Government's ambition to 'level-up' regions of the UK facing economic challenges. In the UK alone, the development of a hydrogen market could contribute up to £18 billion in Gross Value Added (GVA) annually[11] and, as stated in the Ten Point Plan could add 100,000 jobs to the economy.

The nuclear industry currently directly supports 60,000 jobs across the UK, disproportionately outside London and the South East.[12] Hydrogen production using nuclear power would add tens of thousands of high-skilled, well-paid jobs to this total. The South West of England is already home to many leading companies that are developing hydrogen solutions, while the North West Nuclear Arc, a cluster that spans the North West of England and North Wales, and the North East of England have great potential for integration of hydrogen and nuclear.

By seizing the opportunity to incentivise nuclear-hydrogen from electrolysis, and develop thermochemical nuclear-hydrogen, we can bring benefits to communities in which nuclear is deep-rooted, such as Copeland, Hartlepool, Anglesey and Bridgwater, which are also likely to be disproportionately affected by the economic impacts of COVID-19. This would support the UK's twin goals of hitting net zero and securing stable employment and economic prosperity across all parts of the country.

6. RECOMMENDATIONS FOR CLEAN HYDROGEN DEPLOYMENT

While this report has made a number of key recommendations, the initial call is for the whole industry – across energy, nuclear, renewables, transmission and beyond – to work together to tackle the challenge of achieving the UK's hydrogen ambitions as part of net zero. No single sector, energy source or hydrogen type possesses all the answers, therefore collaboration will be vital for success.

11] Hy-Impact Series Study 1: Hydrogen for economic growth, Element Energy, November 2019 www.element-energy.co.uk/wordpress/wp-content/uploads/2019/11/Element-Energy-Hy-Impact-Series-Study-1-Hydrogen-for-Economic-Growth.pdf

12] Jobs Map 2020, Nuclear Industry Association, September 2020 https://www.niauk.org/resources/jobs-map/

The nuclear sector has considerable expertise and is eager to cooperate closely with Government as we develop answers to the defining challenge of net zero.

Figure 8 *Nuclear green-hydrogen capabilities*

	COLD-WATER ELECTROLYSIS	STEAM ELECTROLYSIS	THERMOCHEMICAL WATER SPLITTING
Gigawatt-scale reactors	✓	✓	
Small Modular Reactors	✓	✓	
Advanced Modular Reactors	✓	✓	✓

Strategic Parameters

1. The following parameters for hydrogen deployment in the Hydrogen Strategy would help facilitate nuclear-hydrogen solutions and other clean hydrogen solutions:

    a. Classification of hydrogen created from nuclear power as green hydrogen, because it is emissions-free and would have a very low lifecycle carbon footprint.

    b. Identification of green hydrogen, produced directly from zero-carbon generators, as the preferred option where possible.

    c. Transition from grey hydrogen as practical.

2. To ensure collaboration between the nuclear industry and Government, the latter should include direct nuclear industry representation on the Hydrogen Advisory Council, in line with previous commitments, to ensure that green hydrogen from nuclear is incorporated into the overall vision of a hydrogen economy.

    a. Direct nuclear industry participation in the Hydrogen Advisory Council Working Groups to provide expertise on how to implement the recommendations of this report and develop green hydrogen production and distribution capability.

3. A target consistent with the NIC-approved Forty by ’50: The Nuclear Roadmap for nuclear to produce 75 TWh of hydrogen would drive ambition and innovation in the industry.

4. A definitive analysis of systemic infrastructure challenges would be extremely useful to determine the maximum possible extent of electrification, and the area in which hydrogen should be used instead. This would include the following actions to examine the key challenges to hydrogen deployment:

    a. Grants for the study and development of solutions to improve hydrogen storage, as part of the Hydrogen Strategy, including the potential to use depleted uranium metal to store hydrogen at high density.

Investment Incentives

5. The following investment incentives for nuclear-hydrogen and other green-hydrogen should be adopted to drive innovation and reduce costs:

   a. A grant and subsidy scheme to encourage research and development to help reduce the costs of electrolysers. This could be part of a broader scheme for covering electrolysis from all zero-carbon generators, which should include R&D and demonstration programmes for all types of nuclear technologies.

   b. A new funding model to reduce the cost of capital associated with nuclear projects, thereby lowering the price of electricity they produce. Both a Regulated Asset Base (RAB) model and direct government financing during construction could achieve these reductions.

   c. Capital grants to zero-carbon generators to install electrolysers and expand funding for research and development into the technology.

   d. Consideration of a new scheme to gradually replace payments to zero-carbon generators for constraining generation with support for hydrogen production in collaboration with Ofgem.

   e. An ambitious carbon pricing system which reflects the full externalities of emissions and the UK's net zero target.

   f. The removal of the anomaly whereby nuclear-produced hydrogen does not qualify for Renewable Transport Fuel Obligation (RTFO) support whereas renewable-produced hydrogen does.

   g. Confirmation of nuclear's eligibility for inclusion in the recently announced Net Zero Hydrogen Production fund.

   h. An AMR development timeline, involving five-year R&D funding settlements to provide stability, in-line with having a demonstrator by the government's target of the early 2030s.

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