Written Evidence Submitted by the National Engineering Policy Centre (NEPC)

(HNZ0078)

Introduction

1. The National Engineering Policy Centre (NEPC) welcomes this opportunity to respond to the Science and Technology Committee's inquiry on hydrogen. This response draws on evidence from the NEPC Net Zero Project[1] and the expertise of members of its Working Group which include engineering, system science and social science experts.

2. NEPC connects policy makers with critical engineering expertise to inform and respond to policy issues of national importance, giving policymakers a route to advice from across the whole profession. The Centre is an ambitious partnership, led by the Royal Academy of Engineering, between 43 different UK engineering organisations representing 450,000 engineers.

3. This response has been compiled with input from:
   - Members of the NEPC Net Zero Working Group, which includes representation from the Royal Academy of Engineering, British Academy, Energy Institute, Institution of Chemical Engineers, Institution of Mechanical Engineers, Chartered Institution of Building Services Engineers, Institution of Gas Engineers and Managers, Institution of Engineering and Technology, Institution of Civil Engineers, Institute of Materials, Minerals and Mining.
   - Members of the Energy Policy Panel, The Institution of Engineering and Technology,
   - Members of the Hydrogen Committee, Institution of Gas Engineers and Managers.
   - Institute of Measurement and Control

4. Table 1: *Dependencies of a hydrogen system* and Figure 2: *System map of a potential future hydrogen system* were co-developed by the NEPC with the Department for Transport as part of a hydrogen systems workshop.

Key messages

5. The future net-zero carbon industrial and energy systems will inevitably be more heterogenous than today's systems. Every net-zero carbon society around the world will need at least four net-zero energy storage and transmission vectors in different proportions relating to their local circumstances and endowments: electricity, hydrogen, synthetic fuels and biofuels. The main issue that will play out over time is the relative proportions and the roles where each is most suitable. And the latter may even vary by region within the country.

6. We therefore welcome the government's plan to deliver a hydrogen strategy for the UK. Such a strategy will need to address both supply and demand and it will be vital for creating markets and attracting investment. The strategy has the potential to capitalise on the UK's expertise and skills, and to drive international competitiveness, but it will need to be clear about what it is aiming to achieve. Building production capacity and

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[1] More information and full list of publications is available at www.raeng.org.uk/net-zero

transforming markets on the demand side will take time. Scaling up from research and development projects to pilots to commercial scale deployment requires focused attention so that the UK can lead globally, developing capability, new industries and export opportunities. The transformation therefore requires strong vision, drive and commitment from government.

7. Hydrogen is an energy vector rather than a source of energy - once produced from an energy source, it can be stored and transported. To date, there is a lack of consensus both on how hydrogen should be produced and how it should be used. Multiple pathways are possible for the transition to a future hydrogen system, as well as multiple possible end-points. Establishing the optimal solutions across production, transmission, storage and end-use necessitates solving engineering and commercial challenges associated with each for which large-scale technology demonstrations will be key. We therefore welcome the government's commitment to demonstrate and develop technologies and business models for the hydrogen system, including carbon capture, usage and storage (CCUS).

8. It is vital that the strategy considers the whole hydrogen system. This whole-system strategy should address how the individual components will work together, and how the system will evolve and operate alongside other parts of the net zero system. Systems thinking and a clear decision-making framework will be needed to ensure that both the transition and resulting system are both the most cost-effective and most effective in reducing carbon emissions, and that hydrogen is used where it can add most value. As part of a systems approach, social and political issues must be taken into account including the acceptability of hydrogen to end-users. Learning from past policies will be vital. The UK's natural resources, wider energy system, industry experience and infrastructure assets, as well as global use of hydrogen, are also important factors in decision-making.

9. Hydrogen is not a 'silver bullet' for all end-uses. Instead, decision-making could be guided by means of a hierarchy according to the value of hydrogen for each end-use - is it necessary, helpful or not useful at all? What are the system implications? The presence or lack of alternative energy vectors for a particular end-use is a further factor in decision-making. Hydrogen has clear benefits in applications such as industrial heating and processes, and heavy goods transport, and especially where a viable alternative option does not exist. Its use in domestic heating is less clear-cut since electrification exists as a competing option. It will, however, be necessary to keep options open until the appropriate evidence is available and the relative benefits and disbenefits of the various options, and implications for the system as a whole, can be more effectively appraised.

10. If government prioritises uses according to the certainty of investor returns, hydrogen could potentially have greater commercial viability compared to gas in end-uses with larger consumers such as industrial uses. The hierarchy of potential end-uses should also guide the government's approach to R&D funding, while reiterating that all options should be kept open until there is sufficient certainty.

Box 1: Methods of hydrogen production

Grey Hydrogen – High-emission hydrogen produced from natural gas reforming or coal gasification, from fossil fuels (eg natural gas) or biomass, whose CO_2 emitted during production **is not** abated using carbon capture and storage. This is a high-emission process, and the current method of hydrogen production for industrial use (eg in ammonia production).

Blue hydrogen – Low-emission hydrogen produced from natural gas reforming or coal gasification, from fossil fuels (eg natural gas) or biomass, whose CO_2 emitted during production **is mostly (~95%)** abated using carbon capture and storage. Hydrogen produced from natural gas can contain impurities (due to impurities in the natural gas feedstock) which make it unsuitable for use in fuel cells or applications where high purity is needed.

Green hydrogen – Low or zero-emission hydrogen produced through electrolysis of water using zero carbon energy, such as from renewables, nuclear or Biomass Energy with Carbon Capture and Storage (BECCS). This requires water as a feedstock, and produces pure oxygen as a by-product for which commercial markets include welding, medical applications and chemical processes.

<u>QUESTION 1: *The suitability of the Government's announced plans for "Driving the Growth of Low Carbon Hydrogen",*</u> *including:*

a. ***the focus, scale and timescales of the proposed measures;***
b. ***how the proposed measures—and any other recommended measures—could best be co-ordinated;***
c. ***the dependency of the Government's proposed plans on carbon capture and storage, any risks associated with this and how any risks should be mitigated; and***
d. ***potential business models that could attract private investment and stimulate widespread adoption of hydrogen as a Net Zero fuel;***

a. <u>The focus, scale and timescales of the proposed measures</u>

11. The future net-zero carbon industrial and energy systems will inevitably be more heterogenous than today's systems. Every net-zero carbon society around the world will need at least four net-zero carbon energy storage and transmission vectors in different proportions relating to their local circumstances and endowments: electricity, hydrogen, synthetic fuels and biofuels. The main issue that will play out over time is the relative proportions and the roles where each is most suitable. These proportions may also vary according to changes in technology and opportunity, so agility across the vectors and the ability to respond quickly will prove valuable.

12. Multiple pathways are possible for the transition to a future hydrogen system, as well as multiple possible end-points. Uncertainties about deploying the technology at scale - including social, as well as technical and commercial aspects - mean that large-scale demonstrators must play a vital role over the next decade up to 2030 to help us understand better where different energy vectors will play a role and in what proportions. Key lessons still need to be learnt to fully understand the different factors in hydrogen's production, transport and end use, that will influence its role in the UK's energy system. Scaling up from research and development projects to pilots to commercial scale requires focused attention so that the UK can lead globally, developing capability, new industries and export opportunities.

13. We therefore welcome the government's plans to support technology and business model development for multiple aspects of for the future hydrogen system. These are 'low-regrets' options: urgent priorities - given the timescale to develop the system - that unlock pathways towards the net-zero target, rather than blocking them off[2]. These include support for enabling work to help realise medium- and long-term opportunities, as well as quick wins.[3] The urgency, scale and pace of emissions reductions requires learning by doing. The government must act boldly, adapt flexibly as the system evolves, and pursue multiple net zero pathways on the assumption that some will prove to be more viable than others. We look forward to further announcements that address the necessary scale, breadth of deployment and rapid timescales.

14. As the government's plan for the hydrogen system evolve, it is vital they are closely aligned with plans for low-carbon industrial clusters, which will inevitably need more hydrogen. This should also consider the connectivity between the clusters and

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[2] NEPC (2020), Beyond Covid-19: laying the foundations for a net-zero recovery.

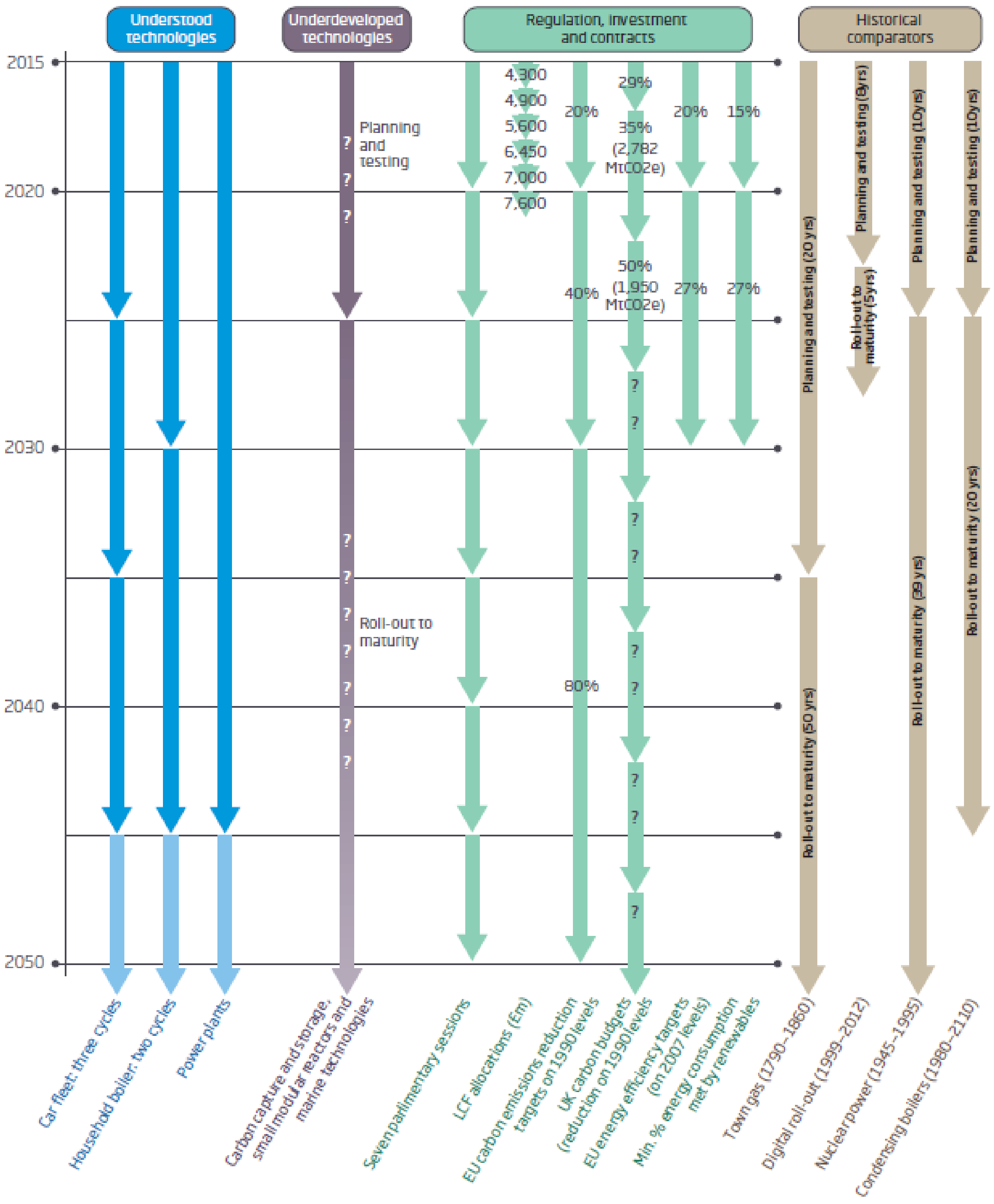
[3] An NEPC paper on low-regrets decision-making in the face of urgent and complex policy challenges is in preparation and will be published at www.raeng.org.uk/net-zero.

overspills into other sectors such as domestic or commercial building heating and transport.

15. Timescale and sequencing of infrastructure deployment will be key for hydrogen and net zero overall. The government has set a target of at least 68% greenhouse gas emission reduction by 2030, recognising the need to frontload progress on reducing emissions. Steps must be taken to ensure that deployment of net zero carbon technologies meets the required pace. Figure 1 below offers some current and historical comparators of infrastructure deployment timescales (as understood in 2015) to demonstrate the scale of the challenge. The timescales for deployment of hydrogen need to be mapped out, taking into account how financing and regulation might impact these. There will be lessons in relation to the timescales for deploying the Town Gas system, and the replacement rates of household boilers. There is a question about to what extent the scale of hydrogen deployment compares to the scale of previous deployments of major infrastructure and technology changes, and how it can be accelerated.

16. The Government's ten-point plan includes the aim for the UK to develop 5GW of low-carbon hydrogen production capacity by 2030. This is larger than a single power station. It is essential to understand and clarify how the ambition will be delivered.

Figure 1, showing engineering timescales for infrastructure deployment and their interaction with political and market factors.[4] Note that this figure was produced in 2015, prior to the legislation of the net zero target and setting of some carbon budgets.



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[4] A critical time for energy policy, Royal Academy of Engineering, 2015.

b. How the proposed measures—and any other recommended measures—could best be co-ordinated

17. Achieving net zero by 2050 is a systems transformation challenge. Developing a low-carbon hydrogen system, potentially with added sequestration[5] to deliver net zero-carbon, combines the unique challenges of designing and deploying a new and complex socio-technical infrastructure system at record pace, while ensuring coherence, compatibility, efficiency, and interoperability with the wider transport, energy, data and other systems with which the hydrogen system will depend on, and which will themselves depend on the hydrogen system.

18. A hydrogen strategy must consider the whole hydrogen system. This whole-system strategy should address how the individual components will work together, and how the system will evolve and operate alongside other parts of the net zero system. Systems thinking and a clear decision-making framework will be needed to ensure that both the transition and resulting system are the most effective in reducing carbon and the most cost-effective, and that hydrogen is used where it can add most value. As part of a systems approach, social and political issues must be taken into account including the acceptability of hydrogen to end-users. Learning from past policies will be vital. The UK's natural resources, industry experience and infrastructure assets, as well as global use of hydrogen, are also important factors in decision-making.

19. Hydrogen falls into a number of different policy areas, responsibilities for which are distributed across several areas of government but will need to be brought together into a unified programme of work under a net-zero delivery body. This must be a high-level systems architect body evidence-driven by data and analytics, with responsibilities, funding and accountability which can align government around the net zero goal; in other words, a systems approach to policymaking will be required.[6,7] A systems approach helps policymakers to gather evidence from the widest, most diverse and critical perspectives leading to a 'bigger picture' view of this policy opportunity and how different parts of the system interact to affect the desired outcome.

20. National strategies must be balanced with bottom-up local and regional co-ordination and decision-making, and strong formal mechanisms for communities and populations to shape their energy future. This will also require strengthening local government systems management expertise.[8] In a more diverse and decentralised energy system, and with potentially significant variations in local need and public attitudes to different technologies, energy infrastructure and other net zero systems must deliver on the needs of a community as perceived by them, and this must be reflected in the national strategy.

21. In addition to the dependency on CCUS, which is discussed further in Question 1(c), Table 1 outlines examples of key dependencies on which the success of a UK hydrogen system will depend. This table emphasises the need to consider the system as a whole when designing and implementing policy.

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[5] Sequestration refers to all negative emission methods which may or may not utilise CCUS; for example, BECCS, DAC, tree planting, rewilding, land use change.

[6] NEPC, May 2020. Net zero: a systems perspective on the climate challenge.

[7] Council for Science and Technology, 2020. A systems approach to delivering net zero: recommendations from the Prime Minister's Council for Science and Technology.

[8] Institute for Government, September 2020. Net zero: how government can meet its climate change target.

Table 1. Dependencies of a hydrogen system. This table builds on insights which were co-developed by the NEPC with the Department of Transport.

Hydrogen is dependent on…	**Because…**
The electricity system	Hydrogen could be produced by electrolysis using renewable electricity.[9] This will increase demand on the electricity system, potentially significantly, for hydrogen production. There are additional uncertainties as different energy futures may have different implications: for example, other demands on the electricity system; whether there will be investment in nuclear power for hydrogen production; and whether hydrogen will be produced from 'spare' renewable energy. Hydrogen could also serve as a storage medium to buffer supply and demand imbalance in the electrical system, to ameliorate intermittency problems associated with renewables such as wind and solar.
Global use of hydrogen and resulting international trade	The decisions being made by other national governments and other actors within the international economic system, including international industries, will have a significant impact on the economics of hydrogen through global economies of scale, learnings, and international trade and markets (for example, import/export opportunities). International regulation, interoperability, and associated geopolitics should therefore be a focus of the UK's efforts. Developing a global hydrogen gas standard could significantly reduce costs of global trading and remove the need for local pre-processing to align with national standards. Common regulation and engineering standards and measurements are needed for trading hydrogen as a product, but also for trading materials to contain hydrogen (for example, vessels, piping, etc). The international journeys made by UK transport, such as freight, aviation and maritime, means that the UK is highly dependent on current decisions by other nations in relation to refuelling infrastructure. If international agreement is not reached in providing the requisite fuelling infrastructure at sufficient scale, this creates a risk of disruption to aviation and maritime services which rely on refuelling at destinations.
Use of ammonia as an energy vector	Ammonia has an established value chain and transport infrastructure, and is produced using hydrogen. Ammonia production is a major use of the hydrogen currently being produced. Ammonia is a potential low-carbon energy vector in its own right[10], and the extent to which this is pursued will have potential knock-on effects on the hydrogen economy.
Demand and demand competition	Interdependencies exist between different end-uses of hydrogen. Hydrogen has many potential uses, some where it is the only viable net zero-carbon fuel such as heating for some industrial processes. Others, such as transport and domestic heat, require infrastructure which may require a continuous hydrogen supply in order to be cost-effective. While broad demand could bring down costs, if there is a situation of limited

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[9] Hydrogen from renewable power: Technology outlook for the energy transition, International Renewable Energy Agency, Sep 2018, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Sep/IRENA_Hydrogen_from_renewable_power_2018.pdf

[10] Royal Society, February 2020. Ammonia: zero-carbon fertiliser, fuel and energy store. https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/

	supply it is unclear how government and regulators will ensure hydrogen supply is prioritised to the areas of greatest need. A hierarchy of need would help ensure that hydrogen is used to decarbonise processes which are difficult to decarbonise by other means.
Business economics	In the longer term, the uptake of hydrogen outside of large individual consumers (those using it for industrial processes, for synthetic fuels, or large-scale energy storage) is dependent on the ability of small and medium sized enterprises (SMEs) to afford the adoption of hydrogen. Some business models like those in rail freight may not have the resources for the change that is urgently needed in the transport sector to meet public expectations and net zero. This could therefore result in a resistance to change from crucial stakeholders. This problem is not unique to hydrogen, but to various energy system adaptations which will be needed.
Markets and regulations	Markets and regulations, both nationally and internationally, have a key role to play in actively driving forward safe, trusted and joined-up adoption and roll out of hydrogen technologies. The readiness and willingness to adapt to markets and regulation the uptake of hydrogen will have consequences for the UK's ability to facilitate the integration of hydrogen thus creating an interdependency.
Public trust and interest	Hydrogen as a fuel will require social license to operate, and indeed enthusiastic take-up for more rapid emissions reduction. This depends on trust and interest of the public in using hydrogen for each purpose, based on factors including, but not limited to, safety and efficacy. Using hydrogen boilers in the home, for example, may have very different trust requirements compared to use in personal and fleet vehicles or grid-scale storage. While it is sensible to prioritise interventions and uses of hydrogen which do not require significant change in public behaviour in order to deliver rapid emissions reduction, this must not be done at the cost of implementing the best solution or be allowed to delay emissions reduction. Extensive prior engagement with communities on their favoured domestic energy strategy is needed. It is estimated by the Climate Change Committee (CCC) that nearly half (43%) of the emission reductions needed to reach net zero in the UK will come from behavioural or societal change in combination with low carbon technologies.[11] But studies have raised concerns that the public's level of awareness about hydrogen and its potential role is lagging behind other low carbon technologies and could pose a barrier to its deployment: Research by Madano for the CCC in 2018 found just over half (51%) of survey respondents have never heard of hydrogen fuel boilers, the lowest awareness of all alternative low carbon heat technologies.[12] Research for the H21 project by Leeds Beckett University found 68% of customers are indifferent or undecided about conversion to hydrogen,

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[11] Climate Change Committee (2020), The sixth carbon budget: the UK's path to net zero, Figure B2.2, Role of societal and behavioural changes in the Balanced Net Zero Pathway (2035).

[12] Public acceptability of hydrogen in the home, Madano and Element Energy. November 2018. https://www.theccc.org.uk/publication/public-acceptability-of-hydrogen-in-the-home-madano-and-element-energy/

	largely because they do not know enough about it, are unconvinced that it is the right solution, or are simply not engaged with the topic.[13]

c. The dependency of the Government's proposed plans on carbon capture and storage, any risks associated with this and how any risks should be mitigated

22. Blue hydrogen, produced from natural gas with most of the carbon dioxide (CO_2) emissions abated by CCUS, presents sustainability issues due to the limitations of CCUS (approximately 95% capture of CO_2 is expected), potential limits on CO_2 storage[14] and utilisation capacity, and the upstream emissions from the oil and gas industry. Blue hydrogen will not achieve net-zero emissions without sequestering the residual CO_2 through negative emissions technologies such as Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC). This additional cost should be included when evaluating blue hydrogen. There remain uncertainties over the efficiencies and costs achievable with next-generation production of hydrogen from natural gas. Blue hydrogen relies on the cost effective scaling up of CCUS technology, which is in an embryonic stage in the UK. These must be deployed simultaneously, or investment in assets for the production of hydrogen from natural gas risks being 'stranded' if the potential of CCUS is not realised. However, it is considered that production of blue hydrogen would likely enable faster scale-up for early production and use of hydrogen.

23. Green hydrogen, produced from electrolysis of water using net zero-carbon electricity, has no intrinsic limits in relation to CO_2 emissions as it has no by-products (beyond perhaps concentrated brine). This is an emerging technology which still requires significant development and cost-reduction in order to be scalable. Because it requires 'surplus' zero carbon energy, this competes with other demands on UK energy generation. This surplus energy may be available either sooner, later, or not at all depending on other choices made in the energy transition such as in deployment of renewable energy assets, competing demands from electrification of other sectors, and how aggressively energy efficiencies such as home retrofit are pursued.

24. These two methods of producing hydrogen each have advantages and disadvantages. They are suited to different functions.[15] For example, blue hydrogen could be produced at industrial hubs or clusters, offering co-location with uses in energy-intensive industry and fuel synthesis. Green hydrogen which is produced, for example, by offshore wind, could be generated onsite or on land from 'spare' wind capacity when electricity generation exceeds electricity demand, and this can be used to provide 'temporal balancing' across daily and seasonal variations in the supply of intermittent renewables and demand for energy, or could be deployed at modest scale at transport hubs and filling stations.

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[13] H21: Public perceptions of converting the gas network to hydrogen. June 2020. https://www.h21.green/projects/h21-social-science-research/

[14] There are still long-term liabilities connected with underground CO_2 storage, including safety and public trust and potential challenges due to seismicity and geology in the UK.

[15] One study by CE Delft (https://www.cedelft.eu/en/publications/2149/feasibility-study-into-bleu-hydrogen) considered the CO_2 emissions associated with both green and blue hydrogen. The study shows that the CO_2 footprint of blue hydrogen (0.82-1.12 kg $CO_{2\text{-eq}}$/kg H_2) is comparable with hydrogen produced via electrolysis with renewable electricity sources (0.92-1.13 kg $CO_{2\text{-eq}}$/kg H_2). As noted in the answer to Question 5, this is one of several methods of environmental evaluation which must be considered.

25. Both green and blue hydrogen capitalise on the UK's natural resources, industry experience and infrastructure for wind power and natural gas respectively.

26. Hydrogen can also be produced through electrolysis using zero-carbon nuclear energy, and this has been proposed as a method of making the best use of the energy output of nuclear power stations. In addition, hydrogen can be produced by gasification of biomass (energy crops), with capture and storage of the resulting CO_2. This is potentially a method of producing negative-carbon hydrogen[16], although it introduces land-use sustainability issues. This highlights once again the need to take a whole-system approach when considering the favourability of hydrogen for different functions, as these would require different infrastructure depending on the approach taken; this may be a way to fast-track transport and storage infrastructure or end-use demand investments.

27. As noted in Question 1, the balance of energy vectors in use in the UK will become diverse and heterogenous and the optimum solution for any given energy need will vary temporally, geographically, and with various other factors, making interoperability crucial. The energy system must be interoperable both physically and in terms of the data and measurement, for example used to monitor and optimise operations. The development of all energy vectors needs to be coordinated, taking into account factors such as storage capability and the efficiencies of individual vectors.

28. The best mitigation against the dependency of blue hydrogen production on CCUS deployment is to pursue both blue and green hydrogen in parallel, and initially for different uses. Pursuing multiple net zero pathways will be crucial to reduce the risk of expensive failure in the future: for example, if blue hydrogen is pursued as an energy vector to the exclusion of all others, a failure to scale-up CCUS would be catastrophic for the prospects of an energy transition at the scale and pace needed to meet the net zero target and prevent critical environmental degradation, and would result in stranded assets. Instead, government must pursue blue and green hydrogen, as well as electrification, and broadly seek to limit the number of components of a net zero energy system which cannot be allowed to fail without jeopardising the net zero transition. There is the possibility of using grey hydrogen on the way to blue, if the CCUS component does not come on stream initially.

29. It will be beneficial to ensure the outputs are compatible downstream; for example, the supply to industry, transport and homes is of a standard quality so it can come from multiple sources. This has implications for developing standards and transportation.

d. Potential business models that could attract private investment and stimulate widespread adoption of hydrogen as a Net Zero fuel;

30. Business models needed for widespread adoption of hydrogen both upstream (production and transportation) and downstream (consumer changes) will require

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[16] Negative-carbon hydrogen here refers to hydrogen produced by gasification of energy crops with CCUS. This produces a net reduction in atmospheric carbon, as the crops draw down CO_2 from the atmosphere which is ultimately stored rather than released. This would likely have similar environmental impacts to BECCS used to generate thermal energy.

government to build long-term certainty. This will require government to create stable and enduring policies, signal the redundancy of high-carbon incumbent technologies, and incentivise investment.

31. The complexity of a hydrogen economy and the pace of deployment needed to meet the 2050 target means that the market cannot be left to evolve organically and instead needs to be driven by government. Consistent policy is also essential if supply chains and markets are to be successfully established and returns on funding realised.

32. Bringing a hydrogen system into being is a ‘chicken and egg’ situation, requiring government intervention on both demand and supply sides simultaneously in order to ensure they are scaled up in a synchronised way, so that supply meets demand, and develop market confidence. Demand may be increased by strong government action on more polluting alternatives; for example, the use of coal in steel production.

33. As projects progress, business models need to change too. In the early stages, a support mechanism to incentivise deployment is likely needed. As the sector becomes established, then carbon pricing may be a dominant mechanism. To support production and adoption, contract for difference and subsidy are examples of potentially necessary mechanisms.

34. In addition to creating subsidies and incentives, there is a significant role for government as an early procurer of hydrogen fuel across its estate and transport activities, creating market confidence to support production and adoption.

35. Blue hydrogen will inherently be more costly overall than the natural gas from which it is made, but this may be offset by carbon pricing. As a result, the initial development of a hydrogen economy should focus on large individual energy consumers such as for energy storage, industrial use, and for fleet vehicles, rather than distributed domestic energy consumers who are less able to bear increased energy prices. This is an example of an important choice relating to a just transition to a net zero society.

36. There is interest among the oil and gas majors in hydrogen, since it is a natural extension of their existing activities. Oil and gas companies, along with gas transmission and distribution companies, could play a part in the investment process.

QUESTION 2*: The progress of recent and ongoing trials of hydrogen in the UK and abroad, and the next steps to most effectively build on this progress*

a. Current status of projects

37. Hydrogen projects in the UK remain in the feasibility stage, with safety issues and other factors being assessed. The largest are focused on domestic heat. Small pilot projects for this and especially for other uses for hydrogen need to be rapidly scaled up. It is also notable that without the rapid scaling of CCUS, which is in an embryonic stage in the UK, the hydrogen produced and used is high-carbon grey hydrogen. The Energy Institute has created a map of different hydrogen pilot projects in the UK.

b. Next steps to build on progress

38. To most effectively build on progress to date, niches in which hydrogen are likely to be most effective need to be identified and built out. It will be especially useful for the government to outline how they plan to scale up production.

39. Hydrogen will be most effective where alternatives do not exist, there are fewer but larger consumers, and there is lower disruption to consumers. In particular, these include uses in energy intensive industries, interseasonal energy storage, and return-to-base fleet vehicles – especially heavy goods vehicles, construction vehicles, and agricultural vehicles.[17] Once hydrogen has been sufficiently up scaled up to meet those demands further expansion can then enable it to be bled into other use cases.

40. To support this, hydrogen pilot projects must test a range of production methods and end-user applications, with the expectation that some will prove more viable than others.

41. It is also important to develop multi-technology demonstration areas which explore the impacts of multiple clean technologies interacting with each other in real-world settings.[18] Several major town or small city conversions to heterogenous low and zero-carbon energy systems may prove highly beneficial to develop UK expertise and experience in all aspects of the energy transition.

42. There is a question as to how small pilot projects can be rapidly scaled up, especially those that depend on other developing technologies such as blue hydrogen, which depends on CCUS.

43. With the likely decentralisation of the UK's energy system, the linkages between the regional and international energy system must also be developed as well as the meld of the different use cases of hydrogen. For example, the favourability and feasibility of different hydrogen transport options should be assessed.

44. This will require stable and supportive policy, and significant investments in UK research and development, scaling up demonstration plants to commercial scale.

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[18] Royal Academy of Engineering, 2015. A critical time for UK energy policy.

45. The decisions being made by other national governments will have a significant impact on the use of hydrogen. Regulations and associated geopolitics therefore will have an impact on UK decision making. Drawing from lessons from hydrogen trials, the UK government should work internationally to standardise regulations on hydrogen across the globe. This is explored further in Table 1 *The dependencies of a hydrogen system* under ‘Global use of hydrogen and resulting international trade’.

46. Opportunities for international collaboration on hydrogen projects should be explored. However, while the UK is currently exploring blue hydrogen, other countries such as Portugal are focusing on green hydrogen and may not want to collaborate on blue hydrogen projects. Conversely, countries that do not have their own renewable energy sources may be less likely to collaborate on green hydrogen projects.

QUESTION 3: ***The engineering and commercial challenges associated with using hydrogen as a fuel, including production, storage, distribution and metrology, and how the Government could best address these***

a. Engineering Challenges

47. Developing a hydrogen system over the next 30 years requires the various engineering and commercial challenges to be overcome at scale and pace, given the timescales involved in developing the infrastructure.

48. Table 2 *Engineering challenges of a hydrogen economy* provides examples of the key engineering challenges. The extent to which each is pursued depends on the eventual pathways towards a hydrogen system that are chosen.

49. Many of these challenges require construction of physical infrastructure. Notably this infrastructure has the potential to create huge amounts of capital emissions through the embodied carbon involved in producing it, with steel, cement and plastic all being material requirements. Urgent improvement and changes to the way in which infrastructure projects are designed, procured and constructed are needed to ensure net zero infrastructure deployment does not work against the UK's climate ambition[19].

50. Several more specific engineering challenges are discussed in the report 'Transitioning to Hydrogen: Assessing the engineering risks and uncertainties', which was authored by several engineering organisations involved in this response.[20]

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[19] NEPC (2020), Decarbonising construction: the route to net zero - summary of a workshop.

[20] Transitioning to Hydrogen: Assessing the engineering risks and uncertainties. IET, 2019. https://www.theiet.org/impact-society/sectors/energy/energy-news/transitioning-to-hydrogen-assessing-the-engineering-risks-and-uncertainties/

Table 2, engineering challenges of a hydrogen economy

Scaling up hydrogen storage	The use of hydrogen for temporal grid balancing, (in which excess grid electricity is used to electrolyse water into hydrogen, the hydrogen is stored, and then used to generate electricity when demand outstrips generation), requires very large-scale hydrogen storage. Developing methods of storage, such as geological storage, which must have high safety, trust and efficiency, is a key engineering challenge.
Developing CCUS to enable blue hydrogen production	Blue hydrogen is synthesised from fossil fuels through processes such as steam methane reforming (SMR) or autothermal reforming (AR). While there is some maturity in these technologies due to the longstanding hydrogen production for uses such as ammonia synthesis, the scale-up required for hydrogen production of this quantity is a significant challenge. Optimisation of these processes and development of next-generation versions could yield significant efficiencies. There is currently uncertainty about the likely efficiency of some of these processes which must be resolved to guide decision making.
Developing Green Hydrogen production capacity	Green hydrogen, produced from electrolysis of water using net zero-carbon electricity, has no intrinsic limits as it has no by-products (beyond perhaps concentrated brine). This is an emerging technology which still requires significant development and cost-reduction in order to be scalable. Perhaps more importantly, there is a secondary challenge of producing the massive amount of 'surplus' zero carbon energy needed to produce the required quantities of hydrogen, which will compete with other demands on UK electricity generation from electrification of other processes. This might be from renewable, nuclear or biomass sources, each with their own specific challenges and requirements. This surplus energy may be available either sooner, later, or not at all depending on other choices made in the energy transition such as in deployment of renewable energy assets, competing demands from electrification of other sectors, and how aggressively energy efficiencies such as home retrofit are pursued.
Linking national and regional energy systems	A challenge exists in linking the regional and national energy systems. Future energy system may become more localised therefore local authorities will need their local energy system to be tightly linked to the national energy system so that they can respond to change in local demand. There is a question about whether cross-nation pipeline transport and sale/purchase of hydrogen are viable options, analogous to cross-nation oil and gas pipelines, or electricity interconnectors.
Developing hydrogen transport and storage	The infrastructure for transporting hydrogen, or if a more local-production focused strategy will be used, must be considered and ultimately deployed. Whether solutions such as cross-nation pipelines are viable must be determined, and compared with other

infrastructure	options such as trailer and tanker transport. This will be dependent on which production methods and use cases win out, and how much hydrogen production can be co-localised to its end use. Transport is likely to represent a significant proportion of the retail cost of hydrogen, so cost reduction will be important. Global collaboration will be needed on how best to store and transport hydrogen - whether in gas form, as a liquid at very low temperatures or through converting to ammonia where the transport chain is already established.
Challenges associated with specific end-uses and technologies	This includes, for example, the challenges of using hydrogen in existing domestic gas pipeworks for domestic heating, and individual technologies that produce power from hydrogen such as fuel cells.
Measurement and metrology	Accurate measurement through flow meters will be crucial for trading and charging the consumption of hydrogen, much as gas flow meters are today for the gas system. Hydrogen has a number of different physical characteristics compared to natural gas; it is lighter and less energy dense by volume than conventional fossil fuels but far more energy dense by mass. This makes it challenging for the flow meters currently in common use, which are not fully tested or calibrated to accurately measure hydrogen. A report from the Institute of Measurement and Control has commissioned research into the metrology aspects of this and identified a number of actions for government. In particular, "there is an urgent need to identify and harmonise flow measurement standards, and test and calibration techniques."[21]

b. Commercial Challenges

51. Achieving certainty for the supply chain is one challenge. If government delivers a long-term position, industry will invest with confidence and they can recoup their investment.

52. There may be different commercial challenges for green and blue hydrogen. Green hydrogen may be considered a premium fuel and therefore carry an additional market value since environmentally-conscious companies may not wish to use blue hydrogen or market it to consumers.

c. Addressing engineering and commercial challenges

53. Investment in research and development: A clear national research agenda would provide the impetus for investment alongside the right incentives for industry to invest; once government steps in, industry will follow. This includes the digital technologies needed to integrate the systems, as well as the technologies for hydrogen production, storage, transportation and end-use.

54. Safety: It will be important to continue to examine the safety case for different uses of hydrogen, as well as different production, storage and transport methods. A full assessment of risks, including those associated with combustion in the built

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[21] Institute of Measurement and Control, Flow measurement requirements for low carbon fuels (hydrogen). November 2020.

environment, and clear communication of them will be crucial.[22]Acceptability to consumers will be vital in successful adoption. Learning from the experience the UK had in changing over from coal gas to methane would be valuable.

55. Skills: given the extensive gas infrastructure, the UK has considerable expertise in safely processing, transporting and storing methane. This expertise could be transferred to design, deployment and operation of the hydrogen system. A clear skills plan will be required.

56. Standards: government can play a key role in engaging stakeholders to drive commonality of engineering standards, from plant design through to operation, as well as hydrogen fuel quality and its measurement, so as to facilitate value chain operation. This would be best done internationally, so as to encourage trade.

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[22] Safety was one of the many issues addressed in the 2019 report: Transitioning to hydrogen: assessing the engineering risks and uncertainties, authored by a number of professional engineering organisations and the Health and Safety Executives Laboratory.

QUESTION 4: The infrastructure that hydrogen as a Net Zero fuel will require in the short- and longer-term, and any associated risks and opportunities

a. Required infrastructure for hydrogen

57. As mentioned in Question 3, developing a hydrogen system over the next 30 years is a large infrastructure challenge, and one of several infrastructure transformations which must happen during this period in order to reach net zero, alongside transformational changes to our systems of electricity, transport, data, and built environment. These must be co-ordinated to ensure they are coherent, their components interoperable, and optimised at the system level for greatest efficacy and least cost. Clarity about the timescales required to develop a hydrogen system, and the sequencing of different stages, will be key.

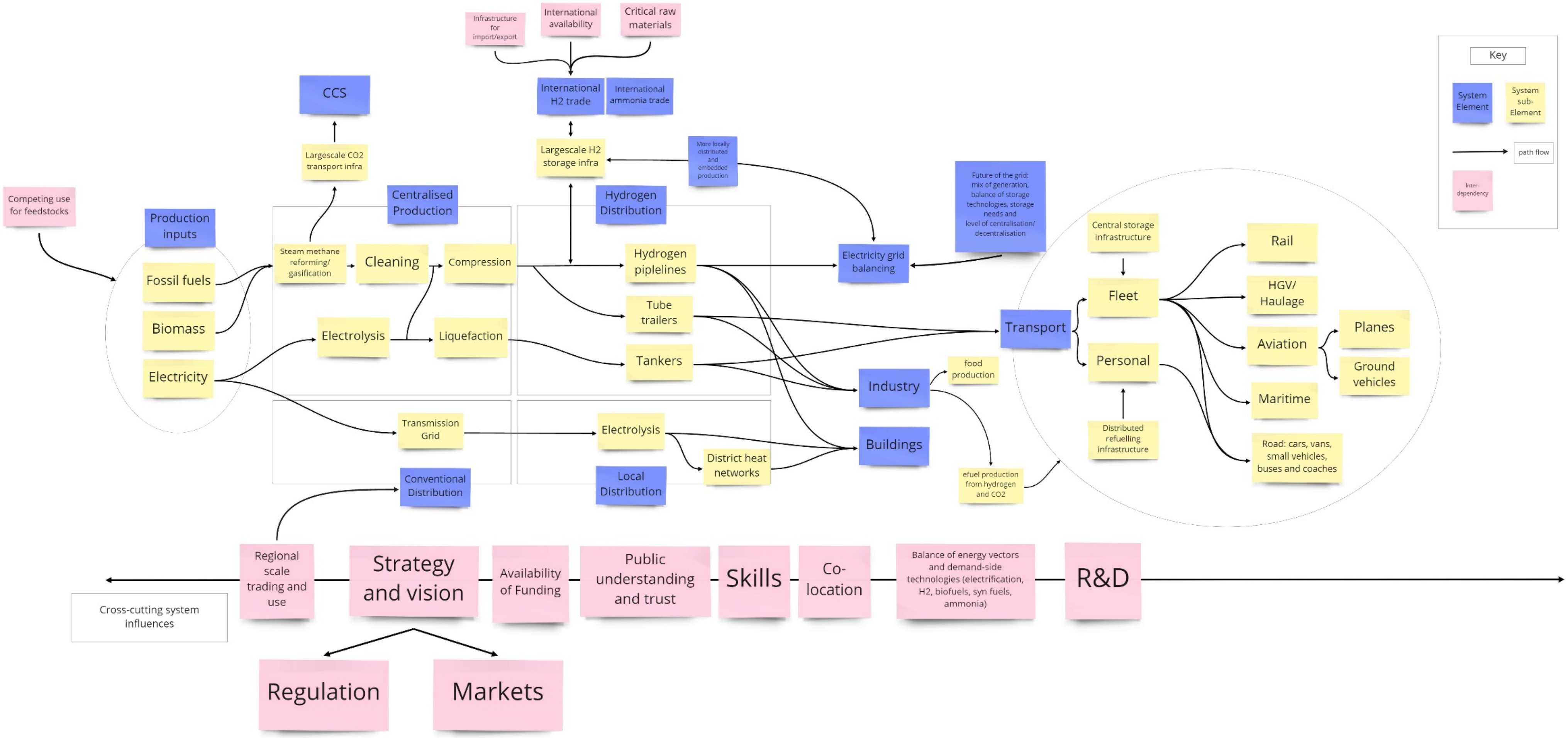
58. Figure 2 shows an illustrative, non-exhaustive, map of a potential hydrogen system, including the infrastructure requirements. A high-resolution version is available on request. This system map shows the flow of hydrogen through its production, transportation and end-use. Major system elements are represented in blue, with sub-elements in light yellow. Pink elements denote key dependencies, with the row at the base indicating cross-cutting factors which may impact across many or all parts of the system.

59. The system shown in Figure 2 contains redundancy, and the ultimate system may comprise fewer or different elements depending on choices made. In fact, a priority should be to determine what components and pathways offer good value in comparison to other decarbonisation strategies.

60. This map does not detail the infrastructure involved in international trade, or details of distribution for potential consumer uses; such as hydrogen refuelling for personal vehicles or piping for use in domestic heating.

61. The potential for hydrogen as a wide-ranging system and ‘energy currency’ means that much of this infrastructure may repurpose, or align with, existing infrastructure – such as pipelines to connect offshore/floating wind power and potentially offshore electrolytic hydrogen production with land.

Figure 2: System map of a potential future hydrogen system, with a focus on use in transport. This map was codeveloped by the NEPC with the Department for Transport



b. Risks associated with hydrogen infrastructure

62. Hydrogen represents a complex set of infrastructures to deploy, and this must be seen in the context of the multiple, interconnected system transformations required to meet net zero across energy and transport systems, the built environment, agriculture and others. Without broad co-ordination of the net zero transformation by a systems architect delivery body, there is a risk that a limited view which looks only at one of these will miss opportunities to design the most optimal overall system; one which provides the best outcomes and greatest value for the investment they represent. Opportunities to create efficiencies and synergies which could be missed. Furthermore, failure to align these system transformations both in planning and in technical and data interoperability increases risk of failure and delay in reducing carbon emissions and reducing broader environmental impact.

63. As an example of a specific risk, blue hydrogen relies on the cost effective scaling up of CCUS technology, which is in an embryonic stage in the UK. These must be deployed simultaneously, or investment in assets for the production of hydrogen from natural gas risks being 'stranded' if the potential of CCUS is not realised. However, it is considered that production of blue hydrogen would likely enable faster scale-up for early production of hydrogen. This trade-off is one of many which must be managed by a clear and system-wide decision-making process.

64. Where repurposing existing infrastructure may involve only minor training of the workforce in certain situations, there are many new elements of a hydrogen system which will require completely new skills. In particular, the consumer-facing work of selecting, installing, programming and maintaining home energy equipment will become considerably more complex to reflect a diversity of heating choices, variation in optimal solutions geographically and otherwise, and the digital aspects of integrating and controlling home energy systems. Lack of these skills and in particular the engineering construction capacity to build out the system infrastructure is a significant risk to the delivery of a hydrogen system, and indeed the delivery of net zero as a whole.[23]

65. Several emissions reduction policies have struggled with the consumer-facing aspects of deployment. Public rejection of technologies which are being pursued as key deployment pathways is a significant risk to the pace of deployment. Mitigating this risk may involve mechanisms for advance engagement with communities on potential technologies, systems, and ways of life.

66. It will be vital to ensure that national strategies, regional and local plans are well aligned, as mentioned previously in paragraph 18, and that local authorities have the skills and capacity to help deliver local infrastructure where needed.

c. Opportunities associated with hydrogen infrastructure

67. A wide-ranging system such as the hydrogen system has many potential benefits, alongside the emission reduction and impacts on air quality that the displacement of fossil fuels inherently provides, some of which depend on the particular approach taken.

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[23] NEPC, (2020). Beyond COVID-19: five foundations for a net zero recovery.

68. The UK missed out on the opportunity to be an original equipment manufacturer for the successful offshore wind sector. The UK still has potential to be a global leader in hydrogen technology and build on intellectual property rights for both blue and green hydrogen as well as the technologies for transporting hydrogen and demand-side technologies. The coming year (2021) will be crucial if the UK is to achieve this.

69. There are also opportunities for the wider contractor and supply chain to gain experience and exportable expertise in executing hydrogen projects.

70. Hydrogen can enable the use and re-use of current plant and infrastructure. This may potentially reduce capital expenditure as part of the transition to a net zero future. Examples of potential reuse include existing fired equipment and processes and pipeline transmission systems.

QUESTION 5: ***Cost-benefit analysis of using hydrogen to meet Net Zero as well as the potential environmental impact of technologies required for its widespread use***

a. Cost-benefit analysis of using hydrogen to meet net zero

71. There is no single appropriate way to evaluate the costs and benefits of a complex system such as hydrogen. Radically different conclusions may be reached depending on the scope of the analysis, and what form of hydrogen strategy is being considered. Different production methods, different transport modes, and different uses of hydrogen can combine to produce different results for each theoretical use of hydrogen.

b. Environmental impact of hydrogen technologies

72. It is crucial to recognise the embedded emissions in infrastructure deployed for hydrogen or other net zero infrastructures. Urgent progress must be made on the decarbonisation of construction, including materials and processes. To prevent this there must be a shift towards outcome-based procurement rather than least cost, which should be reflected in the current review of the HMT Green Book[24].

73. With all new net zero systems it is important to consider environmental impacts other than carbon, including:
    1. Hydrogen combustion emissions such as nitrous oxides (NOx)
    2. Sustainable resource extraction and circular economy principles
    3. Use of critical raw materials
    4. Biodiversity and habitat impacts from infrastructure construction
    5. Re-use or disposal of existing infrastructure
    6. Embedded carbon in new infrastructure.

74. Frameworks such as life cycle assessment, 'zero pollution'[25] and planetary boundaries[26] could be employed to integrate other environmental concerns with carbon and climate.

75. Hydrogen production through electrolysis may additionally result in a concentrated brine as waste, which requires further investigation as to the responsible processing or repurposing of this waste. It will be important to explore the scale and impacts of water purification, use and waste required from electrolysis at this scale, as well as its sourcing.

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[24] NEPC (2020), Beyond Covid-19: five foundations for a net-zero recovery.

[25] For more information on zero pollution, see: https://www.imperial.ac.uk/zero-pollution/research/systems-approach-to-zero-pollution/

[26] For more information on planetary boundaries, see: https://www.stockholmresilience.org/research/planetary-boundaries.html

QUESTION 6: *The relative advantages and disadvantages of hydrogen compared to other low-carbon options (such as electrification or heat networks), the applications for which hydrogen should be prioritised and why, and how any uncertainty in the optimal technology should be managed.*

a. Relative advantages and disadvantages of hydrogen compared to other low-carbon options (such as electrification or heat networks)

76. Hydrogen is an energy vector rather than a source of energy. It is highly reactive and therefore does not occur naturally; it must be produced, stored and transported. It is often not the ideal energy vector in terms of efficiency. For example, the efficiency of producing green hydrogen from renewables for use in home heating compares unfavourably with using the renewable electricity for home heating directly. However, this efficiency measure does not necessarily account for the realities of a complex hydrogen system involving multiple forms of common production, storage, transport and end-use. For example, hydrogen is also one of several fuels which could be used to power heat networks. Interoperability, stability, resilience and security of supply are currently and should remain key factors in decision-making.

77. Hydrogen as an energy vector offers high value to the energy system by providing connectivity across the energy system: it can be produced from various sources such electrolysis from renewables or nuclear, from biomass or fossil fuel feedstocks) and used in several ways (eg combustion for heat, fuel cells for electricity, production of synthetic fuels for aviation and similar). While there is some difference in the purity of hydrogen required for some specific functions, hydrogen could act as a common ‘currency’ for energy, enabling interchange. The specific potential uses of hydrogen do all require critical assessment for whether hydrogen is the best solution, accounting for various environmental, social and economic factors and the system coherence as a whole.

78. Hydrogen production and storage offers potential to increase overall energy security and the security of supply in specific sectors in an heterogenous future energy system. Systems must be in place to ensure energy security in a new energy system with more diverse energy vectors. For example, some nations are exploring a hydrogen-driven approach in which an excess of hydrogen is produced to cover the chosen domestic and export needs, prioritising use to generate grid electricity, thus providing security and simplicity.

79. Some nations have discussed a hydrogen-driven energy strategy in which large amounts of energy are used to produce hydrogen, enough to satisfy domestic and export needs and provide a common and secure energy vector which could yield economies of scale.

80. The relative benefits of hydrogen versus electrification depend on the application. One particular area where there is a lack of consensus is domestic heating. There are benefits and disbenefits, as well as technical and social challenges, for both options. A clear and transparent decision-making framework is needed.

b. applications for which hydrogen should be prioritised and why

81. Hydrogen is not a 'silver bullet' for all end-uses. Instead, decision-making could be guided by means of a hierarchy according to the value of hydrogen for each end-use - is it necessary, helpful or not useful at all? What are the systems implications? The presence of alternative energy vectors for a particular end-use is a further factor in decision-making. Hydrogen has clear benefits in applications such as industrial heating and processes, and heavy goods transport. Its use in domestic heating is less clear-cut since electrification exists as a competing option. It will, however, be necessary to keep options open until the appropriate evidence is available and the relative benefits and disbenefits of the various options, and implications for the system as a whole, can be more effectively appraised.

82. If there is a situation of limited supply, it is unclear how government and regulators will ensure hydrogen supply is prioritised to the areas of greatest need. A hierarchy of need and clear decision-making process is therefore needed to ensure that hydrogen is used to decarbonise processes which are difficult to decarbonise by other means, and where it can offer greatest benefit to the system as a whole.

83. If government prioritises uses according to the certainty of investor returns, hydrogen could potentially have greater commercial viability compared to gas in end-uses with larger consumers such as industrial uses. The hierarchy of potential end-uses should also guide the government's approach to R&D funding, while reiterating that all options should be kept open until there is sufficient certainty.

c. how any uncertainty in the optimal technology should be managed.

84. As mentioned in the answer to Question 1, the urgency, scale and pace of emissions reductions requires learning by doing. The government should pursue multiple net-zero pathways on the assumption that some will prove to be more viable than others. Until there is greater certainty, building evidence on a whole range of individual technologies associated with the different pathways will be vital. Support for hydrogen technologies should be considered as 'low-regrets': an urgent priority - given the timescale to develop the system - that will help unlock different pathways, rather than blocking them off. Investing in technology demonstration is enabling work that will help realise medium- and long-term opportunities.

85. As evidence is gathered, it will be vital to assess the impact of individual technology choices on decarbonisation impacts and cost-effectiveness at a whole-system level, as well as for the individual technology. Effective evaluation of technology demonstration projects will be vital. As the system is built out over time, there will be a need to monitor implementation and outcomes, and be prepared to stop, accelerate or change direction. A clear decision-making framework will be needed.

86. In addition to technical and commercial uncertainties, there are uncertainties associated with the scale of behavioural change and overall decarbonisation impacts over time. As mentioned in Question 1, a systems approach to policymaking will help policymakers gather evidence from the widest, most diverse and critical perspectives leading to a 'bigger picture' view of this policy problem and how different parts of the system interact to affect the desired outcome.

(January 2021)