Low
Carbon
Innovation
Coordination
Group

Technology Innovation Needs Assessment (TINA)

Hydrogen for Transport
Summary Report

Nov 2014

Background to Technology Innovation Needs Assessments

The TINAs are a collaborative effort of the Low Carbon Innovation Co-ordination Group (LCICG), which is the coordination vehicle for the UK's major public sector backed funding and delivery bodies in the area of low carbon innovation. Its core members (at the time of this document's publication) are the Department of Energy and Climate Change (DECC), the Department of Business, Innovation and Skills (BIS), the Engineering and Physical Sciences Research Council (EPSRC), the Energy Technologies Institute (ETI), Innovate UK (IUK, formerly the Technology Strategy Board, TSB), and the Carbon Trust.

The TINAs aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. Beyond innovation there are other barriers and opportunities in planning, the supply chain, related infrastructure and finance. These are not explicitly considered in the TINA's conclusion since they are the focus of other government initiatives.

The purpose of the TINAs is to help policy makers to plan and prioritise innovation support. A report summarising each TINA is published to provide transparency. These reports draw upon much more detailed TINA analysis packs which will be published separately.

The TINAs apply a consistent methodology across a diverse range of technologies, and a comparison of relative values across the different TINAs is as important as the examination of absolute values within each TINA. Published sources of information are drawn upon when developing the values in TINA summary reports, but these are usually just one of many inputs considered and they are usually not referenced.

The TINA analytical framework was developed and implemented by the Carbon Trust with contributions from all core LCICG members as well as input from numerous other expert individuals and organisations. Expert input, technical analysis, and modelling support for this TINA were provided by Element Energy and Prof Nigel Brandon.

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Department for Business Innovation & Skills

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Context

Hydrogen can be used as an energy vector – as a way to move, store, convert and use energy. It is potentially one of the most flexible and broadly applicable energy vectors available, it could have a role in almost every part of the UK energy system, and if hydrogen is produced in a low carbon way then it can be used to decarbonise any sector it penetrates. However hydrogen technologies also face many significant challenges, which must be overcome before they can be deployed at scale. As a result the range of possible futures for hydrogen technologies is very wide, from revolutionising all energy sectors to having no role in the energy system at all.

The very broad potential applicability of hydrogen technologies is one of the reasons it is so difficult to confidently predict their future role. Most hydrogen technologies are immature, with a large but uncertain improvement potential and most of the low carbon technologies they will be competing with also have large but uncertain improvement potentials, so in each sector it is difficult to predict if hydrogen will take a dominant or niche role. For example as the penetration of wind generation increases, the extent to which the supply of electricity can be adjusted to match demand will reduce, creating opportunities for controllable demand and energy storage to help balance the system. Hydrogen technologies might be a very good fit for this opportunity, but the amount of system balancing that will be required, the value attached to that balancing and the extent to which hydrogen technologies will outcompete other balancing options is still very uncertain.

The UK energy system will undergo very significant changes between now and 2050 and many aspects of those changes are still uncertain. Uncertainties about how best to design and operate the UK energy infrastructure at the whole system level further complicate predictions at the sector level and the success or failure of hydrogen technologies in one area affects the likelihood of success in other areas (e.g. due to economies of scale). So the uncertainties in the future role of hydrogen technologies become compounded.

However, the same broad applicability of hydrogen means that it can be used as a broad ‘hedge’ or insurance policy against the many inherent uncertainties in the future UK energy system. Developing a broad platform of hydrogen technologies provides the UK with options which reduce the potential ‘downside’ risk should other low carbon technologies fail to deliver. These hydrogen technology options also provide significant ‘upside’ opportunity should hydrogen emerge as the preferred approach in any energy sector of the UK or the world.

To simplify and focus the analysis this TINA report selects, as an example, one particular energy sector and group of hydrogen technologies, which currently has clear industry momentum. The sector and technologies chosen are road transportation, using fuel cell electric vehicles (FCEV), and a group of hydrogen production and handling technologies which would be necessary to provide those vehicles with fuel. The report recognises that this sector exists as part of a wider energy system, but calculates the costs and benefits of this group of technologies independently from the rest of the system. It is anticipated that this report, on hydrogen technologies for transport, will be complemented by subsequent further analysis on other hydrogen technology areas (e.g. heat and power) and that this analysis will reveal further opportunities for value to the UK, which are additional to the values reported here.

The scenarios used in this report focus on particular hydrogen technologies, but these are just examples selected from a larger group. For example the only vehicle technology modelled is FCEV, other potential technologies include hydrogen internal combustion engines, and micro-turbines. It is too early to say which hydrogen technologies will ultimately be most important to the UK, or the world, and the technology selections made for these scenarios should not be interpreted as predictions. Similarly the deployment scenarios have been selected to explore a range of possible futures and they should also not be interpreted as predictions[1].

Energy system modelling suggests that if the UK is to meet 2050 carbon targets, it will need to make some very significant energy infrastructure investment decisions in the 2020s and these decisions will shape the energy system for decades[2]. This includes decisions about the infrastructure for refuelling/recharging road vehicles. The deployment scenarios in this report assume a roll-out of hydrogen transport refuelling infrastructure starting before 2020, which is consistent with the expectations of many in the automotive industry but is by no means certain.

This context frames the analysis in this report and the conclusions on how the UK should support innovation in hydrogen technologies for transport. It leads to a preference for investments that prepare the UK to make decisions in the 2020s about the role of hydrogen in the UK energy system, by supporting creation of technology options and by improving understanding of the value of those options. It also leads to a preference for postponing committing to very large infrastructure investments in hydrogen technologies for transport until there is more certainty around their value, e.g. in the 2020s.

[1] The deployment scenarios used in this report depend on a number of assumptions, for example they assume that by ~2020 FCEV manufacturers will have achieved the large cost reductions necessary to allow commercial deployment.

[2] ETI – Creating an affordable energy system for the UK (2013)

Key Findings

Hydrogen technologies have the potential to deliver UK transport with near-zero GHG emissions whilst reducing dependence on imported oil and curtailment of renewable generation. However, the technologies face some very difficult challenges, in terms of cost, performance and policy, which they will need to overcome to achieve this potential. Early cost reductions will be critical for a successful roll-out by 2020. Innovation across the technology chain, from hydrogen production to fuel cell electric vehicles, could reduce the cost of delivering these benefits by £33-80bn from 2020 to 2050[3]. Investment in hydrogen technologies for transport could also create UK industries with the potential to contribute economic value of £10-26bn to 2050 via global sales of products and services, with a further economic benefit of £9-23bn to 2050 via producing transport fuel in the UK from UK primary energy sources.

Potential role in the UK's energy system	• Hydrogen is a very versatile energy vector and energy system modelling suggests hydrogen technologies could have important roles throughout the UK energy system. There are particularly important opportunities for hydrogen in transport, power and heat. This report focuses on transport. • The three main fuel/energy options for transport with near zero greenhouse gas emissions are plug-in electric vehicles, biofuels and hydrogen. Each method has advantages and disadvantages, there is no clear winner yet (no single winner may ever emerge) and hydrogen fuelled transport is sufficiently attractive to make it a credible option. • Most of the technologies required for a viable hydrogen transport system are available now and a roll out starting before 2020 is credible. However keeping to this timeline will not be easy. It will require vehicle manufactures meeting their challenging early cost reduction targets, improvements in the performance, cost and reliability of other critical technology areas such as refuelling, and some potentially difficult changes to policy, regulation and public perception, all by 2020. • There are significant uncertainties in the roles for different hydrogen production technologies: – If power generation with carbon capture and storage (CCS) succeeds this will probably also allow the use of carbon capture in hydrogen production, providing the cheapest low carbon route to hydrogen. In this scenario hydrogen production with CCS dominates centralised hydrogen production in later decades and significantly reduces the cost of low carbon hydrogen for transport. – If CCS fails but hydrogen transport is successful then large-scale centralised electrolysers will need to be developed and hydrogen costs are likely to be higher. In either case smaller scale electrolysers will be important for distributed hydrogen production, particularly in the early years when volumes are low. – Electrolysers could provide valuable balancing for variable renewable generation in the electricity system, which would reduce the cost of hydrogen production. To some extent the specific balancing needs of the future electricity system will affect the preference for different chemistries of electrolyser. • This report uses a range of scenarios to reflect these uncertainties: – UK deployment scenarios range from zero deployment in the low scenario, through 20% of all light duty vehicles in 2050 in the medium scenario, to 50% in the high scenario – There are two variants of the high deployment scenario, one where CCS succeeds and one where it does not.

[3] All value ranges are cumulative (2010-2050) present values, discounted to 2012, across 'Medium', "High 1" and 'High2' scenarios. The 2010-2050 period, and the 2012 base year are used for consistency with other TINAs.

Cutting costs by innovating	• The total cost of ownership (TCO) of a FCEV by could drop by around 80% between 2012 and 2050, with a drop of around 70% occurring between 2012 and 2020. Innovation between 2020 and 2050 could reduce the cost of deployment by £33-80bn. • The short term innovation priorities are mainly about industrialisation of manufacture and improving the likelihood of a successful rollout. – Process innovation will be required to move from the current low-volume laboratory production of demonstration models to high-volume factory production. Very significant economies of scale are possible through this transition, particularly in vehicle costs. – The vast majority of the ~70% reduction in the TCO of a FCEV between 2012 and 2020 is due to a ~70% reduction in the capital cost of the vehicle itself[4]. – A successful roll out is dependent on reliable and affordable technologies being available throughout the hydrogen supply chain. In some areas, particularly refuelling infrastructure, technology improvements before 2020 could make a significant difference to the cost and difficulty of the initial roll out. These improvements may not deliver much value in themselves, but they would unlock later value in other parts of the system, and they are unlikely to happen quickly enough without public sector support. • The long term innovation priorities are mainly about investing in future generations of technology. This will minimise costs in later decades, when volumes are much higher, and will ensure the UK maintains a strong competitive position. – The areas that will contribute most to the TCO of a FCEV are the costs of the vehicles themselves and the costs of hydrogen production. These areas also offer the greatest cost reduction opportunities. – The TCO of a FCEV is dominated by the cost of the vehicle itself and there are large opportunities for innovation to reduce long term costs in all of the main FCEV sub-technology areas (fuel cell stack, fuel cell periphery, integration with the electric drive train, and hydrogen storage). The biggest cost reductions will be delivered by switching to future generations of technology; public sector support could accelerate these developments. Between 2020 and 2050 innovation could reduce the capital cost of FCEVs themselves by around 50% of 2020 costs. – The next largest long term opportunity for innovation is in electrolysis. There are significant opportunities for innovation to reduce costs by accelerating the development of future generations of electrolyser technology with higher efficiency, scale, temperature, and pressure. – In the long term, if electrolysis becomes a significant part of the hydrogen production mix and electrolysis assets are highly utilised, then the cost of hydrogen produced by electrolysis will be dominated by the cost of the electricity consumed. Increasing flexibility could also reduce overall costs by allowing electrolysis to provide more balancing services to the electricity system. – Power generation with CCS will require innovation in many areas (as discussed in the ‘CCS in the power sector’ TINA). A relatively small amount of additional innovation, mainly around purification, would be required to allow CCS to also provide hydrogen for FCEV in the transport sector. If CCS is successful this could be very important for hydrogen transport, for example the price of hydrogen ‘at the pump’ in 2050 is about one third lower in the ‘with CCS’ scenario than the ‘without CCS’ scenario.

[4] The very large cost reductions assumed to occur by 2020 are consistent with published forecasts and expected changes in production methods. They are also a necessary condition for a roll out starting before 2020, which is what the industry is planning for and what the scenarios in this report assume. However there is a significant risk that the early cost reductions will occur more slowly than this, with consequences for the deployment of the technologies and the value they can deliver for the UK.

Green growth opportunity	• Hydrogen technologies for transport could create UK industries with the potential to contribute economic value of £10-26bn to 2050 via global sales of products and services, with a further economic benefit of £9-23bn to 2050 via producing transport fuel in the UK from UK primary energy sources • The short term green growth opportunities are mainly about attracting inward investment to the UK – In the early years of deployment the demand for hydrogen transport technologies within Europe will be met by a small number of relatively large manufacturing facilities e.g. vehicle production plants. Only a handful of countries will host these large initial capital investments and the accompanying economic activity. – The UK would need to do many things to attract this inward investment, including: ▪ Being one of the first countries to roll out hydrogen for transport ▪ Supporting innovation to accelerate deployment of a viable complete hydrogen transport system ▪ Supporting the process innovation that occurs within manufacturing facilities when they industrialise from laboratory to factory scale • The long term green growth opportunities are mainly about exporting UK manufactured goods and services and 'on-shoring' transport fuel production. – The global market for hydrogen transport could be £368-788bn per year in 2050. The UK is unlikely to dominate any part of the global hydrogen transport market but it could take a strong position in a number of key sectors and this would deliver significant economic value – The economic value is concentrated in the same areas as the largest innovation opportunities e.g. novel vehicle components and hydrogen production. This overlaps well with areas of UK competitive strength. The value to the UK economy from exporting goods and service into this market could be worth £10-26bn to 2050 (with displacement effects) – Shifting the UK transport system away from the consumption of imported oil and towards the consumption of a transport fuel which is largely produced in the UK from UK primary energy sources would have a significant additional effect on the size of the UK economy[5] – The scenarios in this report see hydrogen for transport produced by electrolysis using UK renewable electricity, and by reforming a mix of UK and imported fossil fuels. The economic value to the UK from this shift in fuel consumption could be worth £9-23bn to 2050 (with displacement effects)

[5] This economic benefit for 'on-shoring' transport fuel production is not unique to hydrogen transport. A similar benefit could also accrue from a shift to plug-in electric or biofuelled transport.

The case for UK public sector intervention	• There are significant market failures throughout the hydrogen transport sectors, although the failures with most critical impact are different in the short and long term. – There is a 'first mover disadvantage' for early investors in refuelling stations, with better returns for later entrants. The returns available in the short term are insufficient to drive the innovations which would facilitate a cheaper roll out with a greater chance of success. – The largest short term barrier to private sector investment in innovation and scale-up, throughout the hydrogen transport system, is a lack of market and policy certainty. Confidence in future market support policies would unlock the private sector investment in innovation and large-scale manufacturing capacity which is essential for early cost reductions. – Support for the process innovation that accompanies increasing manufacturing scale could help to attract early investment in production capacity to the UK – In the longer term the lack of market certainty causes cautious innovation investment decisions which will not yield the best long term outcomes – Vehicles have long development timescales, with many years between investment in innovation in a component technology and revenue from the sale of vehicles containing the technology. Furthermore component level innovation often occurs within SMEs that are less able to manage this hiatus in cash flow. To achieve the long term cost reductions which are essential for a least cost system in later decades innovation support is needed now to drive the development of future generations of component technology before the market for the first generation has been proven – Development of future generations of electrolysers, to meet the future needs of the hydrogen transport market and the wider energy system, would have to start now for the technology to be ready in time. The many uncertainties about those future needs make private sector investment very difficult – The potential benefit of CCS for hydrogen transport may be overlooked without public sector direction • In general the UK could rely on others for almost all areas of innovation because the UK hydrogen transport needs are not unusual. – The main exceptions to this are that the UK may develop CCS and offshore wind faster than other countries, causing a need for hydrogen production technologies to integrate with these earlier than other countries – Relying on other countries to deliver innovation in the high value technology areas is likely to result in a weaker competitive position and lower economic value to the UK from those technologies in the long term – Relying on other countries to deliver innovation in the lower value technology areas may be sensible in the long term. However, in the short term it would be much harder to attract valuable early inward investments in supply chain and manufacturing capacity to the UK, if other countries, competing for the same investments, are supporting all of the innovation areas required to ensure a complete hydrogen transport system and a successful roll-out.

Potential priorities to deliver the greatest benefit to the UK	• The differences between the short and long term innovation needs, green growth opportunities and market failures lead to support priorities which change over time. • Short Term (2014~2020) "Facilitate roll-out and attract investment" – Particular priorities are to support urgent innovation in refuelling infrastructure and to support process innovation in manufacturing scale up and supply chains. – UK H_2 Mobility[6] will provide further detail on the priorities for a successful roll out. – Cost of short term innovation programmes would be tens of millions of pounds • Medium Term (2014~2025) – "Start investing now for long term value" – The UK should prioritise innovations which could deliver step change improvements in cost and performance for the 2nd and 3rd generation technologies. – Effort should be focussed on the technology areas with the greatest potential for cost reduction and economic value, i.e. FCEV and hydrogen production. – Innovation support for FCEV should focus on the key hydrogen technology components, e.g. fuel cell stack, fuel cell periphery and electric drive train, on-board storage, and on the integration of these components with the rest of the vehicle. – Since the future requirements for electrolysers are currently uncertain, innovation support in electrolysis should be broad at this stage, promoting improvements in current technologies and bringing forward the development of future technologies, to provide options for later exploitation. The more expensive innovation stages, such as developing much larger products, and demonstrating their operation in the energy system, can wait until requirements are clearer (i.e. after ~2025). – Innovation support in hydrogen production from reformed hydrocarbons should focus on the additional innovation challenges associated with meeting the more stringent requirements of hydrogen transport, in particular purification and verification. To improve economies of scale and utilisation the provision of hydrogen for transport should be incorporated into larger demonstrations of energy generation from bio, waste and with CCS. – This would be building on a legacy of consistent UK support for innovation in hydrogen technologies e.g. in hydrogen and fuel cells combined, IUK[7]/DECC funding between2009 and 2013 has supported programmes with a value of £85m and EPSRC currently supports research projects worth over £43 million. – Cost of medium term innovation programmes would be low hundreds of millions of pounds • Long Term (after ~2025) – "Wait for more certainty on the role of CCS before big investments in large-scale production" – If CCS succeeds, support the scale up of capacity to export hydrogen from CCS to transport (the economics may be sufficiently favourable by this point that public sector support is not needed) – If CCS fails, proceed with demonstrations of large-scale electrolysers. By this time the requirements of the hydrogen transport sector and the energy system will be clearer, allowing a selection of the most appropriates electrolyser technologies from the options generated by earlier innovation support. – Cost of long term innovation programmes would be high hundreds of millions of pounds

[6] The UK H_2 Mobility Project is a partnership of UK industry leaders and Government, working towards a UK roll-out of hydrogen-fuelled transport. For further information see www.ukh2mobility.co.uk

[7] Innovate UK (IUK) was called the Technology Strategy Board (TSB) up until September 2014.

Hydrogen could have an important role to play in the UK energy system

An introduction to hydrogen

Hydrogen – an energy vector

Hydrogen can be used as an energy vector – as a way to move, store, convert and use energy. All energy vectors, including hydrogen, have many potential applications. Different energy vectors have different properties (e.g. energy density, storability, conversion efficiency, applicability, safety) and it is these differences that lead to the advantages, and disadvantages, of using different energy vectors. Hydrogen is a flammable gas which allows it to perform almost all the same heating roles as hydrocarbons (e.g. boilers). Hydrogen can be converted into electricity using fuel cells (or through more conventional combustion in a heat engine such as a gas turbine) and, since they can be miniaturised relatively easily, fuel cells can be incorporated within electrical products allowing hydrogen to provide power on demand (e.g. fuel cell electric vehicles). Similarly this process can be reversed, using electrolysis to split water, effectively converting electricity into hydrogen (e.g. excess renewable electricity generation). Hydrogen's main shortcomings as an energy vector are its low energy density, which can make it inferior to hydrocarbons in some applications (e.g. high density energy storage) and the energy losses when converting it to and from electricity, which can make it less energy efficient than all electric systems. Overall hydrogen is potentially one of the most flexible and broadly applicable energy vectors available and if it is produced in a low carbon way it can be used to decarbonise any sector it penetrates.

The UK energy system is often divided into the three main energy sectors of transport, power and heat, and the infrastructure that connects them. Chart 1 shows how hydrogen could have a role in all three. Within transport, hydrogen can be burnt in an internal combustion engine (ICE) just like petrol and other convenient high density fuels, alternatively a fuel cell or micro-turbine could be used to convert the hydrogen to electricity within the vehicle and this electricity can be used to power an electric drive train.

Within power the story is more complicated; electricity can be used to create hydrogen via the electrolysis of water (or other chemicals), hydrogen can be converted into electricity via a fuel cell or turbine, and hydrogen can be produced as an intermediate step between hydrocarbons and power in pre-combustion carbon capture and storage (CCS). When hydrogen is used to create power, heat is usually generated at the same time, this can be captured and used in 'combined heat and power' (CHP) systems. In heat only applications, hydrogen can be simply burnt, much as hydrocarbons are, for example in domestic boilers or higher temperature industrial applications, or could be used with higher efficiency in gas powered heat pumps. The different energy sectors are likely to become more closely integrated over time, allowing supply and demand in different sectors to be balanced. The use of hydrogen in multiple energy sectors could assist with this integration.

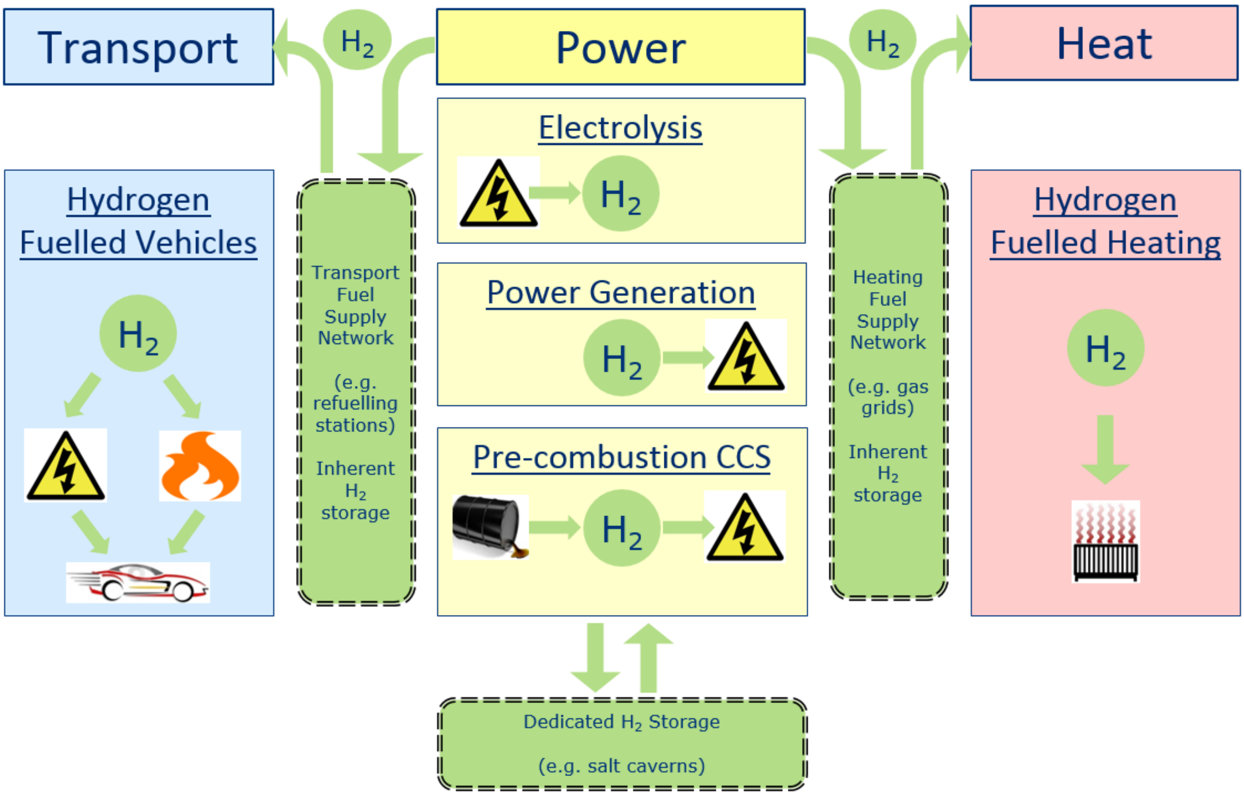
Hydrogen can be stored, allowing its production and use to be separated over space and time. The ease, cost and efficiency of storing hydrogen depends on the application, but in many situations hydrogen storage offers significant advantages over electricity storage. Hydrogen can be stored in various formats: when space is constrained high density formats, such as liquid hydrogen, solid state storage and very high pressure are preferred; when space is not a constraint very large quantities of energy can be stored e.g. by pumping hydrogen into salt caverns. The networks used to move hydrogen between energy sectors (e.g. tube trailers, refuelling stations, gas grids) could also provide very significant energy storage capacity.

Hydrogen in the UK energy system

When considering an energy vector which could potentially have roles throughout the energy system and change the way different parts of the energy system connect with each other, it becomes important to consider the energy system as a whole. Taking a system view avoids the risk of missing the impact that deployment in one sector might have on another sector – for example a very significant demand for hydrogen in one sector might lead to lower production costs (through economies of scale) making the use of hydrogen in another sector more economic. Energy system modelling suggests that hydrogen will have an important role in the UK energy system, and could potentially have roles in transport, power and heat.

However there are significant uncertainties about the future role of hydrogen technologies. One of the reasons for that uncertainty is the broad applicability of hydrogen; future developments in the technologies and markets of almost any part of the energy system could have an impact on the future role of hydrogen technologies. Another reason for uncertainty is the very large changes in cost and volume that could occur in hydrogen technologies between now and 2050. Volumes of hydrogen technologies are effectively zero in most sectors and current costs are those of prototypes and early demonstrators, but if successful hydrogen technologies could rapidly grow to take large fractions of major energy sectors and costs could reduce by an order of magnitude. As energy system modelling of hydrogen technologies continues to improve we will use the improved system level understanding this provides to revisit the analysis in this TINA.

Chart 1 – Potential role of hydrogen in the UK energy system



Source: Carbon Trust and Element Energy analysis

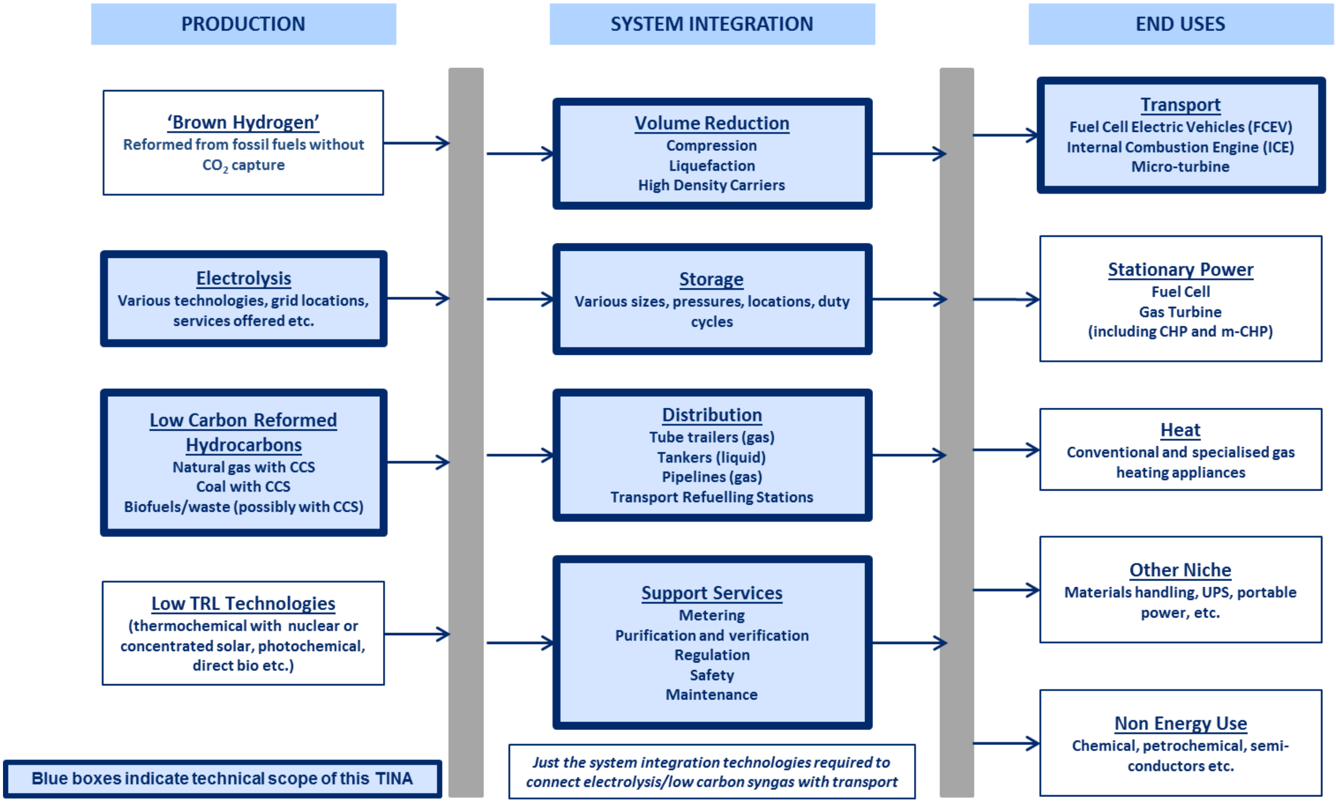
TINA scope: Hydrogen technologies for transport

Chart 2 shows the complexity and breadth of all of the technology areas that could be necessary in a hydrogen system, splitting the technologies into areas and grouping them into hydrogen production, hydrogen system integration and hydrogen end uses. Considering all of these technology areas would be a far larger scope than any previous TINA. ***However it is possible to consider a subset of hydrogen technologies, which would be sufficient to deliver hydrogen fuelled transport, and perform a standalone analysis on this group of technologies; that is what this Hydrogen for Transport TINA attempts to do.***

Transport is a large and important role to consider for hydrogen technologies, but starting the analysis with transport should not be taken to mean that hydrogen technologies in other energy sectors are any less important. Vehicles running on hydrogen produced from sources that result in very low Greenhouse Gas (GHG) emissions provide a route to ultra-low emission vehicles (ULEVs) but there are other technology options for fully decarbonised transport, in particular battery electric vehicles, biofuels and plug-in hybrid vehicles. All of the options face significant challenges, it is too early to say which will dominate or should be preferred and no single winner may ever emerge; therefore hydrogen for transport is an important option to consider.

This Hydrogen for Transport TINA considers all parts of the value chain required to deliver hydrogen for transport, this is shown in Chart 2 with the boxes highlighted in blue. The technology scope includes those needed to provide hydrogen with very low GHG emissions, those needed to provide the vehicles themselves, and the system integration technologies needed to connect these into a viable hydrogen transport system. Chart 3 shows the specific technologies considered in the quantitative analysis in this report and how they are grouped into the four broad areas of production, distribution, refuelling stations and vehicles.

Chart 2 – Overview of hydrogen technology areas, and the transport subset discussed in this report



Source: Carbon Trust and Element Energy analysis

Chart 3 – Technology scope of the Hydrogen for Transport TINA

Technology area	Scope	Other technologies included
Production – electrolysis	• Three chemistries: alkali, proton exchange membrane, solid oxide • Two scales: large (central), small (distributed)	Includes associated purification, verification and on site storage
Production – hydrocarbons	• Steam methane reforming (SMR) without carbon capture and storage (CCS) • SMR with CCS • 'Low carbon syngas' from reformed coal with CCS and reformed renewable hydrocarbons (bioenergy and waste) with and without CCS	Includes associated purification, verification and on site storage
Distribution	• Tube trailers • Pipelines	Includes associated compression, and storage
Refuelling stations	• Medium sized • Large sized	Includes all components
Vehicles	• Fuel cell electric vehicles (FCEV) only	Broken down into five technology sub-areas: • Fuel cell stack • Fuel cell periphery and drive train • Hydrogen storage • Other miscellaneous costs • Maintenance

Source: Carbon Trust and Element Energy analysis

Production

Within hydrogen production the two main low carbon routes considered are water electrolysis and low carbon reformed hydrocarbons. The analysis of water electrolysis includes three chemistries of electrolyser (alkali, proton exchange membrane and solid oxide) at both small (distributed) and large (central) scales. The analysis of low carbon reformed hydrocarbons includes three routes: reformed hydrocarbons from fossil fuels where the carbon dioxide released is captured using carbon capture and storage (CCS), reformed hydrocarbons from renewable sources (i.e. bioenergy sources or waste) without CCS, and reformed hydrocarbons from renewable sources with CCS (potentially providing hydrogen with a negative carbon intensity).

'Brown hydrogen' is a term for hydrogen produced from fossil fuels without the capture of CO_2. Steam methane reforming (SMR) is the main source of 'brown hydrogen' in the UK and the quantitative analysis assumes SMR will be a necessary part of the production mix in the early years, but it is not investigated for innovation needs. Novel hydrogen production technologies, with very low technology readiness levels (TRLs), are acknowledged qualitatively, but their commercialisation timelines are too long and their future costs too uncertain to include them in the quantitative analysis.

System integration

Many of the technologies needed for system integration are grouped into two main technology areas - Distribution and Refuelling Stations.

Within distribution two main routes have been considered, distribution by road on high pressure tube trailers and distribution by pipeline. In both cases these routes include multiple compression and storage steps all of which are included. Distribution in liquid form has not been included on cost effectiveness grounds[8]. The potentially important role of high density carriers in hydrogen distribution is acknowledged qualitatively, but their commercialisation timelines are too long and their future costs too uncertain to include them in the quantitative analysis.

Hydrogen refuelling stations contain many different hydrogen technologies and could come in a variety of formats and sizes. To simplify the quantitative analysis we consider one standard design at two different sizes (500kg H_2/day and 1000kg H_2/day). In a mature market it is likely that larger refuelling stations than this will be necessary.

The remaining system integration technologies have been considered as part of other technology areas, e.g. purification and verification is included within the properties of production technologies, storage is included in many technology areas, and the requirements and costs of safety are included across all technologies.

End uses

Within hydrogen transport only fuel cell electric vehicles (FCEV) are considered in the quantitative analysis and the parameters used are based on a class C/D car. FCEV are broken down into five specific technology sub areas. The 'fuel cell stack' is the set of components which convert hydrogen into electric power and is the core of a FCEV. The 'fuel cell periphery and drive train' is the set of components which support the operation of the fuel cell stack and those which convert the electrical power into the motion of the vehicle. Many of the drive train components are common with other types of electric vehicles. The 'hydrogen storage' is the hydrogen equivalent of a fuel tank in a conventional vehicle, but the properties of hydrogen mean that storing useful quantities is far more challenging than with conventional liquid fuels. The 'other miscellaneous costs' are all of the other vehicle components, some of these will be different on a FCEV compared with a conventional vehicle but overwhelmingly these components are not specific to FCEV. 'Maintenance' is quantitatively analysed as the cost of annual maintenance for a FCEV, in effect this includes the costs of the facilities and equipment required to provide maintenance.

Other hydrogen transport technologies exist or are possible; hydrogen fuelled internal combustion engine (ICE) vehicles have been demonstrated by multiple manufacturers, as has an electric vehicle powered by natural gas micro-turbines, which could conceivably also use hydrogen. These other hydrogen transport technologies might have some advantages over FCEV, for example they are based on more mature technologies, which might reduce the initial cost of retooling production facilities and so make the initial roll-out more affordable, they are also likely to be far more tolerant of impurities in the hydrogen fuel and, depending on how significant purification costs are in the long term, this could prove to be important. On the other hand they have efficiencies as low as half that of FCEV, which means they might need twice as much fuel storage to achieve an acceptable range. The low energy density of hydrogen currently makes fuel storage one of the fundamental challenges for hydrogen transport so, depending on the progress made in hydrogen storage methods, the lower efficiencies of these other hydrogen transport technologies could also be important.

Which hydrogen technologies get developed and brought to market will ultimately be decided by global manufacturers and markets. The current focus of attention for vehicle manufacturers developing hydrogen products is overwhelmingly on FCEV, however this industry is very young and technology trends could change significantly over the next few decades.

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[8] This is discussed in more detail in the section on 'Long term innovation needs'.

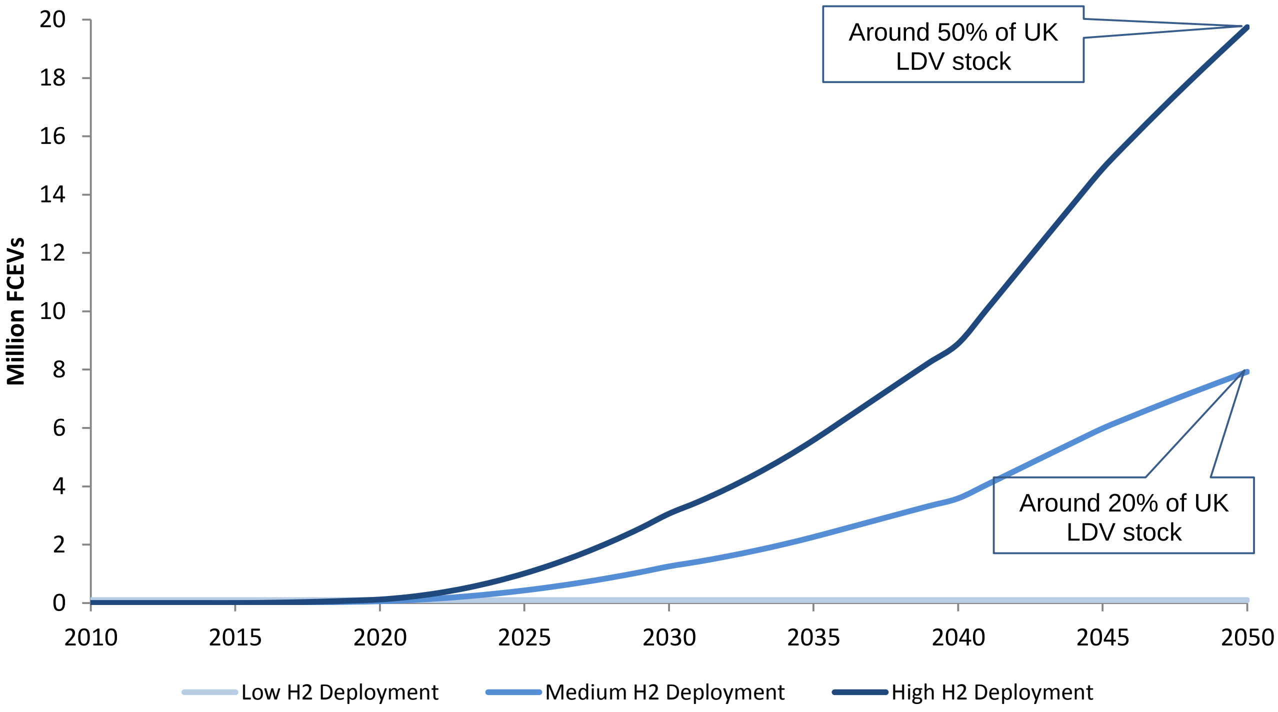
The decision to include only FCEV in the scenarios used in this report is not a prediction, it merely illustrates a possible future and reflects the current dominant view of the industry. Should this view change the scenarios should be revisited.

Deployment scenarios

Deployment scenarios - FCEV

The deployment scenarios in the Hydrogen for Transport TINA start with deployment scenarios for FCEV, use these to determine the demand for hydrogen, and then use the hydrogen demand to determine the deployment of all the other technologies which are needed to provide the hydrogen. Chart 4 shows the UK FCEV deployment scenarios used. The 'High' and 'Medium' FCEV deployment scenarios were derived from scenarios for FCEV and ULEV deployment in the DECC 2050 Pathways analysis[9] and the CCC 4th Carbon Budget[10]. They are also consistent with the shorter term FCEV deployment scenarios published by UK H_2 Mobility[11] and with the press releases of multiple global automotive companies planning to launch their first FCEV between 2015 and 2020.

Chart 4 – UK hydrogen fuel cell vehicle uptake scenarios



Source: CCC 4th Carbon Budget, DECC 2050 Pathways, Carbon Trust and Element Energy analysis

In both the Medium and High deployment scenarios FCEV deployment starts slowly between 2015 and 2020, growing significantly from around 2025. In the Medium scenario FCEV achieve around a 20% stock penetration of Light Duty Vehicles (LDV) in 2050 (~8 million vehicles) and in the High scenario FCEV achieve around 50% (~20 million vehicles). The 'Low' scenario has zero FCEV deployment, this represents a world where the UK roll out fails, for example if the hydrogen transport system cannot achieve the minimum scale needed to be viable because market support mechanisms and policy certainty are insufficient for private sector investment or the necessary cost reductions are not achieved.

These scenarios are not predictions but give a useful range of possible futures to illustrate the potential value to the UK from supporting innovation[12]. Other scenarios are also possible; hydrogen transport could only penetrate niche markets, or could dominate the mass market, and the large cost of dedicated refuelling infrastructure for each different type of vehicle technology might make more extreme scenarios lower cost at a system level. The actual future deployment of

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[9] DECC – 2050 Pathways Analysis (2010) and Transport Addendum (2011)

[10] CCC – The Fourth Carbon Budget (2010)

[11] UK H_2 Mobility – Phase 1 Results (2013)

[12] The deployment scenarios are used as model inputs, not model outputs. So, in the model, although technology costs are affected by deployment, deployment is not affected by cost. This is illustrated by there being two High scenarios with different costs of hydrogen production but the same deployment levels. Therefore these deployment scenarios should not be interpreted as a comment on the level of deployment that would be likely or desirable at these costs.

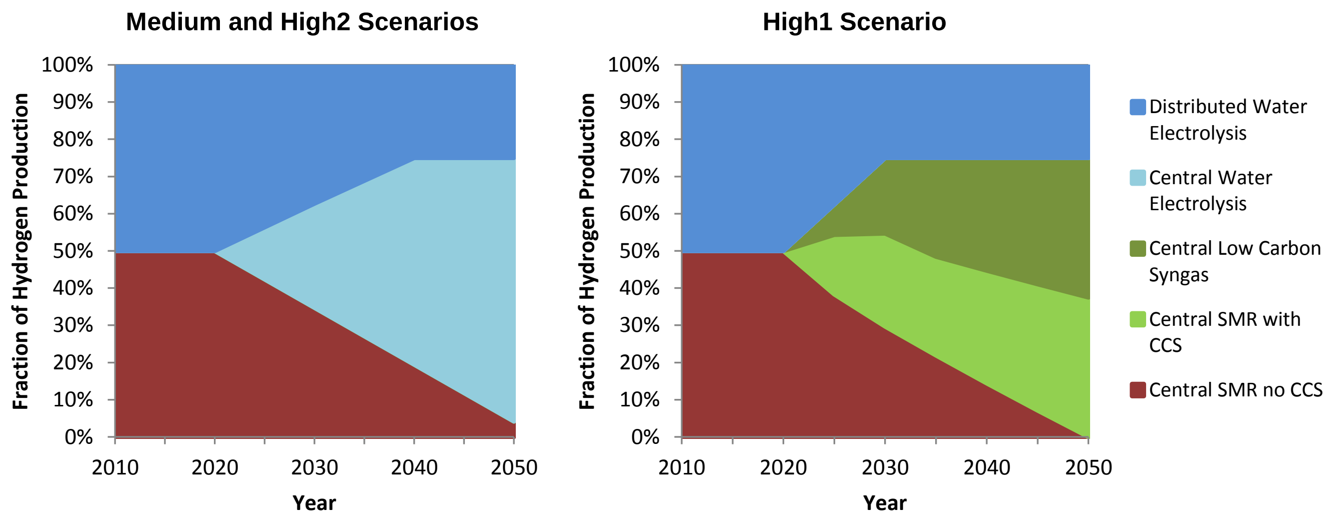
hydrogen transport will be determined by many factors including: the future cost and performance of all low carbon transport technologies, how the rest of the UK energy system evolves and, perhaps most importantly, developments in global vehicle markets. Using higher or lower vehicle deployment scenarios would have little impact on the conclusions about the priorities for support, but developments in other parts of the energy system might, particularly if hydrogen has significant roles outside of transport.

The deployment of new low carbon technologies usually requires some market support to stimulate demand and to overcome high initial costs. In the case of transitioning to a completely new transport technology, requiring adequate utilisation of a completely new refuelling infrastructure, the cost of this market support could be very significant in the early years. The focus of a TINA is on the technology innovation needs and the policies that could support them, rather than the other activities required to achieve a successful deployment, because these are the focus of other work by government departments. However it is important to remember that the deployment scenarios used in this report, and all the analysis based on them, implicitly assume sufficient market support for a successful transition to hydrogen transport.

Deployment scenarios – production mix

The deployment of FCEV creates a demand for hydrogen and hence a deployment of the technologies needed to supply that hydrogen. In some areas there will be competing technology options (e.g. tube trailers and pipelines for hydrogen distribution). The deployment scenarios assume plausible market shares for competing options and a profile for how the mix changes over time which allows us to explore the properties of the key technologies. The deployment scenarios for hydrogen production contain the largest number of competing technologies and Chart 5 shows some of the assumptions for how the hydrogen production mix changes over time.

Chart 5 – Hydrogen production mix scenarios



Source: Carbon Trust and Element Energy analysis

Currently most commercially available hydrogen is produced via steam methane reforming (SMR) of natural gas, without using carbon capture and storage (CCS) to avoid releasing the carbon dioxide that this process produces, because this is by far the cheapest production method. In the early years of these hydrogen for transport scenarios much of the hydrogen consumed by FCEV will come from SMR for the same reason. However the central reason for supporting hydrogen for transport is that it provides a route to ULEV in the long term and so, over time, the use of SMR must be phased out and replaced by very low carbon methods. In the long term two low carbon methods are likely to dominate the hydrogen production mix, these are water electrolysis (using a largely decarbonised electricity network) and low carbon reformed hydrocarbons.

Our production mix scenarios assume a 50:50 mix of SMR (without CCS) and water electrolysis between 2015 and 2025, with SMR getting phased out and replaced with very low carbon production methods between 2025 and 2050. The low carbon production mixes in the scenarios include six different types of water electrolysis (three chemistries at two different scales), SMR with CCS, and low carbon syngas from solid hydrocarbons. The low carbon syngas contains some renewable hydrocarbons (bioenergy and waste) but is dominated by coal with CCS.

The potential impact of CCS on hydrogen transport is very large, as it is for the whole of the energy system[13]. If CCS is successful then this could provide the cheapest low carbon route to hydrogen and could be expected to dominate large-scale centralised production of hydrogen in later years. However CCS has yet to be demonstrated at scale and could still fail, in which case large-scale water electrolysis would probably be the next cheapest, scalable, hydrogen production method. The advantages of small-scale distributed hydrogen production, which CCS probably could not deliver, might allow distributed electrolysis to take a significant share of the market even if CCS succeeds, or the cost advantage of CCS might cause even distributed electrolysis to be 'priced out' of the hydrogen production market. To explore some of this uncertainty the report uses two variants of the High deployment scenario: High1 where CCS 'succeeds' and High2 where CCS 'fails'. Chart 5 illustrates the difference between these two production mix scenarios[14].

Cutting costs by innovating

Short and long term innovation needs, activities and benefits

Many of the innovation needs, market failures, benefits in terms of cost reduction and economic growth, and therefore the priorities for support, are profoundly different in the short and long term. The biggest driver for this difference is that a global roll-out of hydrogen for transport is expected to start between 2015 and 2020, and this event will have impacts on all aspects of the industry. In reality the transition between 'short term' and 'long term' issues will not occur in a single year, or simultaneously for all issues and technology areas, however for consistency 2020 is used as the approximate transition between 'short term' and 'long term' throughout this report.

In the context of technology innovation, the definition of short and long term innovation needs is potentially more complicated, since the innovation need can change over time, the activity addressing the need will tend to continue for a period of time, and the benefit is likely to be delivered sometime after the activity begins. For the purpose of this report short and long term innovation needs are defined as follows:

A *'short term innovation need'* is defined as one where public sector intervention[15] to address the need is required before but probably not after 2020 and the benefit from that intervention will be delivered before 2020. Usually the benefit is that the roll-out of hydrogen transport becomes easier, more affordable, or more likely to be successful. In some cases there is also a short term economic benefit through attracting early investments from large multinational companies into the UK.

In contrast a *'long term innovation need'* is defined as one where public sector intervention to address the need is required both before and after 2020, and the benefit from that intervention will be delivered after 2020. In some cases, in particular for the centralised hydrogen production technologies, the more expensive later components of the intervention, e.g. large-scale demonstration, can be deferred until around 2025, when it will be easier to determine whether they are required. Usually the benefit from the intervention is a long-term impact from meeting targets at least cost and capturing long term business value. Chart 6 shows the short and long term innovation needs and the expected impact of the innovations on 2050 costs, grouped by the technology areas of production, distribution, refuelling stations and vehicles.

[13] For further information on the potential benefits to the energy system from CCS refer to the 'CCS in the power sector' TINA

[14] This report uses the same vehicle deployment in these two hydrogen production mix scenarios. However in reality FCEV deployment might be expected to be lower in scenarios where hydrogen production costs are higher. One explanation for the 'Low' scenario, with zero FCEV deployment, could be an extreme case of this where hydrogen production costs are so high that other ULEV options are overwhelmingly preferred.

[15] In some cases this public sector intervention might be direct financial support, in others it might be non-financial support such as coordination, or target setting.

Chart 6 – Summary of innovation needs, potential impact and urgency

Technology area	Innovation need	Impact potential (2020-2050)[16]	Short term need
Production – electrolysers	▪ **Demonstrate low carbon hydrogen from electrolysis.** Demonstrate electrolyser operation integrated with variable renewable electricity generation and supply of the hydrogen produced to FCEV transport	80%	Med
	▪ **Improve efficiency.** Step change improvement in efficiency (reduced electrical consumption) through changes in stack chemistry, novel materials, higher operating temperatures, novel system designs and larger scale. Overall system efficiency can also be improved by integration with other technologies e.g. compression or an external heat source.		No
	▪ **Improve flexibility.** Improve flexible electrolyser operation with little adverse impact on other performance parameters (efficiency, durability, reliability, purity). Innovations in core electrolyser components and design. Also in power electronics, interface with electricity grid and control strategies to simultaneously optimise for the needs of both the electrolyser and the electricity system. Integration with compression may create additional challenges and innovation needs for flexibility.		No
	▪ **Improve capital cost and durability.** Reduce overall fixed costs, by reducing capital cost and increasing durability, through novel materials, novel system designs, changes to stack chemistry and larger scale. Overall system cost can also be improved by integration with other technologies e.g. compression.		No
Production – low carbon reformed hydrocarbons **(Including purification and verification)**	▪ **Demonstrate 'brown hydrogen' production is ready for roll-out.** Demonstrate SMR and associated purification and verification with necessary purity, reliability, durability and scalability	40%	High
	▪ **Demonstrate low carbon hydrogen from CCS.** Demonstrate the use of CCS to supply H_2 for FCEV transport, including necessary purification and verification		Med
	▪ **Demonstrate low carbon hydrogen from bio/waste.** Demonstrate the use of bioenergy sources and/or waste to supply H_2 for FCEV transport, including necessary purification and verification		Med
	▪ **Improve purification.** Improve cost and efficiency of purification through novel purification processes (e.g. using novel membranes) tailored to the needs of FCEV transport		No
	▪ **Low cost purity verification.** Reduce the cost of quality control through novel processes for low cost, high throughput, high sensitivity, high reliability, purity verification to FCEV standards		No
	▪ **Improve reforming**. Improve efficiency and yield of hydrogen production through novel reforming processes (e.g. chemical looping), potentially tailored to the needs of FCEV transport		No
	▪ **Optimise plant design and business models.** Optimise the design, operation and business models for large hydrogen production assets, to deliver higher utilisation and lower commercial risk by supplying hydrogen to multiple end uses including transport		No

[16] Impact potential is calculated as the cost reduction between 2020 and 2050, as a proportion of 2020 costs. The numbers reported here are approximate and rounded.

Distribution	▪ **Improve materials, compressors and operating concepts for tube trailers.** Develop novel materials to produce hydrogen storage for distribution with improved cost, weight and capacity (overlap with FCEV on-board storage). Develop compressors with improved reliability, pressure, cost and efficiency (overlap with HRS compressors). Develop operating concepts to better integrate the steps and technologies in the distribution process.	55%	No
	▪ **Improve materials and compressors for hydrogen pipelines.** Develop lower cost materials and methods for pipelines, repurposing of gas pipes, improved pipeline compressors, and safe operation of hydrogen pipelines in non-industrial locations		No
Refuelling stations	▪ **Achieve and demonstrate 'roll-out ready' HRS.** Achieve sufficient performance in metering, purity verification, 700bar compressors, static stores, and forecourt integrated designs to allow a successful roll-out	45%	High
	▪ **Improve compressor reliability and maintenance costs.** Improve the mean time between failures for compressors and improve the ease and cost of maintenance and repair. In the longer term shift to novel compressor technologies (e.g. ionic liquid, electrochemical, hydride).		High
	▪ **Improve dispenser meter accuracy.** Improve accuracy and reliability of meters in hydrogen refuelling dispensers to meet requirements of UK Weights and Measures Act		High
	▪ **Faster hydrogen delivery.** Innovation in concepts, equipment and processes for more rapid delivery of hydrogen from distribution vehicle to HRS, and integration of this with delivery methods for other fuels		No
	▪ **Optimise HRS design.** Reduce HRS capital and operating costs, and improve consumer experience, through innovation in component integration, forecourt integration, whole system design, and design for series manufacture		No
	▪ **Standardise HRS components.** Standardise HRS hardware, designs, operating pressures etc. to increase learning rates and economies of scale in supply chain and simplify the HRS design and approval process		No
Vehicles	▪ **Industrialise initial FCEV volume manufacturing processes.** Innovation in manufacturing processes and supply chain integration to deliver the significant initial cost reductions expected from economies of scale as production is first industrialised from laboratory to factory scale	50%	Med
	▪ **Improved fuel cell systems.** Novel materials, concepts, system integration and control strategies to improve the cost, durability, efficiency, size and weight of fuel cell stack and balance of plant		No
	▪ **Improved on-board storage.** Novel materials to produce hydrogen storage containers with lower-cost, higher capacity-to-weight and capacity-to-volume ratios and greater conformability. E.g. stronger, lighter composites for the structure of the container and solid state storage materials to store greater quantities at lower pressures.		No
	▪ **Improved hydrogen contaminant tolerance.** Costs of hydrogen infrastructure could be reduced by improvements in FCEV e.g. contaminant tolerance of fuel cell systems, on-board purification, on-board in-line contaminant detection		No
	▪ **Standardise maintenance facilities and regimes.** Rationalise over-engineering of maintenance facilities and develop best practice maintenance regimes		No
	▪ **Rationalise FCEV safety engineering.** Standardise and reduce over-engineering and excessive redundancy in safety aspects of all vehicle sub-areas		No

Short term innovation needs – "Make the roll-out happen"

The short term innovation needs are about getting the technologies to a level of cost and performance which is good enough to make a successful roll-out plausible before 2020. Most of these needs are concentrated within the system integration technologies, particularly hydrogen refuelling stations (HRS).

Production

Some hydrogen production technologies are generally ready for a roll-out of hydrogen transport. The production of 'brown' hydrogen via SMR is a mature technology, some types of electrolyser (e.g. alkali) are also mature and others (e.g. polymer electrolyte membrane), though less mature, have already shown their compatibility with hydrogen vehicle refuelling in small-scale demonstrations. The two main short term needs are demonstrations to give complete confidence that hydrogen production technologies used in the early years will be sufficiently reliable, durable and scalable to make the roll-out successful, and demonstrations to show that the path to a low carbon production mix is plausible. The demonstration of a path to a low carbon hydrogen production mix needs to include at least one, and ideally both, of electrolysis using renewable electricity and a low carbon reformed hydrocarbon route. Given the timescales expected for completion of a working CCS network the first demonstration of low carbon reformed hydrocarbon route will probably need to be from bioenergy sources and/or waste.

Within hydrogen production via SMR there are some outstanding concerns about how to purify hydrogen to the level required by fuel cell vehicles[17], how to verify that this purity has been reached, and how to deliver this purification and verification in an affordable and scalable way. Within electrolysis it would be helpful to demonstrate that electrolysers integrated with renewable electricity generation can match their operation to the needs of a highly decarbonised electricity network, and that the economic and engineering consequences of operating in this way would be viable in the long term. Within low carbon reformed hydrocarbons, the principle innovation needs are around the purification of hydrogen produced from bioenergy sources and waste, particularly with variable feed stocks, and the integration of that purification with the production process. It is likely that some aspects of these needs will be common to other low carbon reformed hydrocarbon routes.

Distribution

There are no significant, urgent technology innovation needs in hydrogen distribution; the technology is broadly ready for a roll-out of hydrogen transport. The assets currently used by the industrial gas industry to distribute hydrogen are not optimised for hydrogen transport (e.g. they are relatively low capacity), but they will be sufficient in the early years when utilisation will be low. As the rate of hydrogen consumption increases the benefits of distribution assets with higher capacity (e.g. high pressure tube trailers, and the associated compressors and other components) will drive a slow transition in distribution technologies, but this transition will have little impact during the roll out period. Novel and high throughput distribution methods (e.g. solid state storage and pipelines) will become relevant in later decades.

Refuelling stations

A number of small but essential system integration technologies are not quite ready for a UK roll-out of hydrogen transport; most of these are associated with hydrogen refuelling stations (HRS). Rolling out hydrogen refuelling infrastructure without improving these technologies is not impossible, but would mean some undesirable consequences or mitigations.

Particular early challenges related to HRS include: accurate metering of dispensed fuel; purity verification at the point of refuelling; durability, reliability and cost of 700bar compressors; integration of the static hydrogen store and the processes for delivering hydrogen to it with the storage and delivery of other fuels; and safety regulations, particularly those around access and minimum safe distances. Failure to deliver urgent innovation to resolve these challenges might lead to a roll out of early stations that are unnecessarily expensive to build and operate, deliver a poor customer experience, fail to maximize the opportunity for learning, and need special exceptions made with respect to regulations.

Industry coalitions in other countries and regions (e.g. Germany, California and Japan) are already working on their own nation's versions of these issues, typically with government support. These national coalitions are expected to solve most or all of the technical problems standing in the way of a roll-out in their respective countries within a few years. Many of the solutions created in these other countries would be applicable in the UK, but perhaps not all.

One important question that has a large impact on the short term innovation needs of HRS, is the extent to which early stations should integrate the provision of hydrogen with the provision of conventional liquid fuels. The innovation challenges of integrated stations are more numerous and difficult than those of standalone stations, but once these

[17] Draft International Standard ISO/DIS 14687-2 'Hydrogen Fuel – Product Specifications - Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles'

integration challenges have been overcome standalone stations are likely to have higher operating costs and/or poorer user experiences than integrated stations making them an unsustainable operating model in the long term[18].

Vehicles

As with hydrogen production, most of the vehicle technologies are ready or nearly ready for a roll-out of hydrogen transport. Multiple multinational automotive companies have set launch dates for their first commercially available FCEV in the period 2015 to 2020, and they have plans in place to deliver these vehicles which are not dependent on overcoming critical innovation needs. Automotive companies have long product development timelines, with the designs for components, sub-systems, systems and vehicles typically getting ‘frozen’ in concentric layers. As a result most of the significant component level innovation that will be incorporated in the first generation of vehicles has already happened. Incremental improvements in FCEV components will continue and these will be incorporated in early products before 2020 which will deliver part of the cost reduction opportunity expected to occur before 2020. Significant, step-change innovations in components and sub-systems tend to require consequential changes elsewhere in the product which are very difficult to accommodate late in the development process, so these are likely to be incorporated into FCEV after 2020.

The biggest short term innovation need for vehicles is in the industrialisation of the technology innovations that have already happened. Current FCEV are effectively hand-built, in handfuls of units and as a result have costs that mean they could not be commercially launched yet. Chart 9, in the next section, shows the economies of scale that the major vehicle manufacturers expect to occur when the manufacture of FCEV shifts to serial production in automated factories. Significant innovation is required in the production processes and supply chain operations (rather than in the products themselves) to deliver these economies of scale and this presents by far the biggest cost reduction opportunity in this report.

Long term innovation needs – “invest now for long term value”

The long term innovation needs are improvements which deliver most value after 2020. Typically these are significant step-change improvements which will take some time to incorporate into a finished product, or improvements where the value only becomes significant with the higher volumes seen in later years.

Production

In general the long term innovations required in hydrogen production are reductions in capital cost and maintenance cost of hydrogen production equipment, reductions in energy consumption through improved efficiency including by integration with adjacent steps in the process, and improvements in purification and verification.

Electrolysis

Water electrolysis can be achieved with multiple chemistries, sizes and formats. Chart 7 shows the key differences between the three main chemistries of electrolyser: alkali, proton exchange membrane (PEM), and solid oxide (SO). The most important differences affecting their economics are their capital cost (including durability), their operating costs (principally driven by efficiency but also maintenance), their ability to operate flexibly (providing services to the electricity grid), and their ability to integrate with other technologies to deliver a greater overall efficiency (e.g. delivering hydrogen at high pressure to reduce compression requirements, or utilising waste heat to generate steam and electrolysing gaseous rather than liquid water).

Links and similarities between electrolyser and fuel cell technology may also start to affect the economics in the long term. In general each type of electrolyser chemistry has a fuel cell analogue, e.g. alkali electrolysers are the analogue of alkali fuel cells. These electrochemical technologies have much in common, so improvements in the performance or market scale of any one of them could provide some spill-over benefits to all the others. However should one particular technology of fuel cell or electrolyser dominate the market in future, this is likely to provide a particular advantage to the most closely related technologies[19].

Uncertainty in how the UK energy system will develop makes it hard to predict which of these dimensions is most important. For example a future with very volatile electricity prices and a high value for balancing services might favour flexible electrolysers, whereas a future with high and stable electricity prices might favour high overall efficiency, but a

[18] Traditional refuelling stations benefit from high standardisation, integration and utilisation, which allows them to deliver a consistent user experience with a low operating cost. It is possible that a standalone hydrogen refuelling station could deliver a better user experience or a lower operating cost than an integrated station but it will be very difficult to deliver both. The sale of petrol and diesel is almost always integrated in standardised multi-fuel refuelling stations rather than standalone stations for exactly the same reasons.

[19] An often used example is that if FCEV were to become the most successful fuel cell application, and proton exchange membrane fuel cells continue to be the dominant technology in this application, then this could provide economies of scale and other advantages for proton exchange membrane electrolysers over other chemistries of electrolyser.

future with very low electricity prices might prioritise low capital and operating costs. Furthermore uncertainty in the potential for innovation makes it hard to predict how much improvement innovation could deliver in each of these dimensions. Therefore it is currently too early to predict which chemistries, scales and product formats of electrolyser will dominate and the innovation needs across all of these electrolyser types need to be considered.

Chart 7 – Differences between alkali, proton exchange membrane and solid oxide electrolysers

<table>
<tr><th>Alkali</th><th>Proton Exchange Membrane (PEM)</th><th>Solid Oxide (SO)</th></tr>
<tr>
<td>

Alkali electrolysers have a cost advantage through maturity, an ability to use cheap materials and good efficiency and durability
Most of the weaknesses of alkali electrolysers are caused by the liquid alkali electrolyte

Fluid electrolyte makes operating at higher pressures and flexible operation challenging
Tendency to leak caustic fluids causes maintenance challenges

Shifting to an immobilised alkali electrolyte could bring some of the advantages of PEM, but at lower cost

</td>
<td>

In the short term PEM electrolysers need to reduce capital costs

By reducing component cost (e.g. by reducing/eliminating the use of platinum and other expensive catalysts)
By reducing part count
By increasing durability

In the long terms PEM electrolyser costs will be dominated by electricity costs, making efficiency a priority

Stack level efficiencies are close to theoretical limit
Product level efficiencies have room for improvement
Overall system level efficiency improvements are possible through higher pressure operation, reducing the need for subsequent compression

Electricity costs can also be reduced by providing services to the electricity system

PEM electrolysers are currently most able to provide these services through rapid modulation, cycling and short term overloading of power

</td>
<td>

In the long term SO electrolysers could potentially offer the lowest cost electrolysis

Low capital costs by avoiding use of precious metal catalysts,
Low operating costs through very high efficiencies
Integration with external sources of heat could result in even higher efficiencies
Solid electrolyte may be compatible with higher pressure operation, reducing the need for subsequent compression
Some aspects of flexible operation may also be possible

However SO electrolysis has yet to be demonstrated at any significant scale
The immediate innovation need is to design, build and demonstrate a working product at a useful scale

</td>
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Low carbon reformed hydrocarbons

The sources of low carbon reformed hydrocarbons are likely to change over time; however this shift has little impact on the innovation needs as they are largely independent of the source of the hydrocarbon. In the short term low carbon reformed hydrocarbons from renewable sources such as bioenergy and waste could start providing hydrogen for transport relatively quickly. Some of the existing plants which convert bioenergy and/or waste to heat and/or power already produce a hydrogen rich syngas as an intermediate and could be converted relatively easily to produce low carbon hydrogen for transport. Hydrogen from fossil fuels using CCS will take longer to become available because this route is dependent on a CCS network which does not exist yet. In the longer term, when the volumes of hydrogen required for transport could be much higher, bioenergy and waste will probably only be a minor contributor to the hydrogen production mix, because the total bioenergy and waste resource available in the UK will be constrained and competed for by other end uses that may place a much higher value on it. In contrast fossil fuels with CCS could dominate the supply of low carbon reformed hydrocarbons in the longer term because they can scale with demand.

Chart 8 gives an overview of the main types of CCS and how they relate to hydrogen for transport. In summary any type of CCS could provide a low carbon route from fossil fuels to hydrogen for transport, but pre-combustion CCS would provide the earliest opportunity to demonstrate this route.

Chart 8 – Differences between pre-combustion, post combustion and oxy-fuel CCS, when used for low carbon hydrogen production

CCS and hydrogen for transport

- There are three main types of CCS: pre-combustion, post-combustion and oxy-fuel
  - Typically in pre-combustion CCS a hydrocarbon fuel (e.g. coal, natural gas, a bioenergy source or waste) is converted into hydrogen and carbon dioxide ('reformed'), the carbon dioxide is separated and captured, and the hydrogen is burnt in a turbine to produce electricity
  - In post-combustion CCS the hydrocarbon fuel is burnt in a turbine to produce electricity in the normal way, and then the carbon dioxide is captured from the flue gases
  - Oxy-fuel CCS is similar to post-combustion except that the hydrocarbon fuel is burnt in pure oxygen rather than air, so that bulk separation of nitrogen from carbon dioxide in the flue gasses is not necessary.

- Of the three types, pre-combustion CCS has the most obvious link to hydrogen for transport, because it will involve the efficient, low-carbon production of large volumes of hydrogen
  - The main requirement to allow hydrogen from pre-combustion CCS to be exported for use in FCEV would be some additional purification (ideally included in the original design)
  - Pre-combustion CCS could probably give the earliest demonstration of CCS providing hydrogen for transport, since the ability to export hydrogen could be included in the design from the beginning

- However the other two types of CCS could also provide a good route to low-carbon hydrogen in the longer term
  - Once a carbon dioxide pipeline and storage network is in place, which could be receiving carbon dioxide from any type of CCS, it should be relatively simple to build a dedicated hydrogen production facility and connect the waste carbon dioxide produced to the CCS pipeline
    - The dedicated hydrogen production facility would probably be an SMR plant and would be a relatively small adaption from existing mature SMR plant designs
  - The main requirement to allow post-combustion and oxy-fuel CCS to provide hydrogen for FCEV would be that the carbon dioxide pipeline be 'oversized' for the planned CCS power stations so that additional sources of carbon dioxide could be retrofitted. Some additional purification and compression steps would also be required on both the hydrogen and the carbon dioxide sides of the SMR process
  - It seems likely that post-combustion and oxy-fuel CCS would allow a later demonstration of hydrogen from CCS, as the carbon dioxide pipeline would probably be built first and then the dedicated hydrogen production facility retrofitted

- For the reasons above, a demonstration of pre-combustion CCS would be more immediately helpful to hydrogen for transport than the demonstration of post combustion and oxy-fuel, although demonstration of any type of CCS would be helpful

The long term innovation needs in low carbon reformed hydrocarbons are very similar to the short term needs, except that there is a shift in emphasis over time from demonstrating viability to minimising cost.

The first group of innovation needs are around the additional purification required to bring the hydrogen produced to the purity required for FCEV, to verify that this purity has been achieved and to deliver this in an affordable and scalable way. This is very similar to the short term innovation need for 'brown' hydrogen from SMR, but is more challenging for hydrogen derived from more complex hydrocarbons because the contaminants are different and the methods are less mature. Compared to reforming natural gas, reforming solid and liquid hydrocarbons generally produces a higher concentration of contaminants, a greater number of contaminants, more difficult species of contaminant, and, particularly in the case of bioenergy sources and waste, more variability in the contaminants.

Methods already exist for purifying hydrogen, produced from complex hydrocarbons, to the levels currently required by FCEV and for verifying that purity, but the methods currently available have not been optimised for the high throughput that would be required in a mature hydrogen transport market.

This innovation need, within hydrogen production technologies, to purify and verify hydrogen to a very high purity level, is linked to the innovation need, within FCEV, to develop components which are more tolerant to impurities in the hydrogen. There is a need, at a system level, to optimise this cost trade-off across the hydrogen production and fuel cell vehicle sectors.

The second group of innovation needs are related to the economics and engineering requirements of integrating the production of hydrogen for transport with the production of hydrogen for other end uses in one large low carbon hydrocarbon reforming plant. These needs are less about technology innovation and more about developing best practices, regulatory frameworks and market mechanisms.

Low TRL hydrogen production methods

There are many possible alternative low carbon hydrogen production methods which are far more immature than the methods discussed above[20]. The overarching requirement for all of these is to better understand their long term potential, to inform later decisions on whether they should form part of the low carbon production mix for hydrogen. In general this understanding is best improved through fundamental research.

Distribution and refuelling stations

In this report the technology areas of distribution and refuelling stations include volume reduction and storage. Some of these areas are likely to see only incremental improvement in the long term, whereas in others significant step change innovations are likely. Many of the technology innovation challenges stem from the fact that hydrogen has a very low volumetric energy density at standard temperature and pressure and that the solution chosen by the automotive industry to overcome this disadvantage of hydrogen is compression to 700bar. A common feature across many of the technologies currently used to handle hydrogen at these pressures is that they have been adapted from technologies designed and optimised for different gases at lower pressures. Incremental improvements in these technologies have been achieved and will continue to occur but the significant improvements in cost and performance will probably be delivered after 2020 through developing completely new ways to perform the same function.

Within volume reduction the main method for the foreseeable future is compression. Incremental improvements to existing mechanical compressors have been achieved, through adaptations and higher specification components, which have allowed the development of HRS compressors capable of delivering hydrogen at 700bar. These compressors are currently relatively expensive and have a disappointing failure rate but further short term innovations before 2020 could improve this. In the medium term ionic liquid compressors and the integration of compressors with pressurised electrolysers should improve efficiency, reduce the number of compression steps and reduce the part count, allowing further incremental improvements in the capital cost, operating cost, reliability and footprint of compression. In the longer term step change improvements in cost and performance may be delivered by lower TRL technologies using completely different compression methods e.g. electrochemical or hydride compressors.

Another option for volume reduction of hydrogen is liquefaction (i.e. turning it from a gas into a liquid). This delivers much higher energy density than compression, and is a relatively mature technology within the industrial gases sector, however it has some major disadvantages and has now been dismissed by most organisations planning a UK roll-out of hydrogen for transport. For on-vehicle storage it is only useful in vehicles with very high utilisation due to the large proportions of hydrogen that boil-off while the vehicle is not in use. For distribution it only offers economic advantages over compression at delivery distances that are unlikely to be needed in the UK for decades, if ever[21]. Finally, the very low temperature of liquid hydrogen (20K) causes liquefaction of hydrogen to have significant economies of scale, which mean that a single plant would need to be supplying the fuel for hundreds of thousands of cars to be viable.

The scenarios in this report do not include liquid hydrogen for distribution, but there are many scenarios where it could have a role, these include: a very centralised hydrogen production mix; a strategic decision to integrate liquefaction of hydrogen with gasification of liquefied natural gas imports; a significant increase in the use of liquid hydrogen for cooling of superconductors or of liquid air for energy storage; the UK becoming a significant exporter or importer of hydrogen to or from other countries; very significant increases in renewable electricity generation capacity, particularly in locations with limited electricity transmission capacity; or if improvements to purification technologies prove very difficult (very high purity is a consequence of hydrogen liquefaction).

Within storage, much of the innovation to date has been for on-vehicle storage where the capacity-to-weight and capacity-to-volume requirements are most challenging. However there is also a need for improvements in high pressure storage for distribution (e.g. the tubes on tube trailers) and in static storage bulk (e.g. at HRS). Improvements in on-vehicle storage will probably have spill-over benefits for distribution, HRS and storage elsewhere in the system.

Within distribution there may be a shift in later decades from distribution by road towards using pipelines. The economics of pipelines mean that this shift is only likely to happen on a national scale once there is a large and well established

[20] For example: genetically engineered microorganisms which convert organic waste directly into hydrogen, photolysis using light to directly split water over a catalyst, and thermochemical cycles splitting water using very high temperature heat from concentrated solar energy or ‘Generation IV’ nuclear reactors.

[21] Liquid hydrogen distribution is calculated to be more economic than 500bar distribution at distances greater than 275km. In most hydrogen production scenarios this is further than hydrogen will need to be delivered in the UK. See McKinsey and Company - “Urban buses: alternative powertrains for Europe” (2012).

hydrogen market. In certain niche locations pipelines may become economic much sooner if large and closely located supplies and demands for hydrogen develop. Hydrogen pipelines would also become economically viable much sooner if there were simultaneous demands for hydrogen in other energy sectors e.g. heat. Pipelines and pipeline compressors for hydrogen are mature in petrochemical and chemical industries, but innovations would be needed to adapt the technologies for use in non-industrial locations.

Spanning both volume reduction and storage is the possibility of a shift away from compressed gas storage. There are many university groups and company R&D teams researching solid state storage of hydrogen at standard or moderately elevated pressures. In the longer term it is possible that a breakthrough in one of these solid state storage methods could lead to a shift away from 700bar compressed hydrogen for on-vehicle storage, resulting in wide spread changes in storage, distribution, refuelling stations and possibly elsewhere in the system.

Finally distribution and HRS require the integration of many different technologies and much of the innovation potential is in the integration of the technologies rather than in the technologies themselves. Short term innovations are required before 2020 to deliver a functioning refuelling infrastructure that allows a successful roll-out. This should be followed by decades of design optimisation to better integrate the components of a hydrogen refuelling supply chain, and to integrate this supply chain with that of conventional fuels. Step change innovations in how these technologies and processes are integrated could lead to significant reductions in both the capital and operating cost of distribution and HRS.

Vehicles

Although very significant cost reductions appear to be possible in the short term through the industrialisation of FCEV manufacture, the production volumes in the 2020s and 2030s will still be very small compared to those for conventional vehicles. As volumes increase delivering further production efficiency through economies of scale and the integration of a maturing supply chain will continue to be a priority.

Significant cost reductions could be achieved in the long term through step-change improvements in FCEV components and sub-systems. The R&D to deliver this would need to start immediately in order to be incorporated into 2nd and 3rd generation vehicles which will be launched after 2020. There are opportunities for significant cost reduction in all of the main areas of novel components (fuel cell stack, fuel cell periphery, electric drive train, fuel storage, and other hydrogen specific components e.g. sensors) and in how these components are integrated. Some of these innovation needs will be common to other types of electric vehicle. If the evolution of internal combustion engine vehicles since their launch is any indication, it is likely that many aspects of FCEV design will change so significantly that the innovations are currently difficult to imagine.

As the roll-out progresses and more data on the costs of FCEV and their supporting infrastructure becomes available, many of the assumptions underpinning design choices should be revisited with further analysis to understand whether changes in the design of FCEV would result in lower overall system costs. For example novel low-pressure high-capacity hydrogen storage methods and fuel cell systems that are more tolerant of impurities might increase the cost of the vehicle whilst reducing the cost of hydrogen production and refuelling infrastructure. System level optimisation of these trade-offs could lead to new innovation needs within FCEV.

There are also long term innovation needs in the technologies and services that will support fuel cell vehicles, such as maintenance facilities, emergency breakdown services and the structures that FCEV will occupy (e.g. domestic garages, tunnels, ferries etc.). In the early years many aspects of these services are going to be over-engineered to ensure safety but at an unnecessarily high cost. Innovations in hydrogen sensing and measuring are likely to provide benefits in many areas, as will the development of expertise and established best practice in the design of safety systems.

Value in meeting emissions and energy security targets at lowest cost

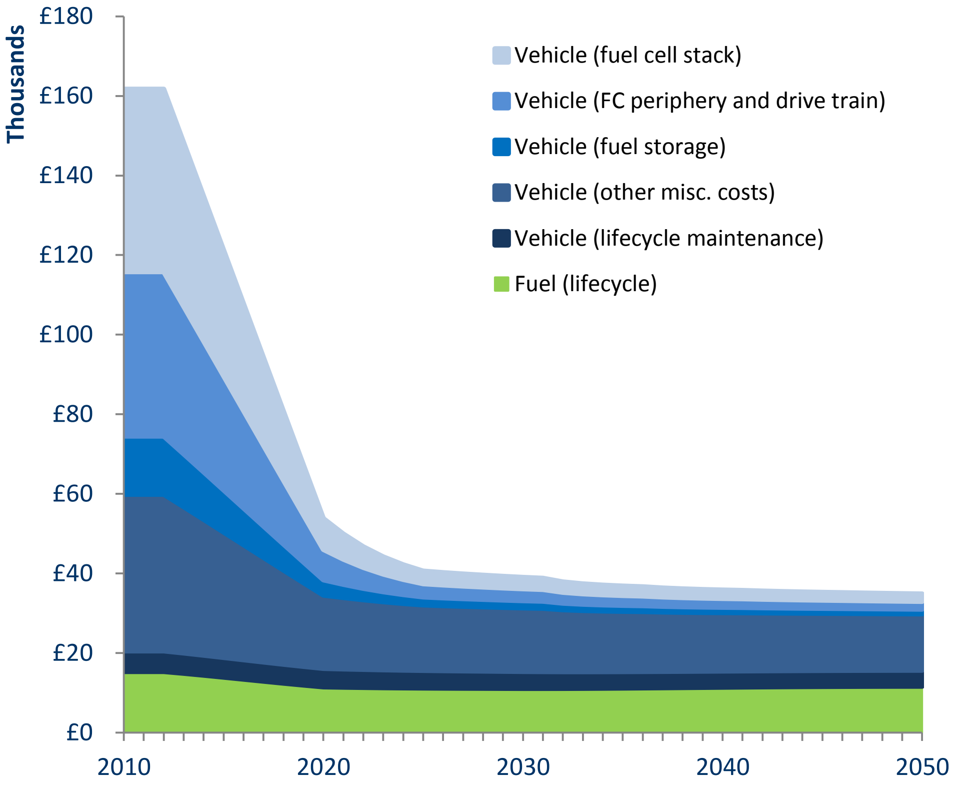
Cost savings through economies of scale and innovation

It is common in the automotive industry to consider costs in terms of the Total Cost of Ownership (TCO) of a vehicle. This is the capital cost of buying the vehicle plus the lifetime operating cost of 15 years of fuelling and maintaining it. TCO is also a useful unit to illustrate how innovation can deliver cost reduction, since the cost of refuelling captures almost all of the costs of hydrogen production and system integration, with the remainder captured in the cost of maintenance and the capital cost of the vehicle itself.

Chart 9 shows how the TCO for a FCEV could change over time. The cost of hydrogen transport could reduce very significantly, with a potential TCO reduction of 78-81% between 2012 and 2050. The vast majority of the cost reductions are associated with the shift to volume manufacturing and so could occur quickly, with a potential TCO reduction of 67-68% between 2012 and 2020. Continuing innovation could then deliver a further 35-41% reduction from the TCO in 2020 to the TCO in 2050.

These cost curves were developed by reviewing published product and component level cost forecasts, combining these published sources with unpublished analysis, and reviewing the numbers through interviews with industry experts. The very large cost reductions assumed to occur by 2020 reflect the shift from small batches of hand-built prototypes for demonstrations to commercial deployment and the high volume manufacturing methods of the automotive sector. However these are **potential** not **predicted** cost reductions; they provide an indicative upper limit on the cost reductions that could be achieved if all barriers to innovation were removed[22]. Actual cost reductions may be slower than this, which would probably result in the roll-out being delayed and deployment being lower.

Chart 9 - Vehicle 'total cost of ownership' (TCO) in Medium and High2 Scenarios (lifetime £/vehicle)[23]



Source: Carbon Trust and Element Energy analysis

Chart 9 also shows that most of the cost reduction is delivered through the FCEV itself and its novel components (i.e. the fuel cell stack, fuel cell periphery and drive train and hydrogen storage). After 2020 the vehicle costs are dominated by

[22] They also assume certain things are achieved before 2020 which are outside the scope of this analysis, such as that 'pull' policies exist which give sufficient market support to drive both sales of vehicles and installation of refuelling infrastructure, that the industry has sufficient confidence to invest in scaling up manufacturing capacity and that safety concerns around hydrogen have been addressed.

[23] Chart 9 shows the TCO in the Medium and High2 scenarios, i.e. with no CCS. In the High1 scenario the use of CCS for hydrogen production reduces the cost of fuel by about 35% in 2050, reducing the TCO by about 12%.

the category 'other miscellaneous costs', which reduces far more slowly because it contains the components which are common to all vehicles and are already very mature.

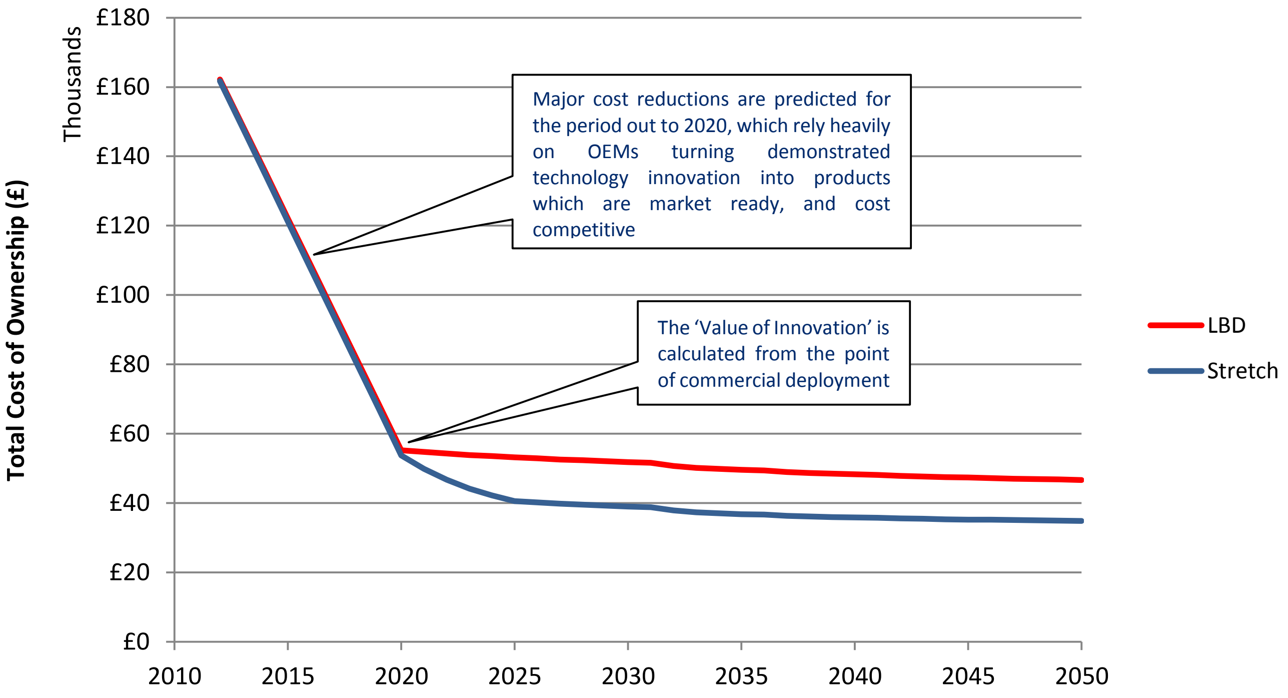
In the scenarios used in this report the cost of refuelling the vehicle does not change much over time, even though significant innovation and cost reduction is expected in the technologies which contribute to the cost of hydrogen. This is because the impact of technology improvements is balanced by increases in primary energy costs and a steady shift from relatively cheap 'brown hydrogen' towards more expensive lower carbon hydrogen production methods.

The value of innovation

Chart 10 shows how the TCO for FCEV drops over time and how the 'value of innovation' is calculated. Through an analysis of the literature, and expert input from industry and academia, a target cost was established for all of the technologies at around 2020. These target costs include both cost reductions that manufacturers can foresee and have plans in place to deliver, and a proportion of the additional cost reductions which are expected by 2020 although the exact innovations needed to deliver them have not been identified yet. Consistent with other TINA reports, this report only 'values' innovation that delivers improvements after the technology has reached a cost and performance level at which it can be commercially deployed with subsidies. In the scenarios used for this TINA this occurs in 2020.

After 2020 two cost curves are calculated for each technology using cumulative volume driven learning rates; a theoretical Learning by Doing (LBD) curve where costs progress as if LBD were the only contribution to innovation and there were no learning by research development and demonstration (RD&D), and a Stretch curve which is the best case scenario of costs being reduced by innovation as a result of both LBD and learning through RD&D. The 'value of innovation' is calculated as the difference between these two costs in each year, multiplied by the volumes of the technology sold in that year, discounted back to 2012. This 'value of innovation' is calculated for all technologies in all three scenarios.

Chart 10 – Impact of innovation on vehicle total cost of ownership (TCO) in Medium and High 2 Scenarios[24]



'Total cost of ownership'	=	Includes the capital cost for the vehicle, plus 15 years' worth of fuel and maintenance costs. All costs of H_2 supply chain are included in the cost of fuel. Costs are based on a category C/D medium-sized vehicle.
'LBD'	=	Learning by doing
'Stretch'	=	Learning by doing PLUS learning by RD&D

Source: Carbon Trust and Element Energy analysis

The assumptions used in the calculation are relatively conservative: the High scenarios only reach 50% of all UK LDVs by 2050, implying that other ULEV technologies also have a significant role, and the value of RD&D is only calculated

[24] Chart 10 shows the TCO in the Medium and High2 scenarios, i.e. with no CCS. In the High1 scenario the use of CCS for hydrogen production reduces the cost of fuel by about 35% in 2050, reducing the TCO by about 12%.

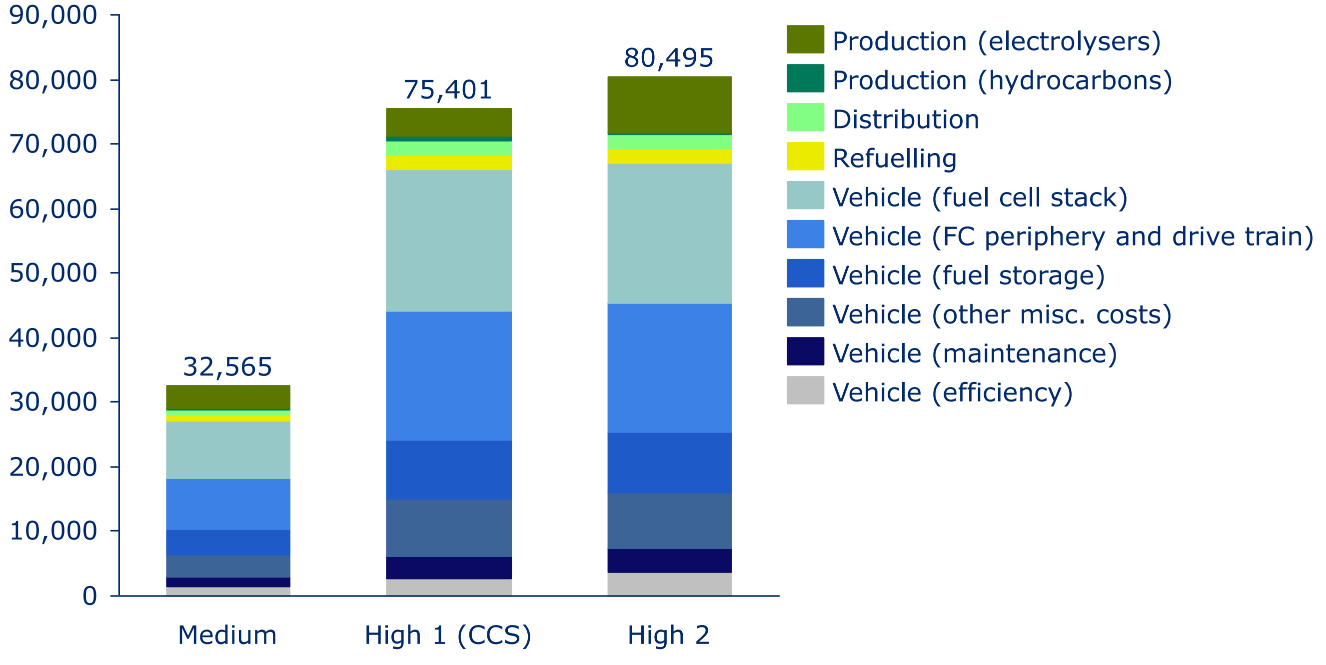
from after 2020 when the vast majority of the cost reductions have already happened. Nevertheless the value of RD&D calculated for hydrogen transport technologies is still large relative to other TINA reports, primarily because the automotive sector is a significant part of the UK economy and energy system, so transitioning to a new transport technology could have a very significant impact.

Large innovation opportunities in FCEV and hydrogen production

The value of innovation in meeting targets at least cost is £33-80bn to 2050 (across the Medium, High1 and High2 scenarios). Chart 11 shows that the long term opportunities to reduce cost through innovation are concentrated in broadly the same areas as where transport costs are concentrated in conventional vehicles; the biggest area of cost is the vehicle itself, the next biggest area is the cost of producing fuel and all of the other costs that contribute to the TCO are far less significant.

Around four fifths of the value of innovation is in improvements to the vehicle itself. The components making the biggest contributions are the fuel cell stack, the fuel cell periphery and electrical drive train, and the on-vehicle hydrogen storage. Improvements in efficiency (which reduces refuelling costs), maintenance and other miscellaneous FCEV components also result in significant savings. The next largest area of opportunity is hydrogen production. Innovation here is worth much more in the scenarios where CCS fails, because electrolysis is an inherently more expensive production method and there is a far larger opportunity to reduce the cost of electrolysis than to reduce the cost of exporting hydrogen to transport from CCS and other low carbon reformed hydrocarbons[25]. The opportunity for cost reduction in distribution and refuelling is far more limited, primarily because these sectors will contribute relatively little to the TCO once they are mature.

Chart 11 - Value of reducing costs through RD&D (£m cumulative to 2050)[26]



Source: Carbon Trust and Element Energy analysis

[25] The 'value of innovation in meeting targets at least cost' calculated for hydrogen from CCS within 'Production (hydrocarbons)' is just that attributed to producing hydrogen for transport, i.e. it is additional to the value of CCS in other sectors, which is calculated in the CCS TINA.

[26] When interpreting the value of cost reductions presented here it should remembered that in these scenarios hydrogen technologies are only deployed in the transport sector. If hydrogen technologies are simultaneously deployed in other sectors, such as power and heat, this might lead to higher volumes for technology areas that can serve multiple sectors, such as hydrogen production and distribution, which might in turn lead to larger economies of scale, faster cost reductions and higher values of innovation in these technology areas.

Green growth opportunity

The size of a global hydrogen transport market

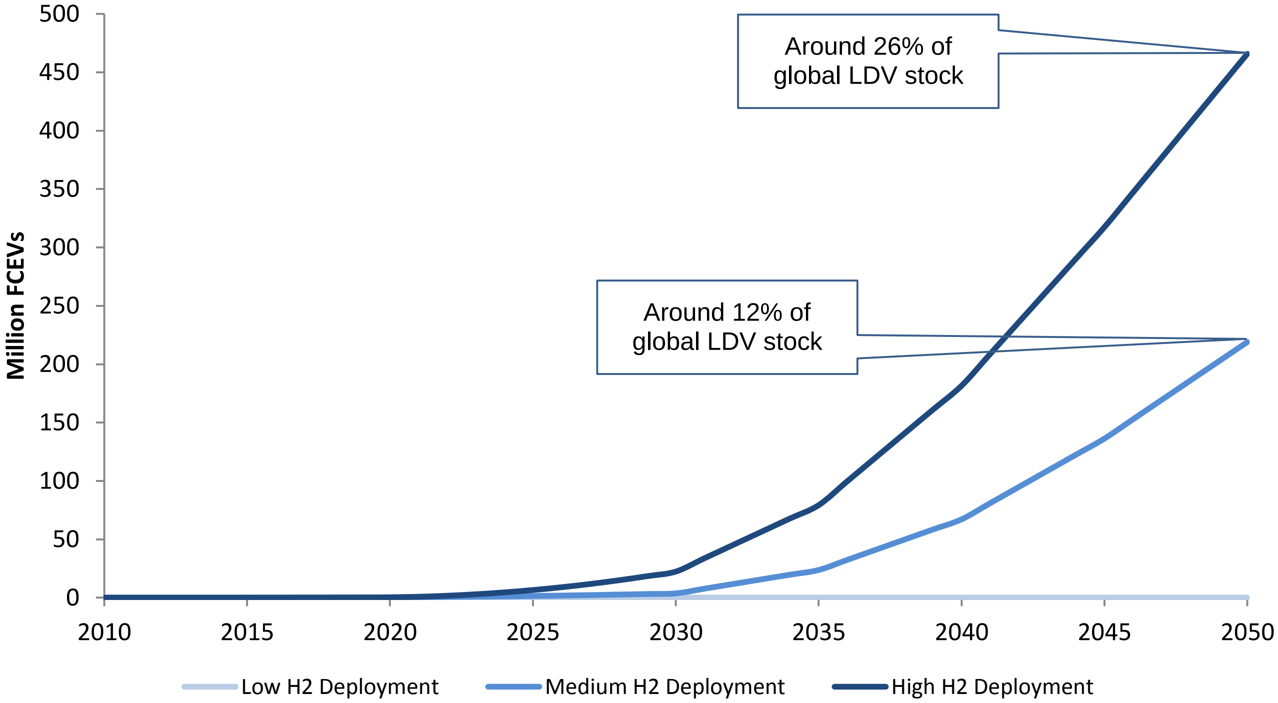
The global deployment scenarios for hydrogen technologies are derived in the same way as the UK scenarios, starting with global deployment scenarios for FCEV, using these to determine global demands for hydrogen, and then using these hydrogen demands to determine the deployment of all the other technologies which are needed to provide the hydrogen. Chart 12 shows the global FCEV deployment scenarios used. The Low, Medium and High FCEV deployment scenarios are derived from FCEV deployment scenarios in the International Energy Agency 'Energy Technology Perspectives 2012' report (IEA ETP 2012)[27].

In the High global deployment scenario FCEV deployment starts just before 2020, growing significantly after 2025 to achieve around 26% penetration of the global LDV stock (~450 million vehicles) by 2050. In the Medium scenario FCEV deployment starts just before 2025, growing significantly after 2030 to achieve around 12% penetration of the global LDV stock (~200 million vehicles) by 2050. As with the Low UK deployment scenario, the Low global deployment scenario has zero FCEV deployment. This represents a world where the global roll-out fails, for example if too few of the countries with large LDV markets provide effective market support to drive the required economies of scale in global FCEV manufacture.

None of the global FCEV deployment scenarios used have FCEV dominating the LDV market by 2050. This implies that FCEV share the global market with other vehicle technologies. In the IEA ETP 2012 scenarios these other technologies are conventional ICE, hybrid ICE, plug-in hybrid electric vehicles and pure battery electric vehicles.

The FCEV deployment scenarios are used to derive the deployment of all the other hydrogen technologies and, as with the UK scenarios, the High deployment scenario is split into High1 (where CCS succeeds) and High2 (where CCS fails).

Chart 12 – Global hydrogen fuel cell vehicle uptake scenarios



Source: IEA 'Energy Technology Perspectives 2012', Carbon Trust and Element Energy analysis

[27] The Low, Medium and High global FCEV deployment scenarios are derived, respectively, from the '2DS – no H_2', '2DS' and '2DS – high H_2' scenarios in International Energy Agency 'Energy Technology Perspectives 2012'.

The value to the UK economy from the export of hydrogen technologies for transport

The global market for hydrogen transport technologies implied by these deployment scenarios would have an annual turnover of £368-788bn in 2050. The UK is unlikely to dominate any hydrogen technology sector, but given the competitive strengths currently held in related sectors, the UK could be a significant player in many of the higher value parts of the market. Chart 13 shows that the value to the UK economy of selling goods and services into this global market could be worth £10-26bn (cumulative to 2050, discounted to 2012, with displacement effects).

Just as FCEV contribute the majority of the TCO, and offer the biggest opportunity for reducing costs through RD&D, they also offer the by far the biggest green growth opportunity. This is due to both the large potential market size for FCEV and the relatively high strength of the UK in the technology sectors which would support it. The biggest contributions to this opportunity come from the fuel cell stack, the fuel cell periphery and drive train, and the on-vehicle hydrogen storage. The UK has a strong and well established industry of suppliers to global automotive manufacture, and strength in related technology areas which could be converted into a strong competitive position in the supply of these new hydrogen vehicle components. In total the value of business creation from FCEV technologies could be around £9-23bn (cumulative to 2050, across the Medium and High scenarios, with displacement effects).

The potential value to the UK economy from all the other technology areas required for hydrogen transport is relatively small compared to the value from FCEV. Indeed the values from technology sub-systems within the FCEV (e.g. the fuel cell stack) are typically many times larger than the value from whole technology areas in the hydrogen supply chain (e.g. distribution or refuelling). Hydrogen production is the next biggest opportunity potentially contributing £0.6-1.7bn to 2050 and facilitating the much larger economic benefit available from ‘on-shoring’ transport fuel production (see next section). Distribution (£0.1-0.4bn) and refuelling (£0.3-0.6bn) are far less significant.

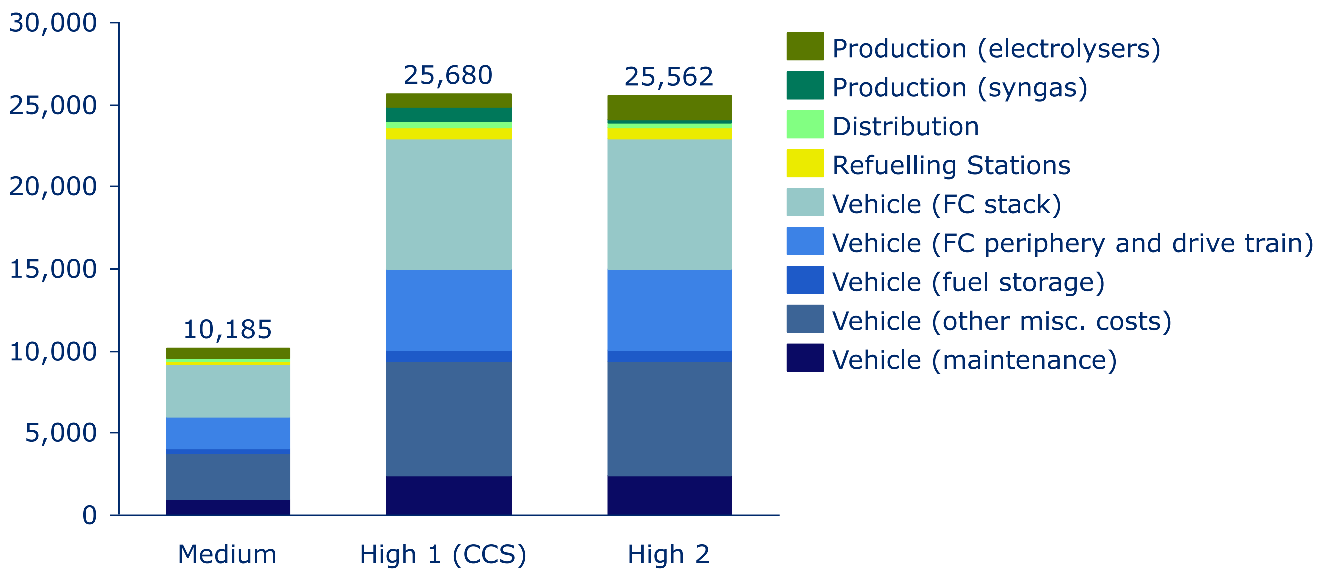
The value to the UK economy from ‘on-shoring’ transport fuel production

In addition to the positive impact that hydrogen technologies could have on the UK economy via the export of goods and services, there could be a second positive impact, of roughly the same value, from a shift in the source of primary energy used to produce transport fuel and hence a reduction in how much the UK spends on imported oil.

Currently the majority of the value of transport fuel purchased in the UK leaves the UK to pay for the import of oil, which is the source of the primary energy used to make petrol and diesel. In contrast, if hydrogen transport fuel is made from imported primary energy sources which are of lower value than oil (e.g. gas, coal, bioenergy sources, and waste) then the processing of the fuel, which occurs in the UK, makes up a higher proportion of the final value of the purchased fuel. Furthermore, if hydrogen transport fuel is processed in the UK and is made from UK primary energy sources then all of the value of the purchased fuel accumulates in the UK. The hydrogen production scenarios in this report are a mix of reformed hydrocarbons and water electrolysis; the reformed hydrocarbons (coal, natural gas, bioenergy sources and waste) are assumed to be a 50:50 mix of UK sources and imported fuels whilst the electrolysis is assumed to be driven entirely by UK renewable electricity. The economic value to the UK from this shift in fuel consumption could be worth £9-23bn to 2050 (cumulative to 2050, across the Medium and High scenarios, with displacement effects), which is similar in size to the total economic value from the export of all goods and services related to hydrogen for transport.

This economic value from ‘on-shoring’ transport fuel production is not specific to hydrogen transport; there would be a similar economic impact from any vehicle technology, e.g. electric vehicles, which replaces consumption of imported oil with consumption of UK primary energy sources. The value is also not entirely dependent on UK strength in hydrogen production technologies; in theory the UK could use only imported hydrogen production equipment and still benefit from producing its own transport fuel. However if hydrogen transport is going to create a large new UK market for hydrogen production, it will be easier to deliver this transition and to capture value from it if the UK takes a strong role in developing the technologies and systems required for producing hydrogen and the skills required to install and service these products.

Chart 13 – Potential value to UK economy from business creation (£m cumulative to 2050)



Source: Carbon Trust and Element Energy analysis

Short term business creation opportunities - "Attracting inward investment"

In general most of the value from business creation occurs well after 2020, because before this point both UK and global volumes will be too low for significant revenues and utilisation of assets will be too low for significant profit margins. However there will be a small number of significant inward investment opportunities before 2020 e.g. the global vehicle manufacturers might build a handful of FCEV production facilities in Europe to serve the early European market. The UK could credibly compete with a small number of other European countries to host one or more of these early investments and benefit from the accompanying economic activity.

The UK would need to do many things to attract this inward investment, much of which is not about technology innovation support and so is outside the scope of this report, however there are some areas where innovation support could help. Firstly there are some innovation activities which will tend to happen in and around FCEV manufacturing facilities, such as the innovations in manufacturing process and supply chain integration which lead to economies of scale as production shifts from laboratory to factory. Countries which support this type of innovation would make more attractive locations for FCEV manufacture. Secondly it seems likely that FCEV manufacturers would only choose to locate their early production facilities in a country which showed a clear commitment to being one of the first countries to have a viable FCEV market. A programme of technology innovation support, which targets the urgent improvements needed to facilitate a roll-out, would help to demonstrate this commitment[28].

The value of these early inward investments are not explicitly included in the numbers quoted in this report, and if they were they would probably seem small in the context of a total value to the UK economy from hydrogen transport, measured in tens of billions of pounds, to 2050. But when considered over the period to 2020, and in the context of likely levels of economic activity and inward investment in UK high value manufacturing over that period, these early investments could have a very valuable short term impact. Supporting inward investment in the UK automotive sector would also be consistent with recent trends[29] and industrial policy[30].

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[28] Supporting development of the skills required to facilitate a roll out will also be essential to attracting inward investment. For example the UK would need technicians and engineers with the skills required to support a hydrogen transport system, e.g. vehicle maintenance and roadside breakdown services. This need has not been analysed in this report, however given the relatively large skills gap between servicing a conventional vehicle and servicing a FCEV, and the relatively low market concentration of the vehicle servicing sector, this could be a significant challenge.

[29] For example investments in UK manufacturing of electric and hybrid vehicles in 2011 and 2012 by Nissan, Toyota, Jaguar Land Rover and BMW.

[30] For example the launch in June 2013 by UKTI and UK Automotive Council of the 'Automotive Investment Organisation' to attract inward investment to the UK automotive sector.

Long term business creation opportunities - "Exporting technology and on-shoring transport fuel production"

The technology areas with the largest potential market size in the long term are those contained within FCEV, followed by those used to produce low carbon hydrogen for those vehicles. The markets for most of these technologies do not really exist yet but the UK has a strong competitive position in many related technology areas which can be taken as indicators of the potential for future strength in these markets.

In these hydrogen for transport scenarios the biggest area of potential long term economic value is in FCEV and their components. The biggest opportunities in the FCEV specific components are in the fuel cell stack, the fuel cell periphery and drive train and the hydrogen storage. Developing strength in these FCEV specific areas would also have spill over economic benefits in the production of the non-FCEV specific vehicle components and in FCEV maintenance. The UK is one of a small number of countries responsible for a significant share of the supply chain for automotive components, and is well positioned to support that supply chain in shifting towards the components needed in new vehicle technologies, for example the UK has a relatively strong set of technology focused small and medium enterprises (SMEs), across all of the key FCEV component technology areas and world class academic research in many of the key areas. This opportunity has already been recognised in the UK industrial strategy for the automotive sector[31], which explicitly includes enhancing supply chain competitiveness, investing in innovation and technology, and fuel cell vehicles.

The next largest area of potential long term value is in the production of hydrogen from low carbon sources; principally water electrolysis and reformed hydrocarbons.

The UK strength in electrolyser technology is not as strong as that for hydrocarbon routes and a number of countries could claim greater strength, particularly through the involvement of larger companies. However the UK benefits from a legacy of effective government support for fuel cells and related technologies which has tended to focus on innovation support within SMEs and academia and has resulted in important 'world firsts' in a number of key performance dimensions. The UK hosts some electrolyser SMEs with world leading technology performance, a number of similarly impressive fuel cell companies that could potentially move into electrolysis if the market were attractive, and some world leading electrolyser and fuel cell component suppliers. Whilst few UK universities have dedicated electrolyser groups, many have world class fuel cell or electrochemistry groups, which require the same core skills, and could rapidly move into electrolysis in response to a shift in market or policy emphasis.

The most likely way for hydrocarbon routes to be a large part of the hydrogen production mix in the long term is if CCS is successful, because this will open up a scalable, low-cost, low-carbon source for hydrogen and will allow both transport and power sector demands to contribute to the economies of scale for CCS. The UK's CCS demonstration program, combined with a long and strong history in the processing of hydrocarbons, makes it credible that the UK could be one of the world leaders in CCS, and if hydrogen transport requirements are included in the early demonstration projects then a sector using CCS to produce low carbon hydrogen for transport could share in this strong position.

The other main low carbon way to make hydrogen from hydrocarbons is by reforming bioenergy sources or waste and the UK is also relatively strong in these areas. UK policy which supports the production of useful energy from bioenergy and waste is comparable with the leading countries in Europe. This has resulted in an emergent industry in the production of power, heat and transport fuel from bioenergy and waste, which could provide a strong starting point for the production of renewable hydrogen. The world's largest energy from waste plant is being built in the UK[32] and has been deliberately designed with the potential for a subsequent conversion to hydrogen from waste. The UK also contains some world leading academic groups working on low TRL methods that could be used to convert waste and bioenergy to hydrogen, such as plasma based methods and direct biological generation of hydrogen.

The largest economic value opportunity is from 'on-shoring' transport fuel production. This is a long term opportunity since it only becomes significant once the UK has a large fleet of FCEV needing refuelling. This opportunity is not dependent on strength in any particular technology area, but there would be advantages to combining a growing market for hydrogen production with a strong position in hydrogen production technologies.

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[31] The Department for Business Innovation and Skills and the UK Automotive Council, 'Driving success - a strategy for growth and sustainability in the UK automotive sector' (July 2013)

[32] Air Products is building an advanced gasification energy-from-waste plant in Teesside which will produce 50MW of electricity. Some or all of the output could be taken as hydrogen instead of electricity.

The case for UK public sector intervention

Market failures impeding innovation

System level market failures

Some of the most critical market failures impeding innovation in the technologies required for hydrogen transport are at the level of the whole hydrogen transport system, rather than within the markets for specific technologies. The principal reasons for these system level market failures are that all parts of the hydrogen transport system need to coordinate and succeed for any one part to succeed, most of the technology areas will take many years to demonstrate commercial viability, investments in technology innovation may take decades to deliver a financial return and there is no long term government commitment to ensuring a successful transition to hydrogen transport. This compounding of commercial risk, technology risk, coordination risk and policy risk affects all of the technology areas and makes it very difficult for companies to make the business case for significant investment in innovation in hydrogen technologies.

Another significant challenge faced by many of the technology areas is a first mover disadvantage for early investors. The economics will be worse for early investments in hardware than for later ones because later investors benefit from lower capital costs and better utilisation, at the same time being an early investor is unlikely to lead to any enduring commercial advantage, so there is a strong incentive for everyone to wait for someone else to go first.

The lack of either an existing hydrogen transport market or a strong indication that there will be one in the future removes the incentive to develop the skills and knowledge necessary for a strong sector. At an individual level this leads to a shortage of engineers, scientists and technicians with the necessary skills to design, build and support the technologies. At a system level this leads to a lack of appropriate regulations, codes, standards and best practice, particularly around safety and how to combine safety with practical operation and viable economics.

Finally the challenges of analysing hydrogen for transport as part of a wider energy system, which in turn sits in a wider social and economic system, make it difficult to identify, understand and quantify some potentially very significant benefits that hydrogen for transport could bring. For example, at the level of the energy system, the flexible operation of electrolysers to provide variable load, the inherent energy storage in a hydrogen distribution system, and the potential to utilise very large hydrogen assets across multiple energy sectors could bring significant cost and energy security benefits. At a wider societal level many of the benefits that hydrogen transport could bring are often not included when pathway options are evaluated, such as improvements in air quality and noise pollution, or the advantage of offering consumers multiple ULEV options with different performance characteristics, allowing them to choose the technology which provides them with the most utility. Without a better understanding of all the potential benefits that hydrogen transport could bring, and how these compare to other options, it is difficult for companies to confidently prioritise investment in technology innovation.

There are also significant technology-specific market failures and barriers to innovation which differ in the short and long term.

Market failures by technology area

Chart 14 shows the market failures and barriers to innovation, by technology area, which have the most significant impact on innovation, and whether these are likely to be short or long term issues. The market failures with the most significant impact in the short term are those impeding the innovations needed for a successful roll out before 2020; typically these are market failures causing an undervaluation of innovation in ‘lynchpin’ technologies. The market failures with the most significant impact in the long term are those impeding the innovations which will have the biggest impact on long term costs and on the long term value to the UK economy; typically these are market failures causing excessive technology and policy risk.

One feature which is common to many of the short term barriers to innovation is that many of the technologies required in the hydrogen supply infrastructure are currently at a performance or cost level which would make a successful roll-out difficult, but the volumes of these technologies needed in the first ~10 years of the roll-out are so low that companies investing in innovation to improve the technologies would be unlikely to achieve an acceptable return on their investment. At a system level investment in these innovations is justified because they unlock the value of the whole hydrogen for transport system, but the value will be captured in other sectors (e.g. FCEV components) and not by the companies that need to make the investments (e.g. compressors).

There are two barriers to innovation which are important in the long term and are common to many of the technology areas. Firstly the combination of long technology development timescales and uncertainty about future market requirements makes it very difficult to start the innovation process early enough for future technologies to be ready when they are needed. Secondly some technologies will only be needed in very low volumes even in a mature market, which makes the business case for investing in innovation in these technologies very difficult.

If the UK government[33] were to give a clear position on the future of hydrogen for transport, with long term commitments to the policies needed to deliver it, this would remove or reduce many of these barriers to innovation. Innovation support would still be needed, but in fewer areas, at lower cost and with greater impact.

Chart 14 – Table of market failures by technology area

Technology area	Extent of market failure	Barrier to innovation	Short term issue?
Production – electrolysis	Critical[34]	Hydrogen production technologies are safety critical but, in the absence of established standards, demonstration of safety for novel technologies is difficult and expensive. A long industry track record is often used by equipment buyers as a proxy for evidence of safety. This creates a barrier to entry for new companies and technologies.	Yes
		The incumbent industrial gas companies control much of the route to market and require considerable product development and de-risking before a new technology / concept can be accepted into their product mix. The significant cost of this process is a barrier to entry, particularly for technology SMEs.	Yes
		New electrolyser technologies may take decades to get from fundamental R&D to market, so the process must begin ahead of market need. Multiple uncertainties about the future will tend to cause the industry to make short term decisions with sub-optimal long term outcomes.	No
		Uncertainty in future energy system requirements, future energy policy and future competitor technology performance makes it difficult to justify and focus innovation effort (e.g. whether to prioritise flexibility, efficiency or capital cost)	No
		The economics of electrolysers are likely to be dominated by capital cost in the short term but efficiency in the long term. Initially, mature low-cost low-efficiency technologies consistently out-compete novel high-cost high-efficiency technologies, making it difficult for manufacturers of novel technologies to fund their development.	No
		The electrolyser business case is supported by providing services to the electricity grid. These services are not well characterised technically or commercially, nor is how electrolysers would compete with other service providers. The organisations best placed to improve understanding in this area (TSOs, DNOs and utilities) currently have little incentive to do so.	No
Production – low carbon reformed hydrocarbon (including purification and verification)	Critical[33]	There is currently no incentive for converting bioenergy and waste into hydrogen for transport, but there are incentives for converting bioenergy and waste into power, heat and liquid transport fuel (e.g. RO, FIT, RHI, RTFO) which distort the market.	Yes

[33] Due to the global nature of the automotive industry, a commitment to hydrogen for transport by the UK government alone would probably not be sufficient. It would need to be supported by similar commitments by other countries with large automotive sectors.

[34] Although there are critical market failures affecting both hydrogen production from water electrolysis and hydrogen production from low carbon reformed hydrocarbons, these are only assessed as critical from the perspective of the particular technology area. The impact of these market failures is less severe when considered at a system level, because there are multiple hydrogen production technology options, so it is less likely that a critical market failure in any one technology area would lead to a failure of the whole system.

Technology area	Extent of market failure	Barrier to innovation	Short term issue?
Production – low carbon reformed hydrocarbon (including purification and verification)	Critical	The uncertainty in whether CCS for power will succeed causes uncertainty in the success of CCS in other sectors including to provide hydrogen for transport	Yes
		The format of early CCS for power demonstration plants will be largely determined by the policy mechanisms that support them. Adding the export of hydrogen for transport will complicate projects (e.g. require over/under sizing of components, additional components and more complex operating and business models). This additional challenge will not be voluntarily added to a demonstration project unless it is a requirement of the support.	Yes
		The economies of scale for low carbon reformed hydrocarbon technologies favour very large plant, which tend to have multi-decade lifetimes. This creates a high barrier to entry for novel technologies and system designs.	No
		In the long term bioenergy sources and waste are likely to be resource constrained, and focussed on a small subset of all the potential end uses. Uncertainty over whether this will include hydrogen for transport makes it difficult to justify investment in innovation.	No
		There is a trade-off between the cost of hydrogen purification and verification and the cost of FCEV durability. Coordination between sectors will be required to agree standards which optimally balance these costs, and to develop methods to achieve the standard. No such coordination body exists.	No
		In the long term purity verification markets may be served by a small number of very high throughput products, e.g. the UK may need less than 5 units. The low volumes weaken the business case for developing this product, and reduce the opportunity for volume driven learning effects.	No
Distribution	Significant	The sunk cost in the large existing stock of 200bar steel cylinders for distribution of hydrogen in other sectors will act as a barrier to entry for novel distribution methods (higher pressures, high capacity tube trailers, composites, solid state storage)	No
		At very high volumes hydrogen pipelines become more economic than distribution by vehicle. The high initial cost and long lifetime of pipeline assets mean that investment is only possible once future demand is very certain. It is likely that by the time this certainty is achieved the sunk cost of investment in other distribution methods will delay/prevent investment in pipelines.	No
Refuelling stations	Significant (but critical in the short term)	The very high pressures (>700bar) required by FCEV standards cannot be met with off-the-shelf compressors. Different materials and novel designs are required. This combined with low initial volumes leads to bespoke systems, which are immature and have tended to be a common point of failure. Improved reliability is critical to a successful roll-out but low initial volumes make the business case for investment difficult.	Yes
		There is a first mover disadvantage for early purchasers of hardware. Initial installations are essential to start the market but will probably be loss making. Subsequent installers benefit from higher utilisations and lower product costs. Advantages of the later market are shared by all and no sustainable advantage accrues from being a first mover.	Yes
		Early HRS will be loss making, which drives selection of cheapest equipment in the short term rather than equipment which could be cheaper in the long term if supported now.	Yes
		The standardisation around 700bar (for vehicle range reasons) causes a significant increase in the cost of early HRS and hence the cost of roll-out.	Yes

Technology area	Extent of market failure	Barrier to innovation	Short term issue?
Refuelling stations	Significant (but critical in the short term)	Each HRS may only need 1 or a few units for many of the technologies contained (e.g. static H_2 stores, compressors, dispensers, meters) and the UK may only need high tens /low hundreds of HRS before 2020. Very low initial volumes make the business case for rapid innovation programs to support a successful roll-out particularly difficult.	Yes
		There are currently very few HRS in the UK, they tend to have high availability requirements, and their various components need careful integration. This makes it very difficult for equipment developers to find sites to field trial new products.	Yes
		Long term cost reductions are possible through better integration of technologies and development of standardised designs. There is currently little incentive for competing providers of HRS to accelerate this process by coordinating to share learning.	No
		In the long term standardisation around 700bar could act as a barrier to novel storage methods at lower pressures.	No
		A requirement for very high safety levels combined with very limited knowledge and experience leads to over-engineered 'gold plated' safety systems in HRS, (a similar situation to FCEV maintenance facilities). Rationalising this through improved codes and standards and establishing best practice could significantly reduce the cost and operational impact of safety compliance. This will require the coordination of many bodies with conflicting interests.	No
Vehicles	Critical	Uncertainty in future demand for FCEV makes it difficult to invest in innovations in manufacturing process and supply chain integration that will deliver the economies of scale as vehicle production moves from laboratory to factory	Yes
		Vehicles have particularly long development timelines, with the design of core components (e.g. the fuel cell stack) 'frozen' long before the final product comes to market. This delayed payback can cause cash flow problems and, if high discount rates are used, can significantly reduce the return on investment from innovation. This can be a particular problem for innovative technology SMEs with a high cost of capital and limited cash reserves.	No
		To rapidly deliver cost reductions in fuel cell stacks FCEV manufacturers need to start developing second and third generation stacks before the market for the first generation has been proven	No
		Standardisation around 700bar will make it more difficult to invest in innovation in novel lower pressure storage technologies (e.g. hybrid pressurised solid state), which could be lower cost and more conformable	No
		There is considerable scope for innovation in the technology, facilities and methods for FCEV maintenance. As with HRS, there is a tendency to 'gold-plate' safety and little incentive for competing providers to coordinate to rationalise safety systems and establish industry best practice	No

Source: Carbon Trust and Element Energy analysis

Production

There are critical market failures impeding innovation in hydrogen production technologies. The route to market for hydrogen production technologies is largely controlled by the incumbent industrial gases companies who require significant product development and de-risking before accepting a new technology into their portfolio and have little incentive to support new entrant competitors in doing this. Hydrogen production is a safety critical technology area and is very immature in transport applications; in the absence of established standards and best practice a long track record is used as a proxy for evidence of safety, which creates a barrier to entry.

Within electrolysers, early distributed production installations tend to be loss-making and so products with the lowest capital cost in the short term are preferred by installers. Mature electrolyser technologies consistently outcompete novel technologies in this situation. This deprives the newer electrolyser technologies, which might be lower cost in the long term, of the early volumes which could support innovation and product development. In addition long development times and uncertainty about the future needs of the electricity system, in particular electricity prices and the market for balancing services, makes it very difficult to prioritise which aspects of electrolyser technology to improve.

Within hydrocarbon routes, most production assets are large and have long lifetimes, which makes it difficult to develop and sell new technologies. The format of early CCS plant will be largely determined by the policy supporting them and producing hydrogen for transport will not be included in the design unless the policy encourages it. Uncertainty about the future success of CCS reduces the ability to invest in innovation in both competing and complementary technologies. There are effective incentives for producing power, heat and liquid fuels from bioenergy and waste[35], but not for producing hydrogen for transport. These incentives have supported innovation in bioenergy and waste technologies, some of which would also be helpful for producing hydrogen from the same resources (e.g. advanced gasification), but these same incentives also make it very unlikely that companies will choose to produce hydrogen for transport instead of the incentivised outputs. So developing the specific technologies required to convert bioenergy and waste into hydrogen for transport is not being prioritised.

Any hydrogen produced for use in FCEV will need to by purified to a very high level[36] and have that purity verified. Purification is mainly an issue for hydrocarbon reforming which tends to produce hydrogen with higher levels of contaminants. Water electrolysis tends to produce very pure hydrogen, with little or no purification normally required, however contamination is possible so verification of purity is still important. There are market failures impeding innovation in both the development of high-volume low-cost methods and in the coordination between sectors to develop optimal standards. The simplest way to drive cost reductions in purity verification will be economies of scale with very high throughput equipment. The resulting high market concentration would lead to very low volumes of equipment; the whole of the transport market could potentially be served by one very high throughput piece of purity verification equipment. These low product volumes make it unattractive for companies to invest in innovation. There is a trade-off in hydrogen purity between the cost of the vehicle and the cost of the hydrogen supply chain; and the companies in these sectors tend to be different (e.g. vehicle manufacturers tend not to produce fuel or own refuelling stations). So a change that reduces costs for one group of companies might increase costs for another group. This makes it difficult to coordinate across sectors to agree standards for purification and verification which would have the least overall cost at a system level.

Distribution

There are significant market failures impeding innovation in hydrogen distribution technologies. Compared to the volumes of hydrogen for transport distributed in the early years of the market, the existing capacity of low pressure hydrogen distribution assets in the industrial gasses sector will be significant. The sunk costs in these assets will create a barrier to investment in higher pressure and novel technology distribution assets. In the longer term this barrier will reduce as the distribution volumes required for transport exceed the existing capacity and the business case for higher capacity assets becomes more compelling.

Pipelines become more economic than distribution by vehicle at high volumes, and yet without high certainty in future volumes widespread investment in hydrogen pipelines will be very difficult. Smaller investments in individual distribution vehicles are much lower risk, and so may continue to be preferred after the point when a pipeline would be more economic. The sunk cost of these distribution vehicle assets then further reduces the attractiveness of investing in pipelines.

Refuelling

There are significant market failures impeding innovation in hydrogen refuelling station technologies, and these could have a critical impact on innovation in the short term. For many of the required technologies only one or a handful of units will be required per refuelling station. This implies only tens or low hundreds of units in the first decade of the roll-out and only a few thousand even in a mature market. These low volumes make the business case for investing in innovation

[35] For example the Renewables Obligation (RO), Feed In Tariff (FIT), Renewable Heat Incentive (RHI), and the Renewable Transport Fuels Obligation (RTFO).

[36] For example the limit for many contaminants is in low parts per million, and for sulphur compounds the limit is in low parts per billion. For further information see: Draft International Standard ISO/DIS 14687-2 ‘Hydrogen Fuel – Product Specifications - Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles’.

unattractive, particularly for the innovations needed urgently in the short term to facilitate a successful roll-out. Another problem of the early years is that low volumes of vehicles mean that early refuelling stations will have very low utilisations. This causes a ‘first mover disadvantage’ where the economics for early refuelling stations are far worse than for later ones, and the benefits from the existence of these early stations are shared across the hydrogen for transport system, with no opportunity for the early entrants to capture a sustainable competitive advantage from taking a pioneering market position.

When novel refuelling stations components are being developed it can be very difficult to find trial sites to test and demonstrate them. Very few hydrogen refuelling stations exist, so there is a significant opportunity cost to taking one out of action whilst a new component is installed and tested. Technology SMEs often depend on the larger companies that run refuelling stations to provide access, which can be a significant barrier.

There is a significant opportunity for cost reduction through shared learning and best practice from early refuelling stations, particularly on stations designs, safety engineering and permissions, but this will require the cooperation of many bodies, some of whom have conflicting interests.

Vehicles

There are critical market failures impeding innovation in FCEV technologies. The FCEV themselves contribute by far the largest part of the TCO of hydrogen transport, and also the largest cost reduction and business value creation opportunities. However the biggest opportunities for long term cost reduction in FCEV components come from expensive investments that will only deliver value many years in the future once the market is much larger. This makes it very hard to make the investments now when there is such high uncertainty about the future market size. To rapidly deliver the cost reductions necessary for FCEV to compete with other vehicle technologies, the development of second and third generation vehicles needs to begin before the market for first generation vehicles has been proven. Vehicles have long development timescales and the investment in innovation at the component level needs to happen long before the vehicle the component is part of starts selling. This delayed return on investment and hiatus in cash flow can be difficult to manage, particularly if the component level innovation happens within SMEs.

Standardisation across the industry will help to accelerate cost reductions by increasing economies of scale and reducing transaction costs, but standardisation can also be a barrier to innovation by increasing the cost of integrating innovations that are incompatible with those standards. For example standardisation around 700bar on vehicle storage will make it harder to develop novel storage technologies which might be incompatible with a 700bar refuelling infrastructure.

Maintenance facilities for FCEV have some issues in common with refuelling stations such as the benefits and challenges of coordination in the early years to standardise and share learning. Early maintenance facilities will be very expensive, for example due to over-engineering of safety systems; and the low early volumes shared between multiple providers could make improvements slow. Cooperation between competitors and with official bodies could accelerate cost reduction but will be difficult without public sector support.

In most cases the UK could rely on others, but this would put the 'Green Growth' opportunity at risk

Chart 15 shows that the UK could rely on others for almost all areas of innovation in hydrogen transport; the UK's hydrogen transport needs are not particularly unusual. Most of the products will be designed and built for global markets, using global standards, as they are for conventional vehicles and their refuelling infrastructure. Also the products will generally be required in the UK at about the same time as in other countries.

The main exceptions to this are that the UK is likely to be one of the faster movers in offshore wind and CCS deployment, which will have an impact on the UK innovation needs for hydrogen production technologies. The UK will be one of the first to need extensive balancing for offshore wind generation, which will provide an opportunity for flexible electrolysis, and one of the first to need CCS plant that can provide both power for electricity demands and hydrogen for transport.

If the UK relies on others to deliver the innovation required in a particular technology this tends to result in the UK holding less of the intellectual property in that technology and taking a weaker market position. The UK is currently in a relatively strong competitive position in the technology areas with the highest potential for economic value (e.g. FCEV and hydrogen production). Relying on other countries to deliver the innovation in these technologies would put that strong competitive position and the long term economic value available to the UK at risk.

Some of the technology areas provide relatively little opportunity for long term economic value for the UK (e.g. distribution and refuelling). Relying on others to deliver innovation in these areas might be a sensible prioritisation in the long term. However relying on others to deliver innovation in any of the technology areas might put the short term economic benefits to the UK at risk.

Some innovation will be required in all technology areas to allow a complete working hydrogen for transport system and a successful role out. It would be very difficult for the UK to rely on others to deliver some of this innovation and still commit to being one of the first countries to roll-out hydrogen for transport. It is more likely that choosing to rely on others in some areas would result in a 'wait and see' policy where the technologies needed for hydrogen transport are demonstrated and rolled out in other countries first, then, if successful, rolled out in the UK once solutions for most of the initial challenges have been found. This would make the UK a follower not a leader, which would have consequences for both the short and long term economic value available.

In the short term, attracting the relatively large early investments in manufacturing capacity to the UK is not consistent with a 'wait and see' policy. The global companies making the investment decisions are far more likely to select a country that has wholeheartedly committed to supporting all aspects of the supply chain and market necessary to ensure a successful roll-out. Once the initial round of investments in manufacturing capacity have been made it may be many years before additional investments in further countries are necessary.

In the longer term it may be difficult to overcome the first mover advantage of the countries that chose to go first. The UK currently enjoys relatively strong competitive advantage in the supply chains of global automotive OEMs. As the global automotive industry shifts from current technologies to future technologies, the UK risks seeing that advantage eroded if it is not one of the leading countries in the new technologies. Codes, standards, and norms developed in the early years of an industry can shape its long term direction and they tend to favour the companies and countries involved during their development. If the UK chooses a 'wait and see' policy on hydrogen for transport it risks entering the market once it has been shaped in a way which does not favour the UK's strengths.

Chart 15 – Opportunity to rely on other countries to deliver innovations

Technology area	Innovation need	Are the UK innovation needs similar to those of rest of world?	Will another sector need the technology and drive innovation?	Will another gov't need the innovation before the UK and drive the innovation?	Can UK rely on someone else to drive innovation value?
Production - electrolysis	▪ Demonstrate low carbon hydrogen from electrolysis ▪ Improve efficiency, flexibility, capital cost and durability	**Yes**	**No**: whilst industrial markets exist, they do not have the same requirement for efficiency, low cost and rapid response as the needs for fuelling stations	**Partially**: the UK has a synchronous need for improved efficiencies and responsive electrolysis with other early adopters.	**Partially**: the UK is one of a number of early adopters requiring innovation in electrolysers
Production - low carbon reformed hydrocarbons	▪ Demonstrate 'brown hydrogen' production is ready for roll-out ▪ Demonstrate low carbon production from CCS and from bio/waste ▪ Improve purification, verification and reforming ▪ Optimise plant design and business models	**Partially:** the UK is one of the leaders in CCS. Other early FCEV markets e.g. Germany have rejected the CCS route	**Partially**: CCS, gasification and reforming are all required by other sectors (power generation, waste disposal, oil refining). However the purification and verification required is particular to fuel cell applications.	**No (for CCS derived H_2)**: the UK aims to be one of the first adopters of CCS technology	**No**: the CCS and bio-routes are likely to be required in the UK before or at the same time as other early adopters.
Distribution	▪ Improve materials, compressors and operating concepts for tube trailers and pipelines	**Yes**	**No**: the innovation requirements are specific to hydrogen transport. Distribution of industrial gases may benefit from but will not drive this innovation.	**Partially**: the UK has a synchronous need for lower cost distribution with other early adopters.	**Partially**: the UK has the same needs for improved distribution systems as the other early adopters
Refuelling stations	▪ Achieve and demonstrate 'roll-out ready' HRS ▪ Improve compressor reliability and maintenance costs ▪ Improve dispenser meter accuracy ▪ Faster hydrogen delivery ▪ Optimise HRS design ▪ Standardise HRS components	**Yes**	**No**: the main innovations required are specific to hydrogen transport. Some learning available from CNG station designs and components.	**Yes (for core forecourt technology)**: Other countries, notably Germany (through the CEP), Japan and the US are already active in programs to improve the ease of integration into forecourts. UK codes, standards and safety norms will still need development	**Partially**: much of the innovation in fuelling stations is being carried out outside of the UK. However, if the UK is to be a early adopter, these technologies are required at the same time as other early adopters.
Vehicles	▪ Industrialise initial FCEV volume manufacturing processes ▪ Improved fuel cell systems, on-board storage and contaminant tolerance ▪ Standardise maintenance facilities and regimes ▪ Rationalise FCEV safety engineering	**Yes**	**No**: the automotive fuel cell requirements are unique. Some benefit from developments in other automotive technologies (e.g. electric drivetrains) and other markets (e.g. fuel cell combined heat and power)	**Yes**: the host nations for the large auto OEM's, have the greatest motivation to fund FCEV innovations (at the vehicle level).	**Partially**: the UK is one of a limited number of early adopter countries, that will need to synchronise deployment to ensure sufficient volumes for OEM's to produce affordable FCEV

Source: Carbon Trust and Element Energy analysis

Potential priorities to deliver the greatest benefit to the UK

Chart 16 shows the benefit of UK public sector support in hydrogen transport technologies by technology area[37]. However the UK has two critical decisions to make before innovation support for hydrogen transport technologies can be prioritised: 1) whether hydrogen technologies should be a significant part of the UK transport mix and 2) whether the UK should be one of the first countries to roll-out hydrogen for transport. The UK H_2 Mobility project, which includes three government departments[38], will play a large role in helping UK government to make these decisions. Decisions within other parts of the energy system (e.g. decarbonisation of power and heat) could also have a significant impact on the role of hydrogen in transport.

If hydrogen technologies are to be a significant part of the UK transport mix then there is very large, long-term opportunity for the UK to capture economic value and help drive down costs by supporting technology innovation. The largest opportunities in this analysis are in the components of FCEV (in particular the fuel cell stack, fuel cell periphery and drive train, and hydrogen storage) and in their integration with the rest of the vehicle.

The next largest long term opportunities are in hydrogen production technologies. The scenarios in this report have the UK producing hydrogen for transport at a rate of around 1-2 million tonnes per year in 2050. At such volumes there is a significant economic benefit from identifying the optimal hydrogen productions methods and focussing innovation support on these to deliver as much cost reduction as possible. However the relative importance of the different hydrogen production technologies is intimately linked to the future of the UK electricity system and is currently difficult to predict.

The scenarios in this report suggest an important decision point around 2025, when the requirements of hydrogen transport and of the rest of the energy system should become more certain, for example at around this point the UK may need to start building large centralised production facilities for low carbon hydrogen. Before this decision point innovation support should focus on developing multiple technology options, particularly for hydrogen production, some of which may be subsequently selected for later stage support to convert them into high volume capabilities[39].

In order to make informed decisions about the long term role of CCS in the production of hydrogen for transport, this technology needs to be one of the options being developed ahead of the ~2025 decision point. Due to the likely timelines for the first demonstrations of CCS for power, this suggests that a demonstration of the production of hydrogen for transport needs to be included in one of the first few CCS demonstrations. In principle this could be achieved with any type of CCS, but in practice it will probably be easiest to achieve before 2025 with a pre-combustion CCS demonstration.

One of the largest long term opportunities for economic growth comes from ‘on-shoring’ transport fuel production, i.e. shifting from importing oil to producing hydrogen transport fuel in the UK, from UK primary energy sources. This ‘on-shoring’ opportunity is not dependent on a strong competitive position in hydrogen production technologies, the UK could import the production technologies and still benefit from producing its own fuel, but there would be advantages to supporting both the supply and demand sides of this transition.

If the UK is to be one of the first countries to roll-out hydrogen transport then there will be additional priorities. A successful roll-out is dependent on having a full working hydrogen transport system and certain key technologies, particularly within refuelling stations, still have performance and cost levels which would make a roll-out difficult. These issues are likely to be resolved within the next few years, whether or not the UK supports innovation in this area, but it would be a high risk strategy to be one of the first countries to roll-out hydrogen for transport whilst relying on other countries to deliver these innovations.

There may be additional short term economic benefits to being one of the first to roll-out hydrogen transport, and supporting this decision with an innovation support program focussed on the short term needs, which would increase the likelihood of a successful roll-out and of achieving the anticipated early cost reductions that come with economies of scale. This could make the UK a more attractive place for global vehicle OEMs to locate their early FCEV production facilities.

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[37] It should be remembered that there are other hydrogen technologies, which have been excluded from the scope of this analysis and therefore from the recommendations for support, but which may still be worth supporting. For example other hydrogen vehicle technologies (e.g. ICE, micro-turbines), low TRL hydrogen production methods, and hydrogen technologies unrelated to transport applications.

[38] The Department for Business, Innovation and Skills (BIS) the Department for Transport (DfT), and the Department for Energy and Climate Change (DECC). See www.ukh2mobility.co.uk

[39] Though outside the scope of this analysis, it seems logical that work to develop technology options should be complemented by work to improve the UK’s ability to value those options, part of which will be energy system modelling, demonstrations and other work that prepares the UK to make the strategic energy infrastructure investment decisions which will be required.

Chart 16 – Benefit of UK public sector activity by technology area

Technology area	Value in meeting emissions targets at lowest cost M (H1 ; H2)	Value in business creation M[40] (H1 ; H2)	Extent of market failure	Opportunity to rely on others	Improvement required by ~2020	Benefit of UK public sector activity/investment (<u>without</u> considering costs)
Production - electrolysis	£3.6bn (£4.1bn ; £8.9bn)	£0.6bn (£0.8bn ; £1.5bn)	Critical	Partial	Low	MEDIUM/HIGH High if pre-combustion CCS **is not** available as a source of hydrogen
Production - hydrocarbons[41]	£0.01bn (£0.7bn ; £0.02bn)	£0.04bn (£0.9bn ; £0.1bn)	Critical	No	Low	MEDIUM High if pre-combustion CCS **is** available as a source of hydrogen
Distribution	£0.9bn (£2.4bn ; £2.3bn)	£0.1bn (£0.4bn ; £0.4bn)	Significant	Partial	Low	LOW Long term value from this sector is comparatively low, and technology is ready for roll-out already.
Refuelling stations	£0.9bn (£2.3bn ; £2.3bn)	£0.3bn (£0.6bn ; £0.6bn)	Significant (critical in short term)	Partial	High	MEDIUM High in the short term. Long term value from this sector is comparatively low, but urgent interventions are necessary to unlock the value in the entire system
Vehicles	£27.1bn (£66.0bn ; £67.1bn)	£9.2bn (£23.0bn ; £23.0bn)	Critical	Partial	Medium	HIGH Significant opportunity to reduce costs and capture value in the short and long term

Benefit of UK public sector activity/investment	
	High
	Medium
	Low

Source: Carbon Trust and Element Energy analysis

[40] The 'Value in business creation' does not include the value of 'on-shoring' transport fuel production, which could be worth an additional £9-23bn to 2050

[41] The 'value in meeting emissions targets at lowest cost' calculated for hydrogen from CCS within 'Production -hydrocarbons' is just that attributed to producing hydrogen for transport, i.e. it is additional to the value for CCS calculated in the CCS in the Power Sector TINA.

Existing innovation support

There are already a number of publically funded UK programmes supporting the innovation needs identified in this report. These current programmes build on a history of support in hydrogen and fuel cell technologies, e.g. between 2009 and 2013 funding from IUK and DECC in hydrogen and fuel cells has reached £41m, and by attracting industry funding this has supported programmes with a value of £85m. Indeed one of the reasons for the UKs relatively strong competitive position in hydrogen transport technologies is that the UK benefits from a legacy of well-targeted and effective innovation support in this area. However the existing support programmes will not be sufficient to deliver all of the improvement assumed in the scenarios used in this report.

IUK, in conjunction with DECC and EPSRC, are supporting a number of targeted projects, often resulting in collaboration between SMEs, large corporates and academia, which have a good coverage of hydrogen transport issues.

- The collaborative R&D programme "Fuel Cells and Hydrogen Whole System Integration" combines £9m of grant funding with £10m of industry funding to support 5 projects which all explore the technology integration challenges of using renewable energy to provide hydrogen for transport, particularly via electrolysis.
- The collaborative R&D programme "Unlocking the hydrogen energy market" provides up to £6m supporting projects aimed at overcoming barriers to the deployment of hydrogen technologies. Though broader in scope than just transport applications many of the suggested topics are related to transport, in particular refuelling infrastructure.
- The collaborative R&D programme "Building fuel cell manufacturing and the supply chain" provides around £1m for feasibility studies. This will help with the challenges identified in this report around industrialising and scaling up of manufacturing. The follow-on "Fuel Cell Manufacturing" collaborative R&D competition provides up to a further £5m to continue developing this theme.

This is in addition to far larger programmes, run by IUK in conjunction with the Office for Low Emission Vehicles (OLEV), which support innovation in low carbon vehicles more generally. For example the Low Carbon Vehicles Innovation Platform has invested £350m between 2007 and 2013. To date very little of this has supported hydrogen transport, but it could potentially in future.

The Carbon Trust in conjunction with DECC is supporting the Polymer Fuel Cell Challenge (PFCC). This programme has identified the fuel cell stack as a key area for accelerating long term cost reductions in FCEV. About £6.4m is being invested in four technologies which have the potential to deliver step change cost reductions in future generations of FCEV. The far-sighted ambition and narrow focus of the programme have created opportunities for UK technology SMEs to develop world leading FCEV components. A similar approach might be effective in other priority areas of hydrogen transport.

There is significant public sector funding for innovation in CCS technologies, however the vast majority of this is not directly relevant to using CCS to provide hydrogen for transport. Some projects could have indirect benefits for transport applications, particularly those related to pre-combustion CCS and the challenges of handling, storing and using hydrogen. ETI has a number of projects related to this areas including investigating using hydrogen as an energy vector and for flexible low-carbon power generation.

Research council funding supports a wide range of primary academic research on hydrogen and fuel cells in universities across the UK. A large portion of this work is prominently led by a small number of SUPERGEN programmes[42], and 'Challenge Calls' related to these programmes[43]. These SUPERGEN programmes bring a cluster of leading universities together around multi-year funding for a set of targeted research priorities and they build upon previous similarly dimensioned programmes[44] that have been running continuously since 2008. The research supported by these various SUPERGEN programmes relate to most if not all of the innovation needs highlighted in this report, although typically at the fundamental research, low TRL level.

The European Fuel Cell and Hydrogen Joint Undertaking, is a large pan European programme that has invested about €470m in hydrogen and fuel cell innovation between 2008 and 2013. Just under half of this was directly relevant to hydrogen transport, with around a third spent on 'Transportation and Refuelling Infrastructure' and around a further 10% spent on 'Hydrogen Production and Distribution'. The funding criteria of the programme promote international collaboration as well as collaboration between industry and academia. Most of the UK companies developing hydrogen transport

[42] For example the Hydrogen and Fuel Cells SUPERGEN (£5m, 2012-17), the Fuel Cells SUPERGEN (£3.6m, 2009-14), and the Biological Fuel Cells SUPERGEN (£3.3m, 2010-14)

[43] For example the August 2012 SUPERGEN Hydrogen and Fuel Cell Challenge (£5m, over 4 years) which is supporting 5 projects, 4 of which are relevant to hydrogen transport and the August 2013 SUPERGEN Hydrogen Challenge Call (£2m) which is inviting applications in 'Storage solutions', 'Purity assurance', and 'Whole system value'

[44] For example SUPERGEN XIV – Delivery of Sustainable Hydrogen (£5m 2008-13) and the UK Sustainable Hydrogen Energy Consortium SUPERGEN (£6m, 2007-12)

technologies are involved in at least one project within the programme and the UK is reasonably successful at competing with other European countries for the programme's funds.

Potential priorities for public sector innovation support

Chart 17 identifies the innovation priorities for support within each technology area, details the current activities, proposes potential further activities, comments on whether the activity would be particularly important should the UK be one of the first to roll-out ('Benefit for early roll-out') and gives an indicative scale for the public funding required for the proposed additional activities.

The two main priorities for the short term are to improve the likelihood of a successful roll-out before 2020 and of the UK attracting early inward investment; demonstrating one or more paths towards hydrogen production with near zero GHG emissions would also be helpful. Across the hydrogen transport system, but particularly in the refuelling infrastructure, innovation programmes that could rapidly reduce costs, improve performance, and demonstrate that the whole system is ready for roll out should be high priorities in the short term; the focus should be on 'quick wins' to deliver 'good enough' cost and performance rather than innovations that would deliver more significant but longer term improvements.

One approach might be to reduce the costs and other barriers for testing and demonstrating new technologies, e.g. a hydrogen refuelling station test facility. This might lower the barriers to entry for new technologies and shorten development cycles, accelerating the move towards more affordable and better performing refuelling infrastructure. This early support may seem expensive, relative to the long term benefits innovation can deliver within these particular technologies, but it would be cheap compared to the long term benefits it could unlock in other parts of the hydrogen transport system.

Early support for innovation to deliver a complete and fit-for-purpose hydrogen supply chain would also demonstrate commitment to a successful roll-out before 2020 which would help to make the UK a much more attractive place for early large capital investments in manufacturing capacity. This could be built upon by also supporting the types of innovation that tend to occur within and around these factories, such as process innovation around scale-up.

Lastly demonstrating the production of hydrogen for transport applications, from electrolysers powered by renewable electricity and from low carbon reformed hydrocarbons would also help in the short term by proving that hydrogen provides a pathway to ultra-low emission transport.

In the early years, facilities providing hydrogen from low carbon reformed hydrocarbons (e.g. gasification of bioenergy sources and waste, or pre-combustion CCS with fossil fuels or biofuel) will be primarily built to deliver power and heat rather than hydrogen for transport, and so will the initial large demonstrations of these technologies. These facilities have high economies of scale, so they tend to be large and require a high and dependable demand for their output. The low volumes and high uncertainty that hydrogen for transport will offer in the early years will not be compatible with this, so early demonstrations of dedicated facilities providing hydrogen only for transport are very unlikely. To reduce costs, improve utilisation, and spread risk, the demonstration of providing hydrogen for transport from these technologies should be integrated into larger demonstrations where the assets are primarily providing energy into other markets. If the transport technology is FCEV then this integration will probably entail including additional purification and verification technologies in the demonstration.

In the longer term the priorities for the UK across all hydrogen technologies are cost reduction and market share. Innovation should also be supported where the long term opportunities for cost reduction and for economic value to the UK are highest, i.e. hydrogen production technologies and the novel components within fuel cell vehicles. To make best use of limited resources, support should focus on the earlier stage technologies, which are still many years from being commercially ready but which could potentially offer significant long-term improvements in cost and performance. Support should initially aim to deliver proof of concept for step change improvements at the component or subsystem level, and then begin to explore how these improvements would be incorporated into products and industrialised. This will be a mixture of industrial R&D, typically conducted by technology SMEs and research departments of large corporates, which might reach the market around 2020-30, and basic R&D, typically conducted in universities, which might not reach the market until after 2030. Supporting technologies at this earlier stage is relatively cheap and by targeting the innovations with the potential to have the largest impacts the UK can maximise the likelihood of developing world beating technologies in specific areas and using these to develop or maintain strong positions in the most attractive markets.

However another feature of supporting early stage technologies is that the risks are higher; there is more chance that the technology will not work (technology risk) or that the needs of the market and energy system will have changed by the time the product is ready (market/system risk). The latter challenge is particularly acute for vehicles and hydrogen production technologies because their development timescales are long and the energy system they will operate within is likely to change dramatically during that development period. Therefore multiple different technology innovations should be initially supported within these priority areas, so that options are available to be selected for more significant support in later decades.

The point in time when innovation support will need to shift from light support for many early technology options to more significant support for a handful of technologies is not precise and will differ by technology area. However it is clear that there will be some changes between 2020 and 2030 which will be critical for hydrogen transport; this report uses ~2025 as an indicative transition point. At around this time certain key things will become much clearer such as: the extent to which CCS will be able to decarbonise the energy system, the amount of value flexible loads like electrolysis can capture by providing balancing for the variable output from renewable generation, and the relative demand for each of the competing options for ULEV (including FCEV).

The area where this opportunity to phase innovation support is most pronounced is in low-carbon hydrogen production technologies. The cheapest way to produce very large volumes of hydrogen for transport will probably be through large centralised production facilities. In general the technologies required to achieve this do not exist yet at the scale required, if at all. The final stages of innovation support for large assets like this, e.g. large-scale demonstrations, tend to be orders of magnitude more expensive than the earlier stages. To reduce the cost to the public sector the most expensive stages of innovation support for large-scale centralised hydrogen production should be deferred until around 2025 when it should be much clearer whether very large volumes of hydrogen will be required for transport and which hydrogen production technologies are most appropriate. Before around 2025 innovation support in hydrogen production technologies should focus on preparing the UK for that decision point by developing technology options and ways to evaluate those options.

Even if it becomes clear, at some point in the future, that hydrogen is not going to be a viable mass market solution for transport in the UK, the innovation support given to hydrogen transport technologies up to that point is unlikely to be entirely wasted. Hydrogen transport may still be the preferred ULEV option in other countries, so the UK could still benefit from a strong competitive position in the technologies. More broadly transport is just one of many parts of the UK energy system where the optimum future technology mix is unclear and where hydrogen could have an important role. Much of the learning in hydrogen transport technologies would also have value in other hydrogen sectors. Since hydrogen technologies could have an important role in decarbonising so many parts of the UK energy system, supporting hydrogen broadly at this early stage provides a platform of hydrogen technology options as an ‘insurance policy’ against underperformance by other low carbon technologies.

Chart 17 – Potential priorities for support by technology area

Technology Area	Innovation need	Current activities	Potential future activities	Benefit for early roll-out	Indicative scale of public funding
Production – electrolysers	Demonstrate viable path to low carbon hydrogen from electrolysis	• IUK/DECC Collaborative R&D programme – "FC&H Whole system integration"	• Additional demonstration needs to be determined when IUK/DECC programme is complete.	Med	High hundreds of thousands to low millions of pounds
	Electrolysis with improved key characteristics: • Efficiency • Flexibility • Capital cost • Durability	• EPSRC SUPERGEN programmes and other academic research	• Increased funding for basic and industrial R&D to demonstrate proof of concept for step-change improvements • Flexibility projects should include analysis of electricity grid requirements, business models, incentives, and regulation ***(Large-scale demonstration can wait until ~2025)***[45]	No	Low millions of pounds
Production – low carbon reformed hydrocarbon **(Including purification and verification)**	Demonstrate 'brown hydrogen' production is ready for roll-out: • Purity • Reliability • Durability • Scalability		• Demonstration of hydrogen supply chain from SMR to HRS with monitoring of quality throughout (leverage existing demonstration programs, add further monitoring and analysis)	High	Tens to hundreds of thousands of pounds
	Demonstrate viable path to production from low carbon reformed hydrocarbon using: • Pre-combustion CCS • Bioenergy • Waste		• Demonstration of partial export of hydrogen stream, with any additional purification, verification etc. required, and use in FCEV (potentially with international collaboration) • FEED study, build and demonstrate • Further analysis of how to optimise plant design, operation and business models with multiple outputs	Med	Millions of pounds

[45] Many of the innovation activities for hydrogen production are to deliver cost reductions at high hydrogen volumes. Some of these innovation activities would end with a demonstration at scale which would be significantly more expensive than the earlier R&D stages. Some or all of these expensive demonstrations may not be necessary. If CCS is not successful, then demonstration of large-scale hydrogen from CCS technologies will not be possible. If CCS is successful then demonstration of large-scale electrolysers may not be necessary. If FCEV deployment is not successful then no demonstration of large-scale production methods will be necessary. The likely timescales for CCS and FCEV deployment mean that the decisions on these large-scale demonstrations can be made around 2025.

	Hydrogen from low carbon reformed hydrocarbons with improved key characteristics: • Improved purification • Cheaper, high throughput purity verification • Improved reforming efficiency and yield • Optimised plant design and business models	• EPSRC SUPERGEN Hydrogen Challenge Call Aug 2013 includes 'Purity assurance'	• Increased funding for basic and industrial R&D to demonstrate proof of concept for step-change improvements • Efforts focussed on requirements for transport, but also integration with existing plant serving other sectors ***(Large-scale demonstration can wait until ~2025)***	No	Low millions of pounds
Distribution	Improve materials and operating concepts for tube trailers and their compressors	• EPSRC SUPERGEN Hydrogen Challenge Call Aug 2013 includes 'Storage solutions'	• Increased funding for basic and industrial R&D *(Overlap with R&D for compressors and storage in other technology areas)*	No	Low millions of pounds
	Improve materials, operating concepts for hydrogen pipelines and their compressors		• Increased funding for basic and industrial R&D *(Overlap with R&D for compressors in other technology areas)*	No	Low millions of pounds
Refuelling Station (HRS)	Achieve and demonstrate 'roll-out ready' HRS	• A small number of refuelling stations exist and are gathering data	• Support for rapid RD&D to accelerate incremental improvements and help a successful roll-out. • Coordination to agree an 'early best practice' HRS design for the first tens of stations (international coordination useful)	High	Tens of millions of pounds Tens to hundreds of thousands of pounds
	Improve compressor reliability and maintenance costs		• Support for rapid R&D to help a successful roll-out	High	Low millions of pounds
	Improve dispenser meter accuracy		• Support for rapid R&D to help a successful roll-out	High	Low millions of pounds
	Faster hydrogen delivery		• Innovation challenges for technology and concept innovation	No	Millions of pounds

	Optimise HRS design		• Coordination of competing HRS designers to accelerate established best practice on optimised HRS design (international coordination useful)	No	High hundreds of thousands of pounds
	Standardise HRS components		• Coordination of competing HRS designers to agree standard specifications for HRS components (international coordination essential)	No	Low millions of pounds
Vehicles	Industrialise initial FCEV volume manufacturing processes	• IUK collaborative R&D programme – “Building fuel cell manufacturing and the supply chain”	• Support for R&D and partnership development • Both operational and technology innovation • Part of a strategy to capture early OEM investment in manufacturing capacity	Med	Low millions of pounds
	Fuel cell systems with improved key characteristics: • Cost • Durability • Efficiency • Size and weight	• Carbon Trust Polymer Fuel Cell Challenge • IUK collaborative R&D programme – “Building fuel cell manufacturing and the supply chain”	• Increased funding for basic and industrial R&D to demonstrate proof of concept for step-change improvements	No	Tens of millions of pounds
	Improved on-board storage	• EPSRC SUPERGEN Hydrogen Challenge Call Aug 2013 includes ‘Storage solutions’	• Increased funding for basic and industrial R&D to demonstrate proof of concept for step-change improvements	No	Tens of millions of pounds
	Improved hydrogen contaminant tolerance		• Increased funding for basic and industrial R&D • Support for coordination between FCEV, production, purification and verification sectors to optimise across whole system	No	Low millions of pounds
	Standardise maintenance facilities and regimes		• Coordination of competing maintenance providers and regulatory bodies (international coordination useful)	No	High hundreds of thousands of pounds
	Mature understanding and methods for safety engineering of FCEV		• Coordination of competing FCEV manufacturers and regulatory bodies (international coordination essential)	No	Low millions of pounds

Benefit of UK public sector activity/investment	
	High
	Medium
	Low

Source: Carbon Trust and Element Energy analysis