UK

Supply Chains to Support a Hydrogen Economy

Final Report

The Department for Business, Energy & Industrial Strategy (BEIS)

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Executive Summary

Low carbon hydrogen is expected to be a key enabler for the UK to meet its net zero targets. The UK Hydrogen Strategy[1] and the recent British Energy Security Strategy[2] define a 2030 production target of 10 Gigawatt (GW), with at least half of this from electrolysis (green hydrogen), and the development of hydrogen networks, storage and a range of possible end-uses. This ambition offers significant economic opportunities. The National Grid Future Energy Scenarios[3] estimate UK hydrogen demand in 2050 of between 147 and 474 Terawatt Hour (TWh) while The International Energy Agency predicts[4] a demand of 17,500 TWh to ensure global net zero emissions by 2050. It is, therefore, important that current supply chains are well understood and development priorities identified.

The supply chain to support the hydrogen economy is complex and wide ranging. It includes:

- Utilities, providing either raw materials or energy to enable hydrogen production
- The supply chain that supports hydrogen manufacture, including the production of hydrogen manufacturing equipment and relevant supply chains
- Hydrogen transport, distribution and storage, including pipeline and vessel/vehicle transport, underground (caverns, saline aquifers, etc.) and above ground (tank) storage and fuelling infrastructure
- Monitoring and control
- Manufacture of fuel cell components and fuels cells
- Hydrogen carrier chemicals and materials
- End user markets
- Decommissioning and end of life valorisation

This report analyses supply chain requirements for ***hydrogen production, transmission, distribution and storage and the manufacture of fuel cells*** over the period to 2050 and identifies economic development opportunities for the UK. This longer timescale ensures that important developments that offer supply chain opportunities beyond 2030 are identified. However, accurately defining the future hydrogen supply chain is challenging as the low carbon hydrogen economy is in the early stages of development, so there are numerous ways in which it may develop as reflected in the numerous published net zero and future energy scenarios. To understand how the hydrogen supply chain may develop we have, therefore, developed models of supply chain requirements under different scenarios for 2030 and 2050 for both domestic and global hydrogen deployment.

Estimated costs, employment and gross value added (GVA) for each part of the supply chain, segmented by product or service category, to address 2030 and 2050 demand under different scenarios have been calculated to identify high value opportunities. In parallel, an assessment of UK capability across the hydrogen value chain, to understand how well placed the supply chain is to deliver expected growth in the hydrogen economy and identify any strengths or gaps/constraints, was carried out. A wide range of

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1 UK Hydrogen Strategy, HM Government, August 2021, see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

2 British Energy Security Strategy, HM Government, 7th April 2022, see https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy

3 Future Energy Scenarios, National Grid ESO, 2021, https://www.nationalgrideso.com/document/202851/download

4 Global Hydrogen Review 2021, International Energy Agency, October 2021

UK manufacturers and stockists for equipment, materials and services needed to support growth in the hydrogen market has been identified. The types of equipment required are typical of those used in the oil & gas, oil refining, petrochemicals and power industries and, in most areas, there is an established range of UK manufacturers that can supply and compete with international companies.

Specific UK capabilities identified were reformer process technology licensors, electrolyser manufacturing, hydrogen compressor manufacturing and engineering services, although in some of these areas the scale of activity is not sufficient to support expected growth requirements.

A number of supply chain gaps were observed where UK supply chain capability requires development to meet significantly increased future market demand. These include:

- Reformers, as no UK suppliers of industrial scale reformers were identified.
- Line pipe, as UK manufacturers of line pipe are not, currently, qualified for production of the full range of higher grades of pipe for hydrogen service.
- Electrolyser packages, although there is one internationally recognised UK-based supplier of industrial-scale electrolyser packages for hydrogen services, future demand is expected to support several additional suppliers.
- Hydrogen compressors, as there is a shortage of suppliers able to support large-capacity, medium-pressure compression required for hydrogen transmission systems.
- CO_2 compressors as there are limited UK suppliers that can provide CO_2 compressor packages for transport of CO_2 away from blue hydrogen plants for permanent storage.
- High integrity valves, as the number of UK manufacturers is small.
- Packaged dehydration units because no UK manufacturers were identified.

Based on this analysis of market opportunities, current UK capability and supply chain gaps, a number of attractive UK supply chain opportunities have been identified, as follows:

Supply Chain Segment	Category	Atractive Market Opportunity	UK Supply Chain Gap
Blue Hydrogen Manufacturing Capacity	Civil and structural materials (including buildings)	●	
	Construction and installation labour	●	
	Reformer package manufacture	●	●
	CO_2 compressors		●
	Engineering services	●	
Green Hydrogen Manufacturing Capacity	Electrolysis package manufacture	●	●
	Electrical equipment and materials manufacture	●	
	Civil and structural materials (including buildings)	●	
	Cooling water package manufacture	●	
Hydrogen Manufacture	Green Hydrogen Manufacture	●	
Hydrogen Transport - Gas Grid Repurposing	H2 Compressor Package		●
Hydrogen Storage (Cavern)	High Pressure H2 Compressor Package	●	●
	Civil/ Structural Materials (Including Buildings)	●	
	Construction and Installation (Labour only)	●	
Fuel Cell Manufacture	Membrane Electrode Assembly (MEAs) Manufacture	●	
Several Segments	High integrity valves		●

Attractive Supply Chain Opportunities

These opportunities are deemed attractive because there is the potential for significant turnover/jobs/GVA growth, either by building on existing capability or developing new capability to address identified supply chin gaps.

The most attractive opportunities, based on average annual employment and average annual GVA data for 2030 and 2050, are:

- Electrolysis package manufacture
- High pressure hydrogen compressor package manufacture for cavern storage
- Green hydrogen manufacture
- Electrical equipment and materials manufacture for green hydrogen manufacture
- Civil/structural materials (including buildings) for cavern storage

Civil/structural materials (including buildings), their construction and installation of equipment are attractive areas across a number of parts of the UK hydrogen supply chain.

A number of constraints to supply chain development were also identified. These all reflect the embryonic nature, complexity and wide scope of the hydrogen supply chain and highlight a lack of clarity and confidence in how the future supply chain will develop. Leadership in the development of the UK hydrogen supply chain and prioritisation of areas for growth and investment is, therefore, required. This is a role that government is taking through the development of its Sector Development Action Plan.

A SWOT analysis of the UK hydrogen supply chain summarising the evidence gathered in this study has been completed, as presented below.

Strengths	Weaknesses
• UK hydrogen, energy security and decarbonisation strategies • Government commitment to commercial development projects • Credible plans for development of commercial scale production • Access to suitable permanent CO_2 stores • Significant availability of offshore wind energy • Significant cavern capacity for hydrogen storage • Industrial commitment to develop capacity • Broad range of suppliers of equipment, materials and services • Internationally recognised UK capability in electrolysis technologies • UK-based technology providers for blue hydrogen production • Commitment to develop fuel cell technologies for automotive applications	• Lack of clarity on supply chain development priorities • Lack of widespread awareness of the opportunities arising • Shortage of qualified producers of line pipe steel • Shortage of UK manufacturers of specialist high-integrity valves and packaged equipment • Shortage of suppliers able to support large-capacity, medium-pressure compression required for hydrogen transmission systems • Limited UK suppliers that can provide CO2 compressor packages for transport of CO2 away from blue hydrogen plants for permanent storage
• Widespread conversion of equipment and infrastructure to run on hydrogen • Expand commercial-scale electrolyser capacity • Exploit globally-recognised institutions for qualification of materials for hydrogen-service • Develop UK compressor capability • Develop capabilities in the conceptual design and engineering of salt caverns **Opportunities**	• European competition for green hydrogen manufaturing • Lack of confidence for supply chain investment • Competition from alternative net zero solutions • International supply chains dominate UK supply opportunities • Lack of high quality water availability • Competiton for renewable energy capacity **Threats**

SWOT Analysis of the UK Hydrogen Supply Chain

An assessment of the turnover UK companies could capture under illustrative assumptions for market share, factoring in evidence on supply chain capability was carried out. This showed that the UK supply chain has the capability to win a share of the market valued at between £4 billion and £5 billion to deliver 2030 UK hydrogen supply chain capacity and between £30 billion and £90 billion to ensure 2050 capacity is in place.

Export opportunities also exist for UK manufacturers of tradeable goods and services. These have been identified as blue and green production equipment, blue and green manufacturing plant design services and fuel cells, while aspects such as construction of plant and infrastructure are not considered to be tradeable. Initial estimates of the export market size in the period to 2030 across all categories are between £800 million and £2,200 million, increasing to between £5,800 million and £9,800 million in the period to 2050, but additional work is required to prepare more robust estimates.

However, delivering a supportive environment is critical to overcoming the complexity and immaturity of the supply chain and optimising supply chain development and growth, as summarised above. Providing clarity in end user market development priorities, to underpin market driven supply chain growth would support supply chain development.

Based on the analysis carried out in this study it is recommended that:

- The UK Government continues to provide consistency in messaging the importance of hydrogen as a key element of the UK's ten-point plan[5] and the British Energy Security Strategy[2], to steadily increase market confidence.
- Further detail is provided on priority areas for hydrogen supply chain development
- Appropriate mechanisms are established to:
    - Support UK companies to expand capacity or capability
    - Encourage international companies to build manufacturing capacity in the UK
- Collaboration with Trade Associations is continued to seek broader engagement of UK-based suppliers of equipment, materials and services to improve awareness of the forthcoming market opportunities and support mechanisms to develop the skills and manufacturing capacity to address these opportunities.
- The attractive areas of opportunity and supply chain gaps, as listed above, are prioritised to prepare and implement appropriate supply chain development programmes
- The following areas, where further research may be valuable, are considered:
    - Analyse supply chain in relevant hydrogen end user markets to identify potential opportunities and supply chain gaps as the basis for supply chain development programmes
    - Evaluate UK supply chain capability at a more granular level (potentially by collaboration with Trade Associations highlighted above) to identify at a product level the share of UK supply chain opportunities that can be obtained by the UK company base
    - Characterise international markets and internationally competitive UK products and services to more accurately identify the export market opportunities that are available to the UK supply base

[5] The ten point plan for a green industrial revolution, November 202, see https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

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Approved By: Deborah Creamer	**Date:** 28th June 2022

1 Introduction

1.1 Context and Objectives

Low carbon hydrogen is expected to be a key enabler for the UK to meet its net zero target. The UK Hydrogen Strategy[6] initially defined the UK Government's vision for the development of a hydrogen economy, with an ambition for 5GW of hydrogen production by 2030 and the development of hydrogen networks, storage and a range of possible end-uses. This has very recently been updated in the British Energy Security Strategy[7] where the 2030 production target has been increased to 10 GW, with at least half of this from electrolysis (green hydrogen). To enable industry to develop strong supply chains across the full value chain that can exploit opportunities in supporting a robust hydrogen economy it is important that current supply chains are well understood and development priorities identified. This report presents the results of the project entitled ***Supply Chains to Support a Hydrogen Economy*** which endeavours to address these requirements.

The purpose of the project, jointly carried out by Optimat Ltd. and Wood plc, was to identify supply chain development needs to ensure that the UK can achieve its hydrogen economy ambitions for 2030 and beyond and realise the associate economic benefits. After providing an overview of the full hydrogen value chain, this initial study explores the detailed supply chain needs for ***hydrogen production, transmission and storage and the manufacture of fuel cells***. This scope was defined to enable an in-depth understanding of the complex supply chains within these areas, recognising that further parts of the value chain could be studied in future work.

Specific project objectives were:

1. Review the key supply chains needed to support a future UK hydrogen economy
2. Characterise supply chains, identifying the key systems, components and materials required and their associated value chains
3. Determine the potential future demand for systems, components and materials that supply chains will need to deliver and their associated economic opportunities
4. Examine existing supply chain capabilities, the ability of supply chains to meet future demand, and map UK strengths and weaknesses against economic opportunities
5. Identify potential constraints or gaps that risk delaying or preventing the deployment of hydrogen technologies and infrastructure

Analysis of potential developments over the period to 2050 has been carried out. This is to ensure that the study took a sufficiently long term view to consider any important developments that offer supply chain opportunities beyond 2030. Of course, this timescale aligns with a number of the published analyses of the development of the hydrogen economy, as referenced throughout this report.

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[6] UK Hydrogen Strategy, HM Government, August 2021, see https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

[7] British Energy Security Strategy, HM Government, 7th April 2022, see https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy

The work was predominantly a desk based analysis of relevant information, combined with some stakeholder engagement, and was carried out over the period from late November 2021 to the end of April 2022.

We would like to acknowledge and thank the Hydrogen Advisory Council Sector Development Working Group for its contribution to the project.

1.2 Report Structure

The results of this research study are presented as follows:

- **Section 1** introduces the study and its objectives
- **Section 2** details the expected scale of the hydrogen economy opportunity
- **Section 3** presents a supply chain framework for the hydrogen economy
- **Section 4** takes a scenario based approach to develop future hydrogen supply chain models
- **Section 5** develops estimates of the potential supply chain impact that may be accrued by the UK hydrogen supply chain
- **Section 6** presents an assessment of current supply chain capability
- **Section 7** presents a SWOT analysis of the UK hydrogen supply chain and identifies priority development opportunities
- **Section 8** assesses UK supply chain development opportunities
- **Section 9** presents study conclusions and recommendations

2 The Hydrogen Economy – The Scale of the Opportunity

The potential growth of the hydrogen economy and the opportunities that it will offer to the supply chain are highly uncertain so scenarios have been used to illustrate the potential scale of growth and supply chain needs, but, in reality, the hydrogen economy could develop differently from the way it is presented in this report.

Market growth has been assessed at a UK, European and global level. This provides input to the future scenarios described in Section 4 and offers an evidence base to estimate the scale of the opportunity for the UK supply chain in both domestic and export markets. Market growth projections are summarised below, with further information in Appendix A.

2.1 UK Market

UK government ambitions for 10 GW of hydrogen production capacity were described in Section 1, above.

UK market growth estimates are based on the expected growth defined in the UK Hydrogen Strategy[6] and projected demand in the three National Grid Future Energy scenarios[8] that are projected to deliver net zero by 2050. These can be presented as shown in Figure 1[9]: These projections are consistent with a number of other analyses, as summarised by, for example, the Energy Networks Association and discussed in more detail in Appendix A[10].

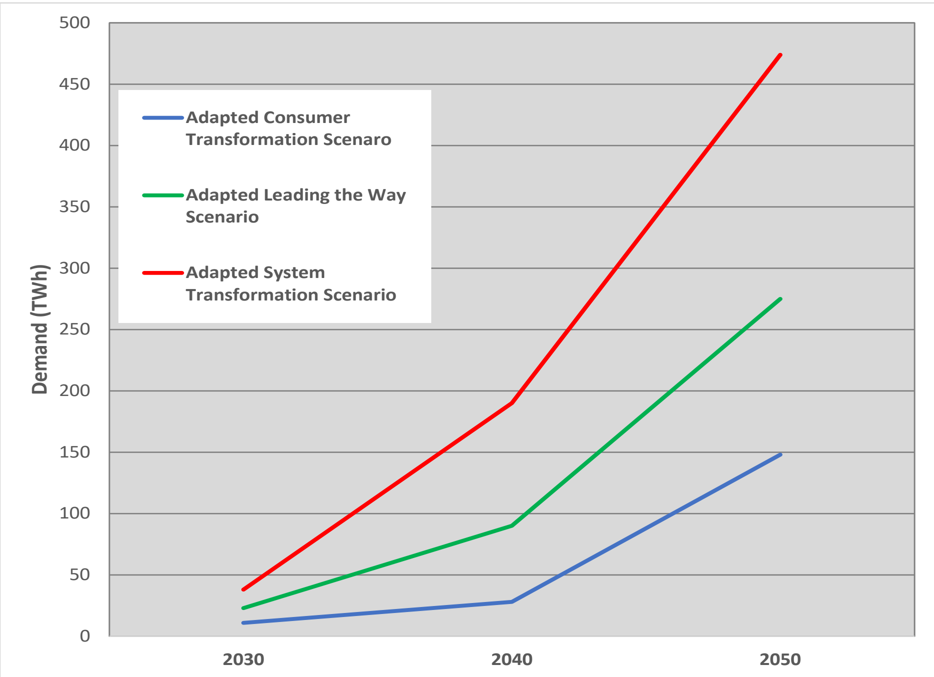

Figure 1: UK Hydrogen Demand, 2030 to 2050

8 Future Energy Scenarios, National Grid ESO, 2021, https://www.nationalgrideso.com/document/202851/download

9 Data for 2030 are the low (11 TWh), median (23 TWh) and high (38 TWh) market demand figures quoted in the UK Hydrogen Strategy while the 2040 and 2050 figures are from the National Grid Future Energy scenarios. The 2030 demand figures are allocated to the scenarios in line with later demand figures.

10 Britain's Hydrogen Network Plan, Energy Networks Association

2.2 European Market

The European Union hydrogen strategy[11] asserts an explicit focus on the deployment of renewable hydrogen (i.e. production of hydrogen through electrolysis with electricity from renewable sources, often termed "green hydrogen") with an objective to install at least 6GW of renewable hydrogen electrolysers between 2020 and 2024 and 40GW by 2030. Recently, new targets have been proposed to reduce dependence on Russian gas. An additional 15 million tonnes of renewable hydrogen production are proposed for 2030[12], consisting of 10 million tonnes of imports and 5 million tonnes of European production.

There are numerous analyses of the potential scale of the European hydrogen market over the period to 2050. Representative examples are those published by the Gas for Climate Initiative[13] and the European Project, Hydrogen4U[14] which provide the scale of demand shown in Figure 2.

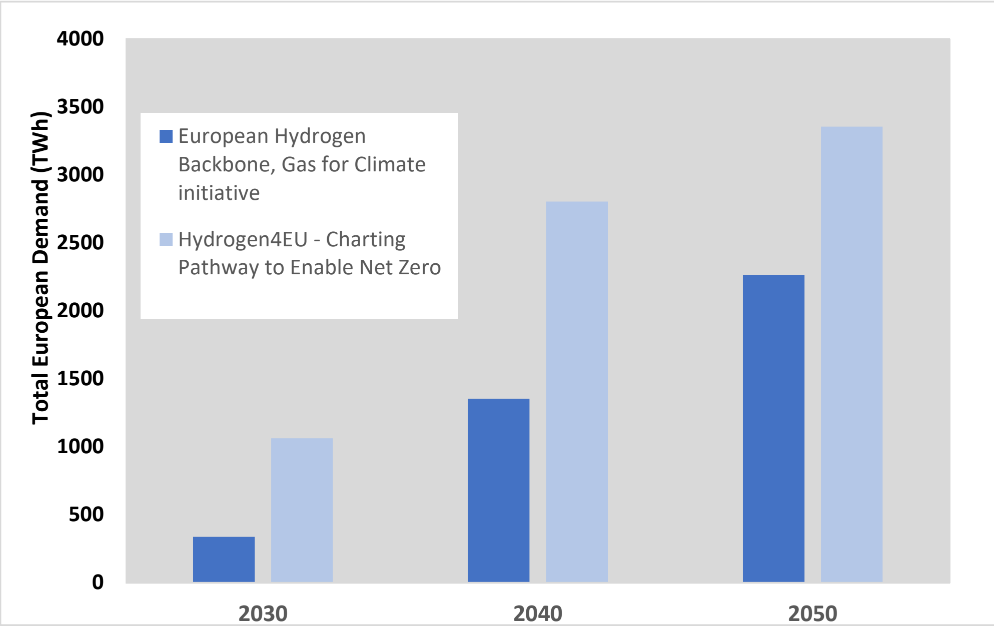

Figure 2: Potential Scale of European Hydrogen Demand (2030 to 2050)

2.3 Global Market

2.3.1 Hydrogen

There is a huge amount of uncertainly regarding development of global hydrogen demand. Data from the IEA Global Hydrogen Review[15] has been used to show the scale of the potential market. IEA estimates for the global demand for hydrogen are based on (a) projects that are in construction or

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11 A hydrogen strategy for a climate-neutral Europe, European Commission, July 2020

12 REPowerEU: Joint European Action for more affordable, secure and sustainable energy, European Commission, March 2022

13 European Hydrogen Backbone, Gas for Climate Initiative, June 2021

14 Hydrogen4EU – Creating Pathways to Enable Net Zero, Deloitte, 2021

15 Global Hydrogen Review 2021, International Energy Agency, October 2021

planned, (b) pledges that have been announced and (c) a scenario the leads to net zero by 2050. Demand growth for the latter two of these options is summarised in Figure 3.

	Demand (TWh)		
	2030	2040	2050
Announced Pledges	3,800	6,100	8,400
Net Zero Emissions by 2050	6,900	12,900	17,500

Figure 3: Hydrogen Demand by Sector in the Announced Pledges and Net Zero Emissions Scenarios

This shows a development option that meets net zero targets (high market demand) and one which is significantly below this target (low demand).

The scenario that leads to net zero by 2050 shows a demand of 17,500 TWh of hydrogen in 2050, with the balance between blue and green hydrogen as detailed in Figure 4[15].

	2030	2040	2050
Blue Hydrogen	27%	30%	35%
Green Hydrogen	36%	55%	60%

Figure 4: Projected Percentages of Blue and Green Hydrogen to Meet Global Demand

The remaining production is predominantly grey hydrogen.

3 Characterisation of Supply Chains to Support a Hydrogen Economy

3.1 A Supply Chain Framework to Support the Hydrogen Economy

A comprehensive supply chain framework to support the future hydrogen economy, including all activities, from basic raw material to market applications, is shown in a simplified format in figure 5.

This framework was developed using the project team's knowledge of supply chain mapping and the hydrogen supply chain, review of a range of relevant documents[16] and input from key stakeholders (e.g. the Hydrogen Advisory Council Sector Development Working Group).

Key stages of the core supply chain shown in Figure 5 are:

- Utilities, providing either raw materials or energy to enable hydrogen production
- Hydrogen manufacturing, including
    - The supply chain of components and systems for the production of hydrogen manufacturing equipment
    - The production of hydrogen manufacturing equipment and ancillary equipment
    - The production of hydrogen
    - The processing and management of hydrogen
- Hydrogen transport, distribution and storage, including
    - Pipeline and vessel/vehicle transport
    - Underground (caverns, saline aquifers, etc.) and above ground (tank) storage
    - Fuelling infrastructure
- Monitoring and control
- Manufacture of fuel cell components and fuel cells
- Hydrogen carrier chemicals and materials
- End user markets, namely power generation, industrial and commercial heat, domestic heat, transport and export markets
- Decommissioning and end of life valorisation

The core supply chain is supported by

- Services to develop, install, commission, operate and maintain the hydrogen infrastructure
- R&D and education provision
- Professional services, such as scientific, design, engineering and environmental consultancies, measurement and testing organisations and health and safety specialists
- Ancillary services, including policy making, regulatory bodies, software and IT services and other consultancy services.

16 For example, the Scottish Offshore Wind to Green Hydrogen Opportunity Assessment, Scottish Government 2020 and Value Added of the Hydrogen and Fuel Cell Sector in Europe, September 2019, FCH 2 JU

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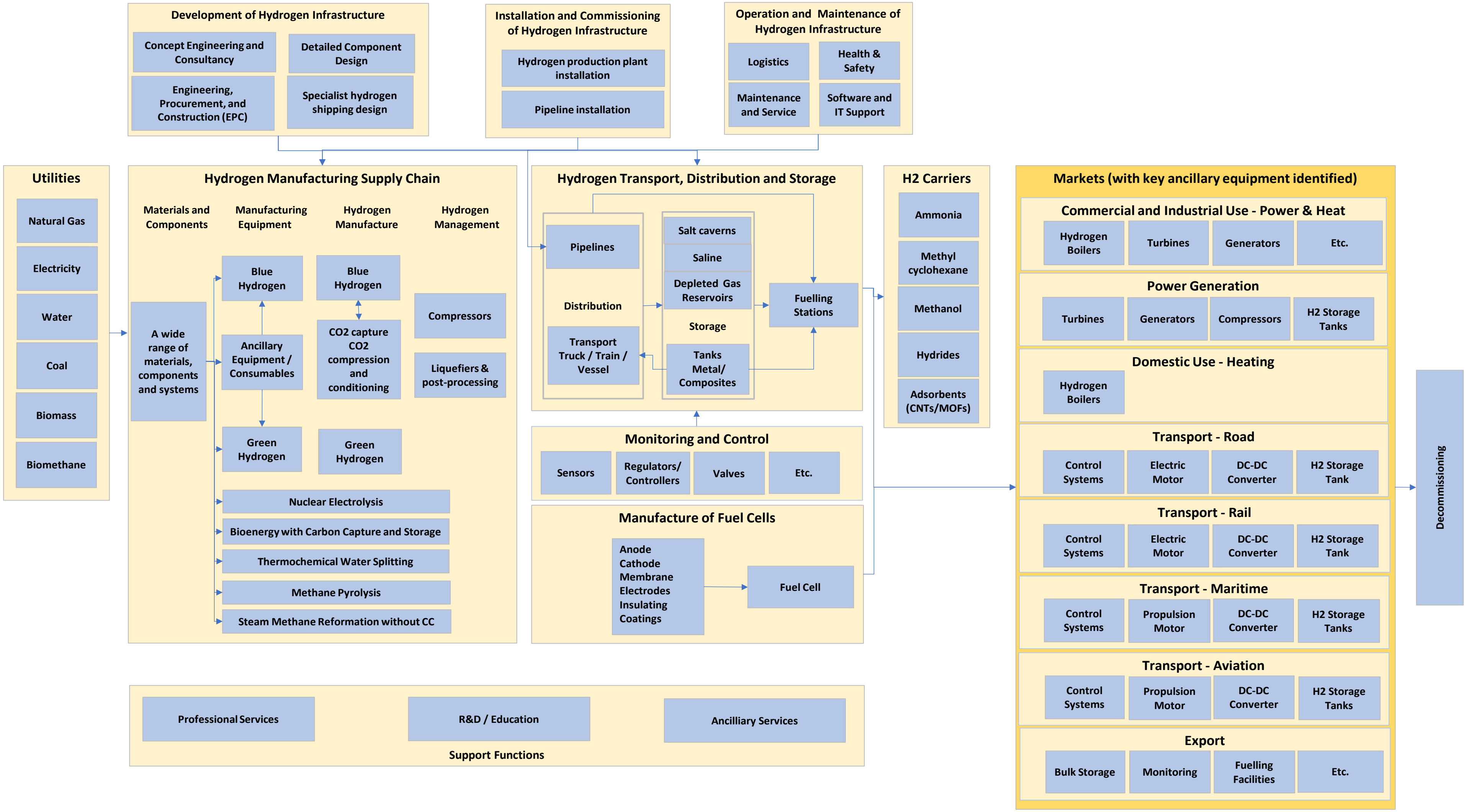

Figure 5: Supply Chain Framework for the Hydrogen Economy

As already highlighted, the scope of this study covered hydrogen production, transmission and storage and the manufacture of fuel cells to enable a more granular understanding of these areas, as detailed in this report. This scope is shown in Figure 6, with a more detailed version of this supply chain framework included in Appendix B.

This work, therefore, provides a starting point to examine the supply chains needed to support a hydrogen economy.

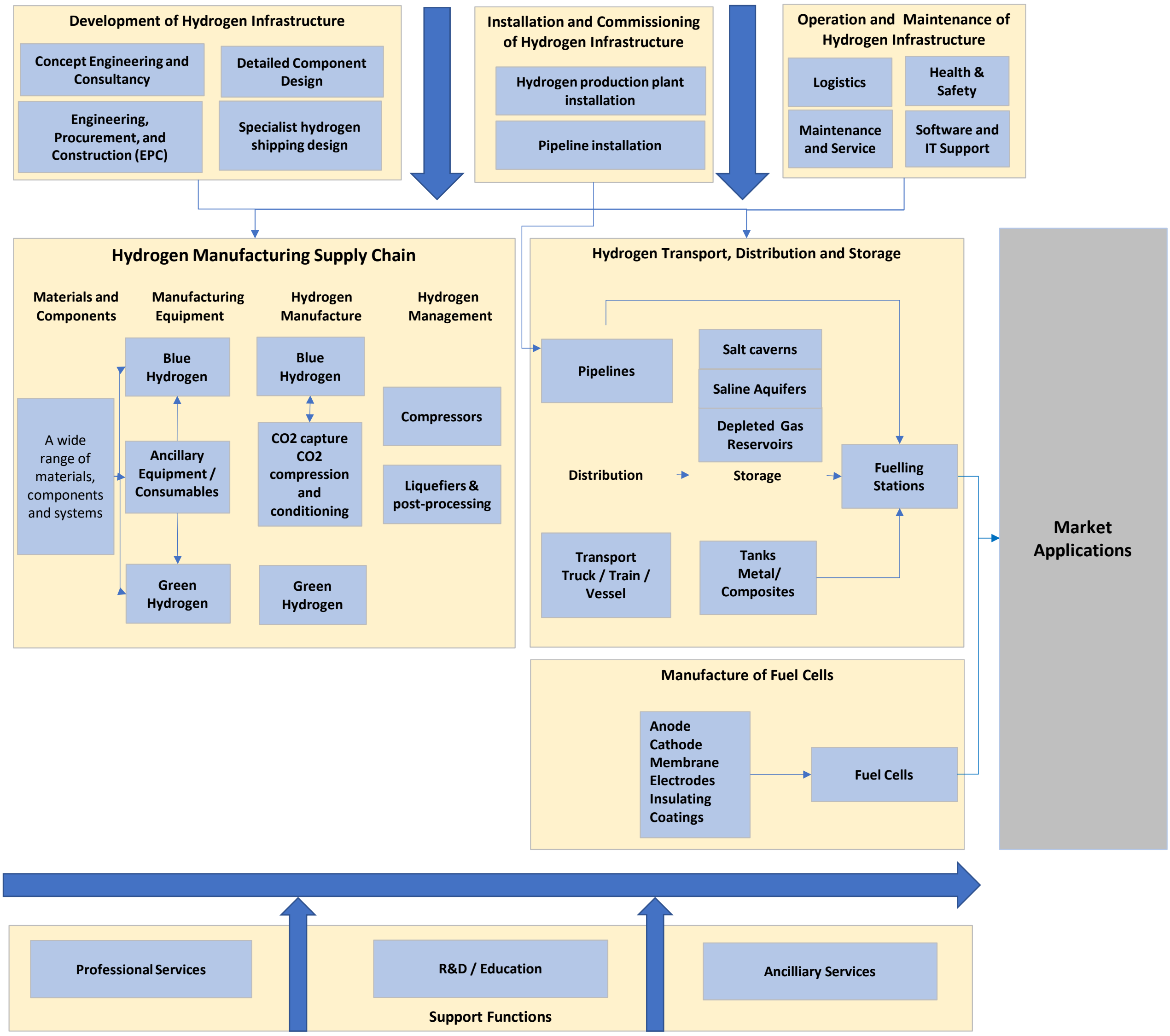

Figure 6: Simplified Supply Chain Framework for this Study

3.2 Detailed Supply Chain Models at Product Level

Supply chain models have been prepared at product level building upon the model shown in Figure 6. As shown in this figure, the scope of the supply chain assessed is hydrogen production, hydrogen transportation, distribution and storage and the manufacture of fuel cells.

Hydrogen production can be further defined by the source of the hydrogen. The two sources considered for this analysis are:

Blue Hydrogen: Natural gas reforming with carbon capture and storage (CCS).

Green Hydrogen Water electrolysis utilising low carbon electricity, which in all scenarios is predominantly offshore wind.

Hydrogen may also be produced through other routes such as coal, biomass or even waste plastic gasification and processing, however these routes are not included within this analysis as they have not been identified as major contributors of hydrogen production in any of the scenarios adopted by the study. It is recognised, however, that this may change in the future. Also, the importing of Hydrogen is not included in the analysis as this does not provide significant opportunity to the UK supply chain and there is significant uncertainty around the role of imports in meeting UK Hydrogen demand.

Hydrogen transportation, distribution and storage has also been further defined by type:

Physical Storage Covering both high-pressure gas and geological storage within salt caverns.

Methods of chemical storage of hydrogen by way of metal and chemical hydrides, adsorption utilising metal organic frameworks (MOFs) and carbon nanotubes (CNTs), and reformed organic fuels such as methanol and ammonia are considered to be outside the scope of this analysis.

Transport and distribution Covering pipelines and also road and rail transport of high-pressure gas. Transport of hydrogen by ship within the UK is not considered in the analysis. Pipelines cover new dedicated industrial networks, New high-pressure pipelines for the NTS (National Transmission System) and repurposing of the existing natural gas distribution network to varying degrees depending on the level of hydrogen utilised as heat for residential and commercial users.

Liquid storage and transportation are not considered in the analysis as it is judged unlikely to deployed within the UK owing to the typical distances required for transportation and the high energy penalty associated with liquefaction and regasification processes. The ETC Global Hydrogen report[17] estimates that for small volumes (less than 10 tonnes per day) liquid transport only becomes competitive if transported over multiple hundreds of kilometres which is not likely within the UK.

Fuel Cells manufacture Covering the manufacture of fuel cells for transport i.e. fuel cells for use in fuel cell electric vehicles (FCEV). As such, only two types are considered for automotive purposes: PEM and alkaline fuel cells. This is because only these two technologies operate at lower temperatures (<120oC) and allow sufficiently fast start-up times required for transport application.

3.2.1 Characterising Systems

For each product a key characterising system or technology underpinning it that influences the supply chain has been used as a basis for analysis. This might be a particular application of equipment type or a specific technology. Some of these are listed in Figure 7.

[17] Energy Transitions Commission, Making the Hydrogen Economy possible: Accelerating Clean Hydrogen in an Electrified Economy version 1.2, April 2021

Product	Characterising System or Technology
Blue hydrogen manufacture	Thermal gas reforming, CCS
Green hydrogen manufacture	Electrolysis
Gas storage	Very high-pressure systems and equipment Salt cavern construction
Gas transport and distribution	Compression, pipelines
Fuel cells	Fuel cells

Figure 7: Characterising System or Technology

These characteristics not only determine the supply chain from a materials perspective (physical equipment and materials required for construction or manufacture, e.g. a compressor, motor and electrical cables) but also for some key services where knowledge and experience are required in specific areas.

3.2.2 Technology Differences

There are some distinct technologies supporting each of these systems, however, within each system most components are similar in scale, type, and application for example the utilisation of compressors, pumps, and electrical equipment, such as transformers and rectifiers, particularly in the case of Green Hydrogen production

3.2.2.1 Blue Hydrogen

The reformation of natural gas is a common method used to produce hydrogen globally. There are 3 main technologies currently used at an industrial scale for reforming natural gas into hydrogen: steam methane reforming (SMR), auto thermal reforming (ATR) and partial oxidation (POx).

These processes all have a similar configuration: they all consist of a reforming step to convert the natural gas to syngas, followed by a shift reaction; removal of CO_2 using a solvent absorption process; purification, compression and export of the hydrogen; and compression, drying and export of the CO_2. The key difference between them is the way in which the natural gas feedstock is converted to a syngas consisting mainly of hydrogen and carbon dioxide. Both ATR and POx based technologies require pure oxygen as a feedstock and, therefore, require an air separation unit (ASU). However, the component equipment and materials utilised by each of these systems is very similar. All rely on the utilisation of pumps and compressors and reaction vessels containing catalysts able to operate under high temperature and pressure conditions. The difference lies in the scale and application of the materials and equipment as one technology may require slightly larger pumps for example or a larger fired heater. For the purposes of the analysis, we have taken SMR as representative for blue hydrogen production. The impact of selecting another technology would likely increase the cost and therefore the scale of the associated supply chains due to the generally increased capex required for ATR and POX technologies. These technologies are also reliant on oxygen as a feedstock and therefore there would be considerable opportunity for air separation unit manufactures--usually packaged units supplied by industrial gas manufacturers.

3.2.2.2 Green Hydrogen

Green Hydrogen utilises low carbon electricity for the electrolysis of water. This results in the electrochemical liberation of hydrogen. Requiring a direct current, the decomposition of water produces extremely pure hydrogen.

This process remains the same for all technological options of electrolysis, however the reactions at the anode and cathode differ depending on the choice of electrolyser.

Currently there are three types of electrolysers considered as potential technologies to support future Hydrogen production at scale[18]:

- Alkaline electrolysis
- Proton exchange membrane (PEM) electrolysis
- Solid oxide electrolysis

However, only two of these technologies are currently commercially available at an industrial scale: alkaline and PEM type electrolysis. For the purposes of the analysis, PEM electrolysis is taken as representative for green hydrogen production. Although it is recognised that there are technological differences between the core technologies and, thus, their respective supply components the analysis is undertaken at a sufficiently holistic level to assume that the magnitude of the potential supply chain is analogous between the technologies. At the level of analysis undertaken selecting a different technology will impact on the scale of the supply chain value due to the forecast capital costs for the different technologies. The split of project components is unlikely to be significantly different however the materials that make up the electrolysers themselves is different -with precious metals being used in PEM electrolysers but not in Alkaline or Solid Oxide Electrolysers for example.

Again, all supporting systems are similar and, thus, there is commonality across the supply chains.

3.2.2.3 Hydrogen Storage and Transport/Distribution

Storage of hydrogen will be required at scale under all scenarios adopted. Hydrogen can be stored, either physically, as a gas or a liquid in pure form, or chemically using Hydrides, Adsorption (Metal Organic Frameworks (MOFs) or Carbon Nanotubes (CNTs)) liquid organic Hydrogen carriers (LOHC), and reformed organic fuels such as methanol and ammonia. As stated above chemical methods of storage and transport are not included in this analysis. As also described above Liquid storage is not considered in the analysis as it is judged unlikely to deployed within the UK owing to the typical distances required for transportation and the high energy penalty associated with liquefaction and regasification processes.

Above ground storage of hydrogen as a compressed gas requires the use of pressure vessels or tanks. The greater the pressure the greater the volumetric density and therefore the smaller the vessel. Above ground compressed Hydrogen storage will be required in many applications including vehicles, hydrogen refuelling stations, and industry where security of supply to a given process is required. For conventional (manufactured steel) pressure vessels very high pressure increases the thickness and cost of the vessel. At very high volumetric density requirements storage is likely to become uneconomical for conventional pressure vessels. Therefore, advanced materials for vessels are required such as carbon fibre and glass

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[18] Department for Business, Energy, and Industrial Strategy. Hydrogen Production Costs 2021

reinforced plastics (GRP). These types of vessels are limited in size due to manufacturing limitations and are therefore typically supplied in banks connected by a manifold system. This method of storage would only be relevant for inter-day storage with careful consideration of safety, and therefore location, factors and as such is considered by many to be inappropriate for bulk storage of hydrogen.

Sub surface or geological storage of hydrogen offers potential for storage of hydrogen in bulk. Natural gas has been reliably stored in large volumes in subsurface formations for many years including naturally occurring depleted hydrocarbon fields, aquifer formations and solution mined salt caverns. Hydrogen has been stored successfully in salt caverns on Teesside since the 1960s[19]. In this analysis only salt caverns are considered for bulk storage of hydrogen.

The selection of hydrogen storage type will, largely, be defined by each future scenario based on the dominant method of hydrogen production, the scale of production and the utilisation of the hydrogen product. Blue hydrogen production will likely be based on a centralised production model, centred around carbon capture and storage (CCS) clusters due to the requirement for access to a carbon store. Transportation of hydrogen from these production centres will be by pipeline to storage facilities for onward transport to refuelling stations and other applications, including industry. Green hydrogen production can, however, be decentralised with production closer to the end user as long as there is sufficient water supply and electrical infrastructure. A centralised production and storage model will likely utilise a higher amount of geological storage, which is in line with predictions of the Future Energy Scenarios[8].

For this analysis the quantity of above ground compressed gas storage is linked to the quantity of hydrogen utilised for transport in each of the future scenarios whereas bulk hydrogen storage requirement follows the assumptions of the future energy scenarios and is stored in salt caverns.

3.2.2.4 Fuel Cells

Fuel cells are electrochemical cells that produce electricity though the reduction-oxidation of a fuel (in this case hydrogen) and oxygen. Available fuel cell technologies include the following:

- PEM fuel cells
- Alkaline fuel cells
- Phosphoric acid fuel cells
- Solid oxide fuel cells
- Molten carbonate fuel cells

This work is restricted to the use of fuel cells in fuel cell electric vehicles (FCEV) and, as such, only two types are considered for automotive purposes: PEM and alkaline fuel cells. This is because only these two technologies operate at lower temperatures (<120°C) and allow sufficiently fast start-up times required for transport application. Of these two types, PEM fuel cells are generally favoured and sufficient data is available in the public domain to support analysis. As such PEM fuel cells have been taken as representative.

19 British Geological Survey (2008) Mineral planning fact sheet – Underground storage. https://www2.bgs.ac.uk/mineralsuk/download/planning_factsheets/mpf_storage.pdf

3.3 Product Level Taxonomies

Product level taxonomies have been developed for all products detailed in section3.2, using the categorisation and segmentation in Appendix D. This is based on a detailed review of the make-up of each product, evidence developed by Wood as part of other work and review of publicly available taxonomies[20]. These taxonomies break each product down into its constituent components by type. Each component can be grouped by type and defined by which area of the plant or package[21] in which is it is located or has been allocated to. This also applies to components within key packages, such as the cell stacks in an electrolyser package. This would be categorised as packaged equipment within the electrolysis unit of a green hydrogen production plant. These taxonomies demonstrate the commonality in the type of components required to support each product.

The taxonomy for fuel cells differs from the other products in that they are more discrete manufactured goods and packages. In contrast, blue and green hydrogen product equipment comprise of a large number of products and packages together. This can be observed more in the services supply chain element. These taxonomies are also included in Appendix D.

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20 For example, Scottish Offshore Wind to Green Hydrogen Opportunity Assessment, Scottish Government, December 2020

21 A package is defined as a collection of equipment items packaged together as a subsystem of a larger unit

4 Defining Future UK Hydrogen Economy Supply Chain Models

Accurately defining the future hydrogen supply chain is challenging as the development of the hydrogen economy, excluding established industrial uses of hydrogen, is, currently, in its early stages and, as a result, there are numerous ways in which it may develop as reflected in the numerous published net zero and future energy scenarios. These "alternative futures" for the hydrogen economy will influence the different ways in which the hydrogen supply chain may develop both in terms of specific areas of industrial activity and timescales.

To understand how the hydrogen economy and supply chain may develop, three future scenarios for the growth of the hydrogen economy over the period to 2050 have been prepared, based on the National Grid Future Energy Scenarios[8] and the characteristics of supply chains required to support these scenarios modelled, based on the supply chain framework shown in Figure 6. These supply chain models, therefore, include the full range of activities required to deliver a robust hydrogen economy under each scenario and can then be used to show the full potential for supply chain growth and economic impact.

4.1 Development of Scenarios for the Future UK Hydrogen Economy

As already indicated, the potential growth of the hydrogen economy and the opportunities that it will offer to the supply chain are highly uncertain, so the use of scenarios ("alternative futures") allow a number of different outcomes to be considered. Three of the four National Grid Future Energy Scenarios[8], published in July 2021, adapted for consistency with the UK hydrogen strategy[6] and government ambitions for 2030[7] and to reflect international growth predictions, as summarised in Section 2, have been used to illustrate potential futures[22]. Key adaptations were:

- A 10 GW target for low carbon hydrogen manufacturing capacity by 2030, with rapid growth thereafter as defined in the recent UK government Energy Security Strategy
- 2030 hydrogen demand of between 10 and 37 TWh as defined in the UK Hydrogen Strategy. Different levels of hydrogen demand are included in each scenario reflecting the minimum, median and maximum figures of the range defined.
- Adaptation of the percentages of blue and green hydrogen production in each scenario to provide illustrative scenarios, consistent with government ambition
- The 2030 European Commission target[11] for >40 GW of renewable hydrogen manufacturing capacity
- European and global demand as defined in Section 2, above.

These scenarios were selected as they build on the Climate Change Committee's sixth carbon budget, provide detailed evidence of hydrogen demand, estimate potential growth in a range of market applications over the period to 2050 and place hydrogen demand within wider energy needs. More detail on these scenarios and the adaptations made are described in Appendix C.

Schematic roadmaps, with key milestones and scale of activity, which can then be used to consider the parts of the supply chain that will develop and grow under each scenario are shown in Figures 8 to 10.

[22] The fourth scenario was not considered as it does not deliver a net zero economy by 2050

	2025	2030	2035	2040	2045	2050	Source
Hydrogen Manufacturing Capacity		10GW		10 GW		~37GW	UK Energy Security Strategy / FES, National Grid ESO, July 2021
Manufacturing Technology		25% blue/75% green				25% blue/75% green	Illustrative scenario consistent with govt ambition/ NGFES
Hydrogen Storage		1 TWh		~3.5 TWh		~14 TWh	Future Energy Scenarios, National Grid ESO, July 2021
UK Market Trends							
a) Industrial & Commercial		Mainly Industrial				H2 only where electricity not possible	Future Energy Scenarios, National Grid ESO, July 2021
b) Residential			Sale of NG boilers banned			2.5 million homes with H2 boilers	Future Energy Scenarios, National Grid ESO, July 2021
c) Transport		Ban on sales of new petrol/ diesel cars and vans	H2 lorries uptake begins to increase			H2 mainly in HGV using regional infrastructure.	Future Energy Scenarios, National Grid ESO, July 2021
d) Aviation and Shipping		Roll out of H2 converted to Ammonia begins					Future Energy Scenarios, National Grid ESO, July 2021
UK Market							
Total Demand, consisting of		11 TWh		28 TWh		147 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
a) Industrial & Commercial		10 TWh		~8 TWh		19 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
b) Residential		0 TWh		~10 TWh		15 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
c) Transport		1 TWh		~10 TWh		32 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
d) Aviation and Shipping		No data		No data		80 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
e) Power Generation		0 TWh		Negligible		2 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
European Market							
a) Manufacturing Target	> 6 GW	> 40 GW					A hydrogen strategy for a climate-neutral Europe, EC
b) Manufacturing Technology	All Green	All Green					A hydrogen strategy for a climate-neutral Europe, EC
c) Expected market - low demand		338 TWh		1353 TWh		2266 TWh	Gas for Climate Initiative
d) Expected market - high demand		1062 TWh		2805 TWh		3356 TWh	Hydrogen4U Consortium
Global Market							
a) Manufacturing Technology		36% Green / 27% Blue		~55% Green / ~30% Blue		~60% Green / ~35% Blue	IEA, Global Hydrogen Review, 2021
b) Expected market - low demand*		3,800 TWh		6,100 TWh		8,400 TWh	IEA, Global Hydrogen Review, 2021
c) Expected market - high demand**		6,900 TWh		12,900 TWh		17,500 TWh	IEA, Global Hydrogen Review, 2021

* Announced pledges scenario ** Net Zero in 2050 scenario

Figure 8: Roadmap – Adapted Consumer Transformation Scenario

	2025	2030	2035	2040	2045	2050	Source
Hydrogen Manufacturing Capacity		10GW		~35 GW		~75GW	Future Energy Scenarios, National Grid ESO, July 2021
Manufacturing Technology		45% Blue/55% green				70% Blue/30% green	Illustrative scenario consistent with govt ambition/ NGFES
Hydrogen Storage		1 TWh		10 TWh		52 TWh	Future Energy Scenarios, National Grid ESO, July 2021
UK Market Trends						Widespread use for home heating, industry and HGVs	
a) Industrial & Commercial		Mainly Industrial					Future Energy Scenarios, National Grid ESO, July 2021
b) Residential	H2 ready boilers & appliances available	Switch of Natural Gas network to H2 begins				High residential hydrogen boiler uptake	Future Energy Scenarios, National Grid ESO, July 2021
c) Transport		Ban on sales of new petrol/ diesel cars and vans in 2032	H2 FCV increase in line with infrastructure	National refuelling network develops	HGVs switch to H2	Over 3 million HGVs / some H2 trains	Future Energy Scenarios, National Grid ESO, July 2021
d) Aviation and Shipping		Roll out of H2 converted to Ammonia begins					Future Energy Scenarios, National Grid ESO, July 2021
UK Market							
Total Demand, consisting of		38 TWh		190 TWh		474 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
a) Industrial & Commercial		21 TWh		65 TWh		141 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
b) Residential		1 TWh		110 TWh		190 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
c) Transport		6 TWh		~15 TWh		62 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
d) Aviation and Shipping		No data		No data		80 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
e) Power Generation		10 TWh		Negligible		1 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
European Market							
a) Manufacturing Target	> 6 GW	> 40 GW					A hydrogen strategy for a climate-neutral Europe, EC
b) Manufacturing Technology	All Green	All Green					A hydrogen strategy for a climate-neutral Europe, EC
c) Expected market - low demand		338 TWh		1353 TWh		2266 TWh	Gas for Climate Initiative
d) Expected market - high demand		1062 TWh		2805 TWh		3356 TWh	Hydrogen4U Consortium
Global Market							
a) Manufacturing Technology		36% Green / 27% Blue		~55% Green / ~30% Blue		~60% Green / ~35% Blue	IEA, Global Hydrogen Review, 2021
b) Expected market - low demand*		3,800 TWh		6,100 TWh		8,400 TWh	IEA, Global Hydrogen Review, 2021
c) Expected market - high demand**		6,900 TWh		12,900 TWh		17,500 TWh	IEA, Global Hydrogen Review, 2021

* Announced pledges scenario ** Net Zero in 2050 scenario

Figure 9: Roadmap – Adapted System Transformation Scenario

	2025	2030	2035	2040	2045	2050	Source
Hydrogen Manufacturing Capacity		10 GW		~25GW		~63GW	Future Energy Scenarios, National Grid ESO, July 2021
Manufacturing Technology		10% blue/90% green				5% blue/95% green	Illustrative scenario consistent with govt ambition/ NGFES
Hydrogen Storage		2TWh		~4 TWh		~15 TWh	Future Energy Scenarios, National Grid ESO, July 2021
UK Market Trends							
a) Industrial & Commercial	Uptake of H2 low carbon heating starts to increase						Future Energy Scenarios, National Grid ESO, July 2021
b) Residential	Local H2 networks leads to increased H2 boilers from 2028		Sale of NG boilers banned			3.5 million homes with H2 boilers	Future Energy Scenarios, National Grid ESO, July 2021
c) Transport		Ban on sales of new petrol/ diesel cars and vans	HGVs begin to use H2			Almost 400,000 H2 HGVs	Future Energy Scenarios, National Grid ESO, July 2021
d) Aviation and Shipping		Roll out of H2 converted to Ammonia begins					Future Energy Scenarios, National Grid ESO, July 2021
UK Market							
Total Demand, consisting of		23 TWh		90 TWh		275 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
a) Industrial & Commercial		15 TWh		40 TWh		81 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
b) Residential		0 TWh		32 TWh		44 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
c) Transport		3 TWh		18 TWh		44 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
d) Aviation and Shipping		No data		No data		80 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
e) Power Generation		5 TWh		Negligible		22 TWh	UK Hydrogen Strategy / FES, National Grid ESO, July 2021
European Market							
a) Manufacturing Target	> 6 GW	> 40 GW					A hydrogen strategy for a climate-neutral Europe, EC
b) Manufacturing Technology	All Green	All Green					A hydrogen strategy for a climate-neutral Europe, EC
c) Expected market - low demand		338 TWh		1353 TWh		2266 TWh	Gas for Climate Initiative
d) Expected market - high demand		1062 TWh		2805 TWh		3356 TWh	Hydrogen4U Consortium
Global Market							
a) Manufacturing Technology		36% Green / 27% Blue		~55% Green / ~30% Blue		~60% Green / ~35% Blue	IEA, Global Hydrogen Review, 2021
b) Expected market - low demand*		3,800 TWh		6,100 TWh		8,400 TWh	IEA, Global Hydrogen Review, 2021
c) Expected market - high demand**		6,900 TWh		12,900 TWh		17,500 TWh	IEA, Global Hydrogen Review, 2021

* Announced pledges scenario ** Net Zero in 2050 scenario

Figure 10: Roadmap – Adapted Leading the Way Scenario

4.2 Detailed Supply Chain Models/Diagrams

Detailed supply chain diagrams produced for each of the products discussed in section 3 are included in Appendix E. These models depict how the components listed in the taxonomies combine into various parts/ unit areas of the overall products.

4.3 Estimated Scale and Costs of Supply Chains

Using the categorisation of materials and services depicted in the supply chain diagrams and product level taxonomies, each element of the supply chain can be quantified in terms of a % value contribution to larger units using a breakdown of reference cost data for blue and green hydrogen and infrastructure projects. These can then be applied to published estimated current and future unit costs of production thereby allowing estimates of the scale of each specific supply chain element in any given demand scenario, e.g.:

- Unit cost of blue hydrogen
- % cost contribution of equipment/materials by category for unit cost of blue hydrogen
- Unit cost of green hydrogen
- % cost contribution of equipment/materials by category for unit cost of green hydrogen
- Etc.

This quantification is taken as representative across the scale of deployment and remains unchanged from 2030 to 2050. This is a generalisation as, in reality, the split in material/equipment make-up and services is unique to every project and is influenced by a number of different market drivers and project/location specific items and will change over time. The figures presented should, therefore, be considered to have a degree of variability. It is, however, considered that this approach is appropriate in providing a holistic view of the respective supply chain quantification for the different scenarios adopted. This approach also implies that the components of each of the developments are the same i.e. each project includes the same level of ground preparation and the same type of utility unit support (steam, power and cooling etc).

4.3.1 2030 Hydrogen Production and Demand

In all 3 scenarios, as summarised in Figures 8 to 10, the UK Hydrogen Strategy ambition of achieving 10GW of hydrogen production capacity is realised but the split between blue and green production varies. Consumer Transformation assumes a 75:25 split between green and blue production to meet the 10GW ambition whereas System Transformation and Leading the Way assume 45% and 10% blue hydrogen production respectively. This variance is adopted to depict the effect of a varying range in the production technology mix honouring the ambition of at least half of the 10GW production from electrolytic hydrogen outlined in the British Energy Security Strategy. This broadly aligns with the themes of each of the scenarios described i.e. System Transformation relies much more on blue hydrogen production whereas Leading the Way assumes green hydrogen is deployed to a greater extent.

Hydrogen demand is varied across the scenarios to reflect the range in demand envisaged in the Hydrogen Strategy (10-38TWh). Again, this is modelled to depict a variance across the scenarios but is also done to reflect appropriate load factors for each of the defined production methods. System Transformation relies more heavily on blue hydrogen production methods, which is assumed to have higher load factors because of the base load nature of gas reforming processes. The demand, therefore, is adjusted to the 38TWh which produces a corresponding load factor of 43%. Leading the Way relies, predominantly, on green hydrogen production and, initially, this is assumed to be produced by electrolysis from networked electricity. As the UK energy system transitions to renewables it is assumed that, to begin with, electrolysis is undertaken using curtailed electricity. As such, the demand is set at 23TWh resulting in a load factor of 26%. This is line with the expected load factor stated in literature[18]. Consumer Transformation hydrogen demand is adjusted to 11TWh providing a load factor of 13% which is extremely low but does allow illustration of the effect of different demand rates in the supply chain.

It should be noted that the demand figures are taken from the Hydrogen strategy, published last year, which does not have the increased production ambition of the Energy Security Strategy. It is therefore possible that the demand and load factors will be higher than that modelled.

4.3.1.1 Blue Hydrogen Production

As stated above SMR technology has been taken as representative of blue hydrogen production. This has largely been due to the availability of data for analysis. Internal Wood cost data on SMR developments has been reviewed against each of the material/equipment and services categories depicted in the taxonomies described in Appendix D.

The block flow diagram below depicts what is included within the limits of the analysis.

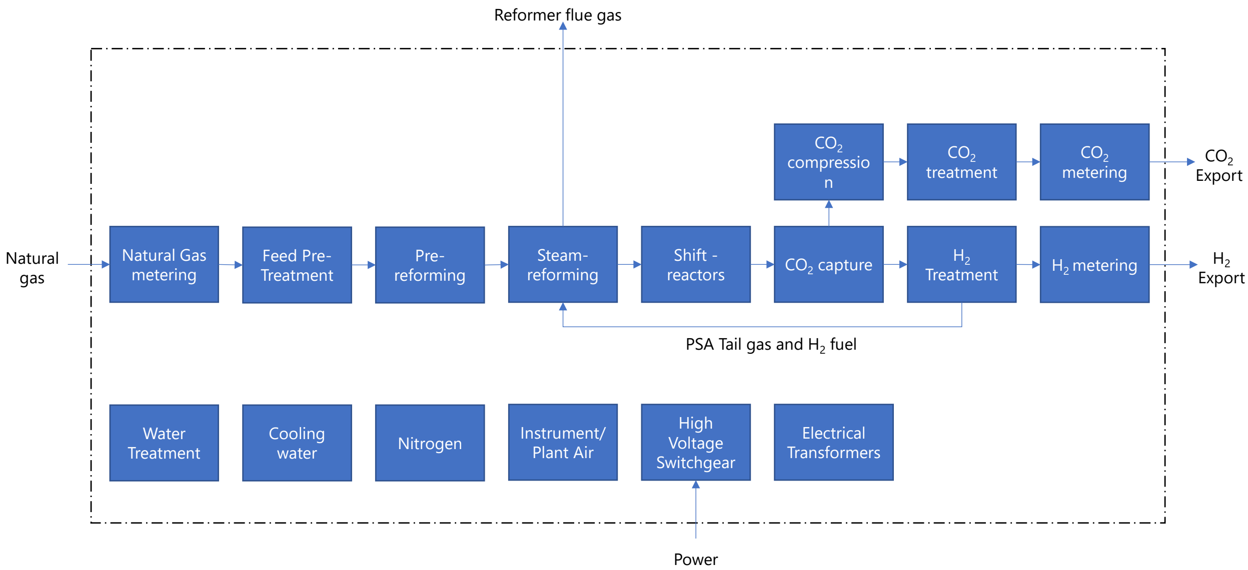


Figure 11: SMR Blue Hydrogen Production Block Flow Diagram

For blue hydrogen, in particular, it should be noted that the associated CCS is only included up to the "facility fence" and does not consider the entire CCS value chain. This involves the capture, treatment and compression up to 30bar_g suitable for transfer into a CO_2 collection network.

It also does not include hydrogen compression facilities, which is covered under the respective transport and storage options.

Based on the above analysis Figure 12 depicts the split of materials and services for a representative project. This is further split by service and material categories as detailed in each taxonomy. Note each secondary chart adds to the total in the first. Other costs include miscellaneous including shipping and spares.

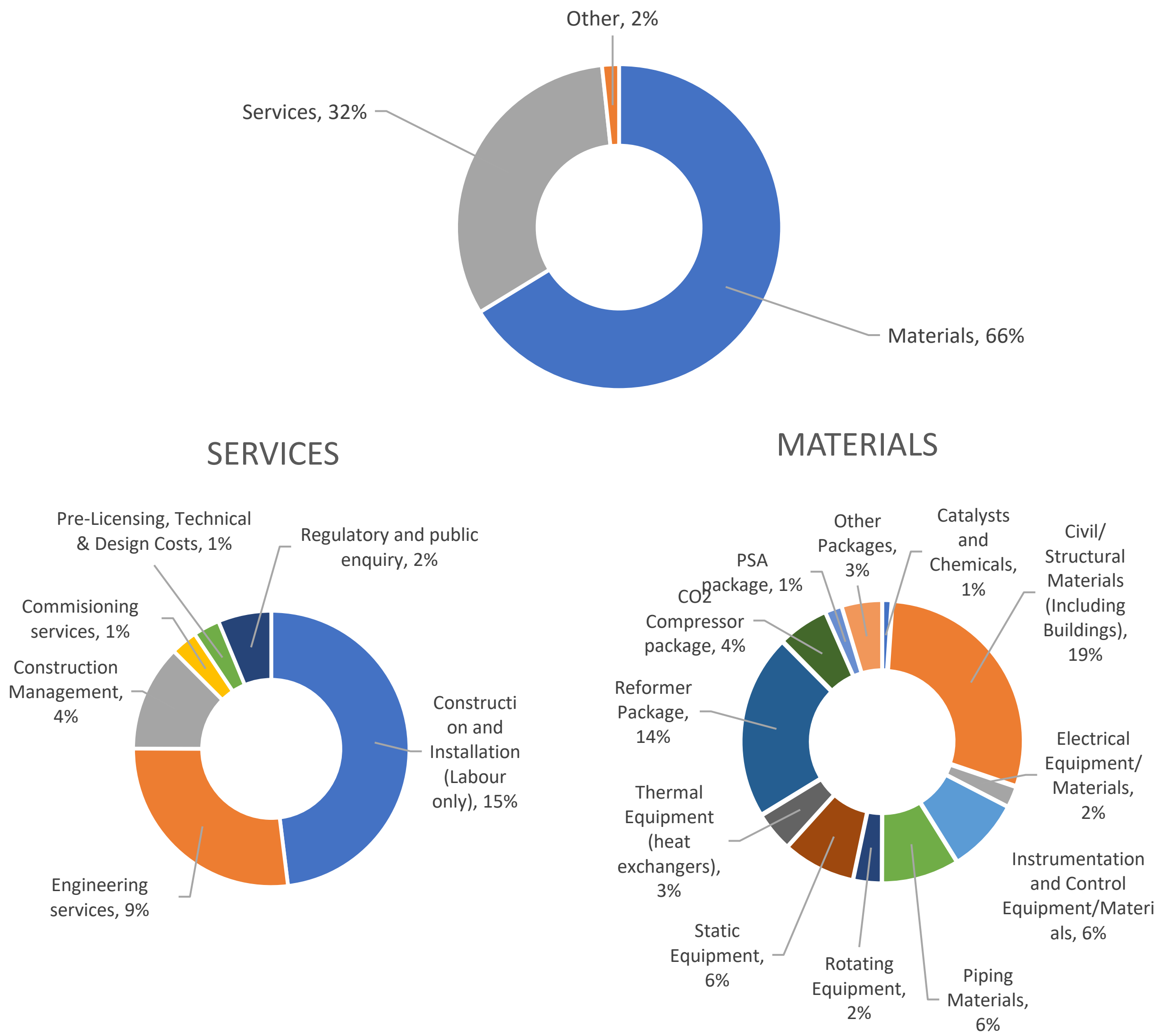


Figure 12: Segment Split for a representative Blue Hydrogen Plant

The overall scale of capital expenditure (capex) required is estimated using figures published in BEIS Hydrogen Production Costs 2021[23]. This provides illustrative capital costs for 2020 to 2050 for both 300MW and 1000MW scale plants to show the impacts of economies of scale and reduction in costs as technology develops/matures. Capex figures are provided on a £/kW H_2 (HHV) basis and, thus, allow calculation of an overall scale, on an illustrative basis, by using production capacity targets/assumptions across the adopted scenarios.

23 Department for Business, Energy and Industrial Strategy. Hydrogen Production Costs 2021. August 2021 (https://www.gov.uk/government/publications/hydrogen-production-costs-2021)

Figure 13 illustrates possible scales and costs of blue and green hydrogen production supply chain segments for each of the adopted scenarios.

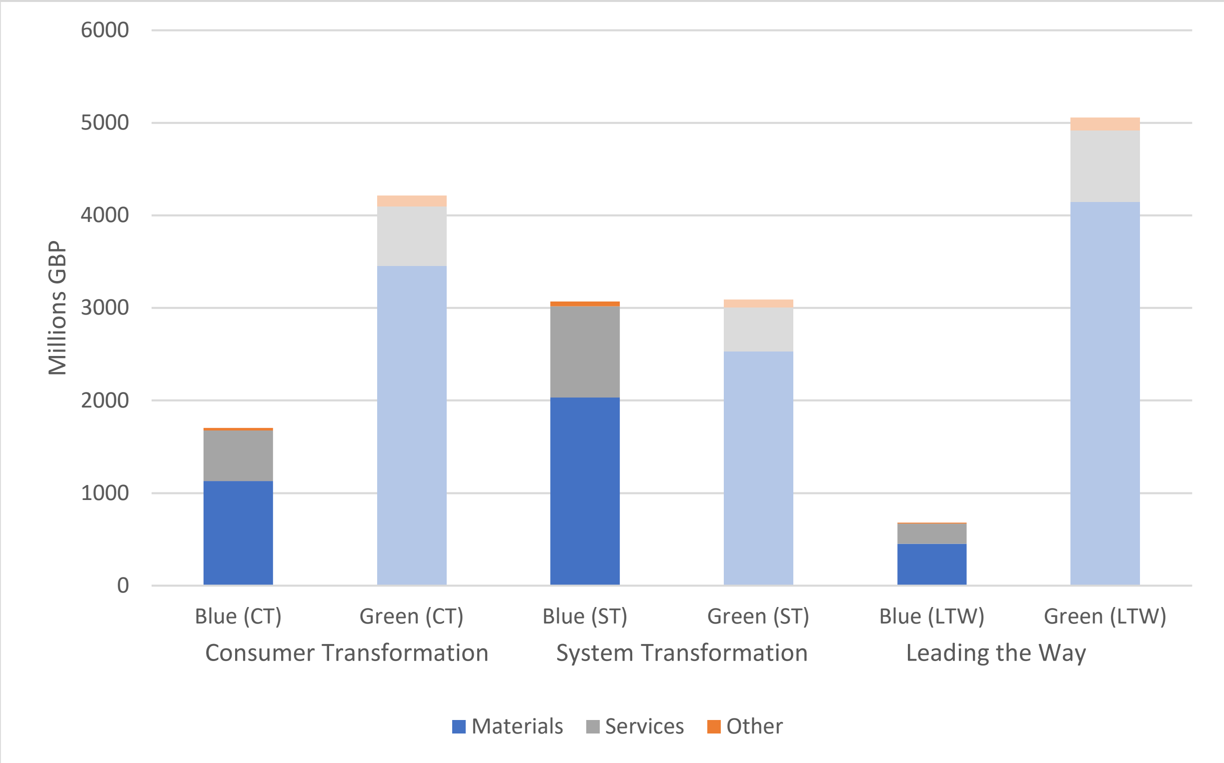


Figure 13: Cumulative Scale of Blue (and Green) Hydrogen Production Supply Chain by 2030

The variance between the scenarios is a result of the predefined production technology mix described in section 4.3.1 i.e. System Transformation relies on a greater deployment of blue hydrogen than the other scenarios. For all scenarios in 2030 it is assumed that the scale of the units is in the 100's of MW range and, as such, pricing figures rely on the year 2030 300MW reference values adopted. This results in a higher value of total materials and services compared to a scenario utilising 1000MW scale plants, however, it is assumed that, to begin with, production assets will be at a smaller scale until the market for hydrogen is better established and market drivers present more opportunity for deployment. This is considered as an appropriate assumption but does risk overestimating the scale and cost of the respective elements by as much as 24% should deployment be undertaken at the 1000MW scale and, therefore, the anticipated economy of scale is achieved.

Across all scenarios civil / structural materials represent the largest cost of materials. Construction and installation services represent the greatest share of the services. The reformer package represents the single biggest cost equipment item followed by the CO_2 compressor package. Note that hydrogen compression is not included in this section of analysis.

4.3.1.2 Green Hydrogen Production

PEM technology has been taken as representative of green hydrogen production. This selection was made on the basis that PEM represents the lowest cost of production of hydrogen in the future although, currently, it is higher than alkaline based electrolysis[18]. Internal Wood cost data for a number of PEM project developments has been reviewed against each of the material/equipment and services categories depicted in the taxonomies described in Appendix D.

The block flow diagram below depicts what is included within the bounds of the analysis. For green hydrogen in particular it should be noted that water is assumed to be supplied from the sea and, therefore, desalination is required. The source of water will vary from project-to-project depending on available resources. Deployment of hydrogen production via electrolysis at significant scale will pose a number of issues for use and prioritisation of inland water resources. It was, therefore, assumed that sea water would be used as a conservative approach. Similarly, as for blue hydrogen production, the analysis does not include hydrogen compression.

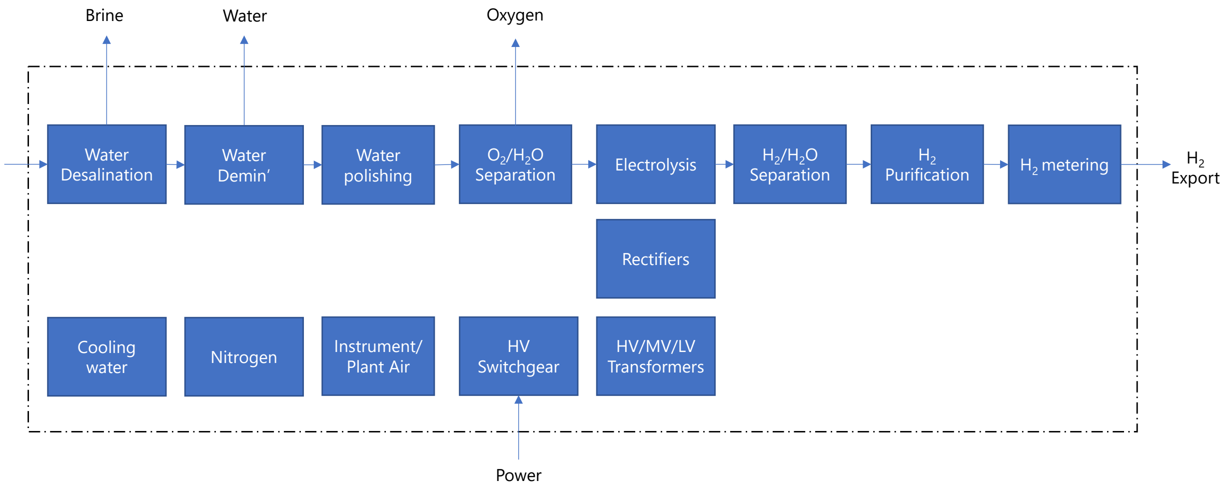
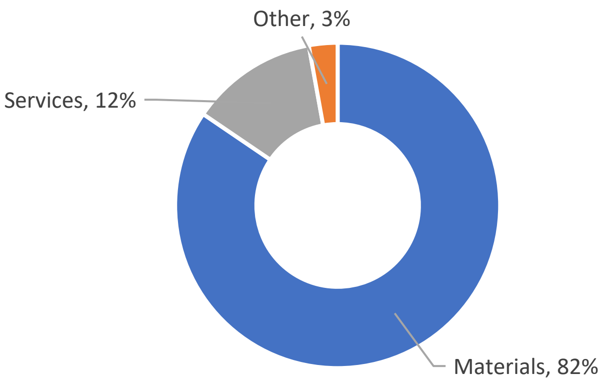


Figure 14: PEM Green Hydrogen Production Block Flow Diagram

Based on the above analysis Figure 15 depicts the split of materials and services for a representative project. This is further split by service and material categories as detailed in each taxonomy.



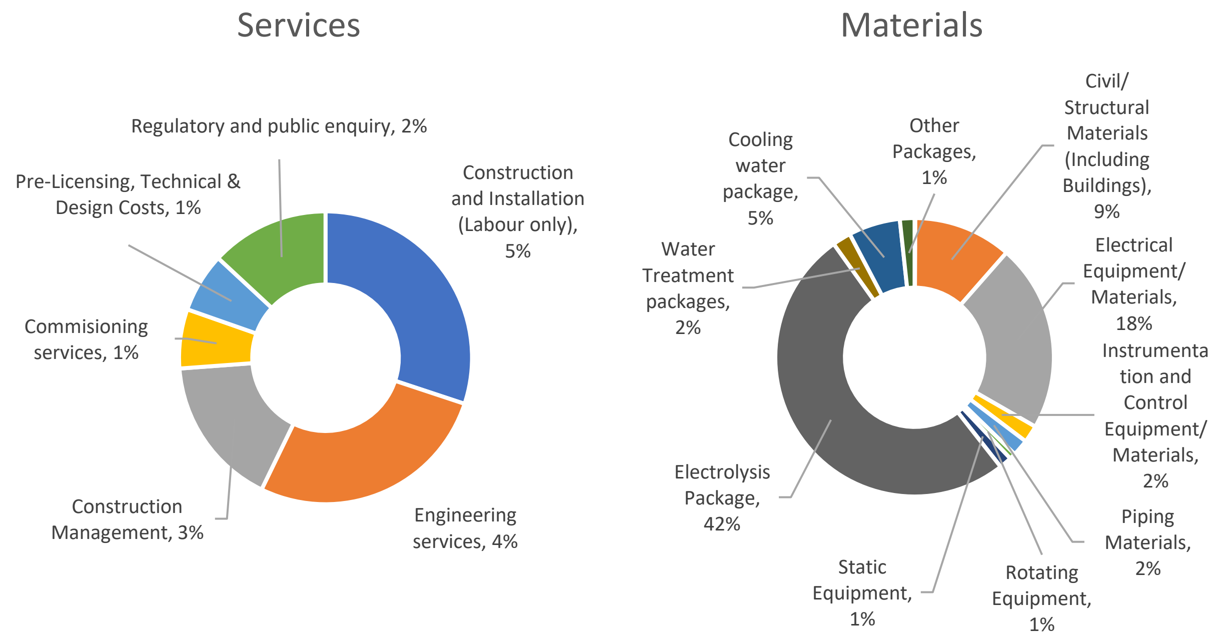


Figure 15: Segment Split for Green Hydrogen Production

The overall scale of capex required is, again, estimated using figures published in BEIS Hydrogen Production Costs 2021[24]. This provides illustrative capital costs for PEM electrolysis from 2020 to 2050 allowing for a reduction in costs as technology develops/matures. Capex figures are provided on a £/kW H_2 (HHV) basis and, thus, allows calculation of an overall scale, on an illustrative basis, by using production capacity targets/assumptions across the adopted scenarios.

Electrolyser technology is assumed to be scalable and, therefore, only one price curve was provided and is utilised in the analysis. Comparison of the breakdown of components against those published in literature support this assumption. Although GW scale facilities do not, currently, exist the Institute for Sustainable Process Technology, though the Hydrohub Innovation Programme - Gigawatt Green Hydrogen plant[25], has produced capital cost estimates for large scale electrolysis plants. On analysis, the current 2020 price agrees with the analysis of Wood Internal data. It is recognised that as electrolysis technology matures the component splits of materials and services will evolve to a greater extent than that predicted for blue hydrogen production and, therefore, presents a greater risk in the likely magnitude of variability within the constituent supply chains.

24 Department for Business, Energy and Industrial Strategy. Hydrogen Production Costs 2021. August 2021. (https://www.gov.uk/government/publications/hydrogen-production-costs-2021)

25 Institute for sustainable process technology - Hydrohub Innovation Programme - Gigawatt Green Hydrogen plant https://ispt.eu/projects/hydrohub-gigawatt/

Figure 16 illustrates possible scales and costs of green and blue Hydrogen production supply chain categories for each of the adopted scenarios.

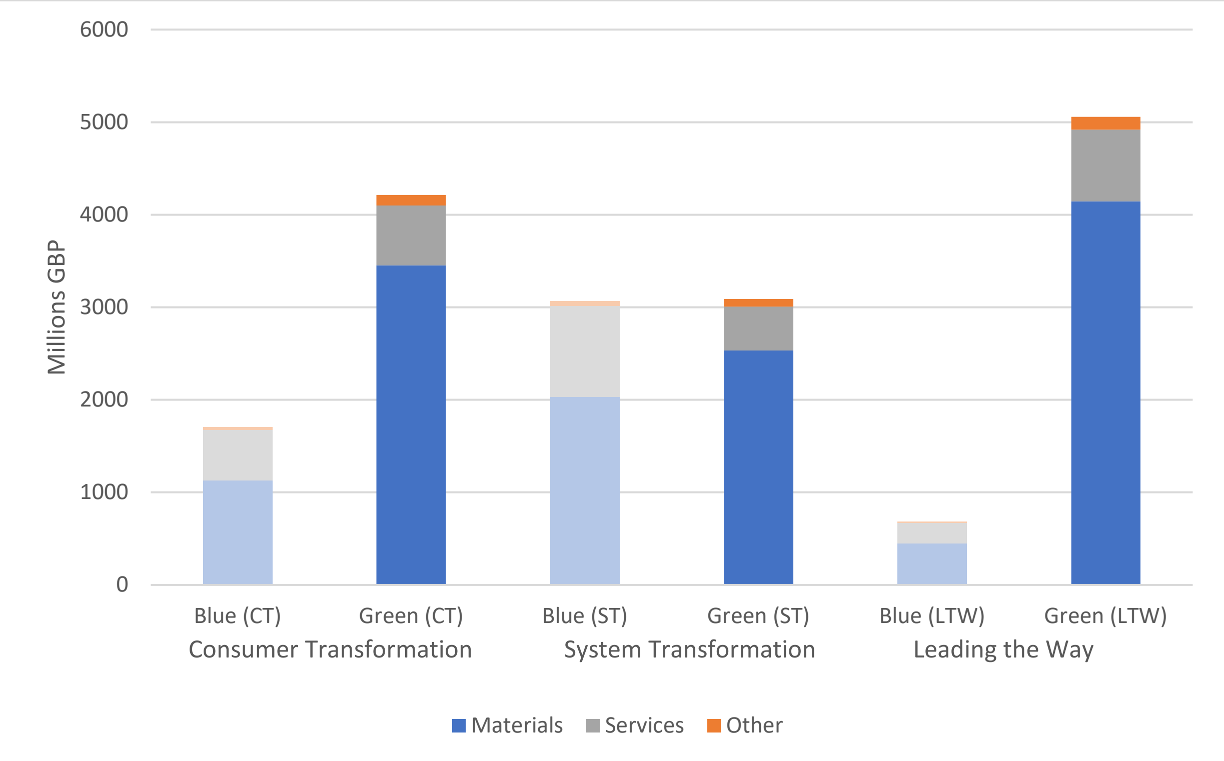


Figure 16: Cumulative Scale of Green (and Blue) Hydrogen Production Supply Chain by 2030

The variance between the scenarios is a result of the predefined production technology mix described in section 4.3.1 i.e. Leading the Way relies on a greater deployment of green hydrogen than the other scenarios. What is clear is that the cost of the electrolyser package is significant. This also explains why the overall cost of materials is greater in this case Figure 15) when compared to the blue hydrogen example (Figure 12). As a packaged item the electrolyser package includes a proportion of the engineering and fabrication/installation services within its cost and this is included within the project estimate as a materials cost. An estimate of the build-up the package cost is depicted below in Figure 17, based on Woods assessment of a typical package supply.

Electrolyser Supplier Package:	% of Cost
Equipment	
Main Equipment	43%
Transformers, rectifiers, switchgear	20%
Bulk Materials	
Piping Materials	3%
Field instrumentation	3%
Electrical and instrument cabling and interface cabinets	5%
PLC for plant control, safeguarding and monitoring	4%
Labour	

Electrolyser Supplier Package:	% of Cost
Piping Installation labour	3%
Electrical and instrument installation labour	2%
Pre-assembly of equipment as a module/skid	10%
Package Engineering design	3%
Installation support/supervision	1%
Commissioning support	1%
Maintenance and Operations support	1%
Other	
Construction Spares	1%
Operating Spares	1%
Capital Spares	1%
Shipping to site	1%

Figure 17 Typical Build-up of Electrolyser Package TIC (Total Installed Cost)

What is also evident from the analysis is the quantity of electrical materials and equipment that is required to support green hydrogen production. This includes high voltage switchgear; high, medium and low voltage transformers and rectifiers as well as cables and cabinets etc. This is not surprising considering the quantity of electrical power required for the electrochemical splitting of water to produce hydrogen. This equipment is not unique to hydrogen production and can be found on any development to a certain extent but what is unique to green hydrogen production is the scale at which it is required and, therefore, contributing a significant portion of the project cost. This electrical equipment is found both within the electrolyser package (MV transformers and rectifiers) and within the wider project (HV switchgear, HV/MV/LV transformers and electrical cables etc).

4.3.2 2050 Hydrogen Production and Demand

In 2050 hydrogen production capacity and demand is taken from the relevant Future Energy Scenarios (FES)[8] respectively for all cases. The split between blue and green production methods is also taken from the FES. This is similar to the scenarios analysed for 2030 in that in 2050 the System Transformation scenario is more reliant on blue hydrogen production (70%) and Leading the Way is almost exclusively Green Hydrogen production (95%). The Consumer Transformation scenario relies predominantly on green hydrogen (75%).

4.3.2.1 Blue Hydrogen Production

The same methodology and basis used for analysis in 2030 has been used again for 2050. The limits of the gas reforming plant remain the same. What is different is the price per kW used to estimate the scale of capital required to install the assets required to meet the production target. Costs are taken from the same source[18], but a 2050 price is used. The 2050 prices include for cost reduction from learning of deployment at scale. This, potentially, underestimates the value of the supply chain up to 2050 as it is clear that these assets would be developed over the years approaching 2050 and, thus may have higher costs than those modelled as not all cost saving will have been realised. However, for illustrative purposes, looking multiple decades into the future it is considered a reasonable approach as any number of changes could occur that would change the quantification of a supply chain moving prices up and down for example a bottleneck in supply capacity forcing a higher price/cost or a deployment of new technology lowering future prices/costs.

In 2050 for the System Transformation scenario, we have assumed a greater number of larger scale production units are deployed as technology will have matured and the hydrogen market will become more established. For Leading the Way scenario, we have assumed that blue hydrogen production remains at the lower scale capacity as the hydrogen supply chain has moved to be predominantly supplied by green hydrogen production. In Consumer Transformation we have selected a 50:50 mix between scale of assets to demonstrate a variety in contrast to the other scenarios.

Figure 18 illustrates the possible scale of the supply chain associated with the deployment of blue and green hydrogen production assets in 2050.

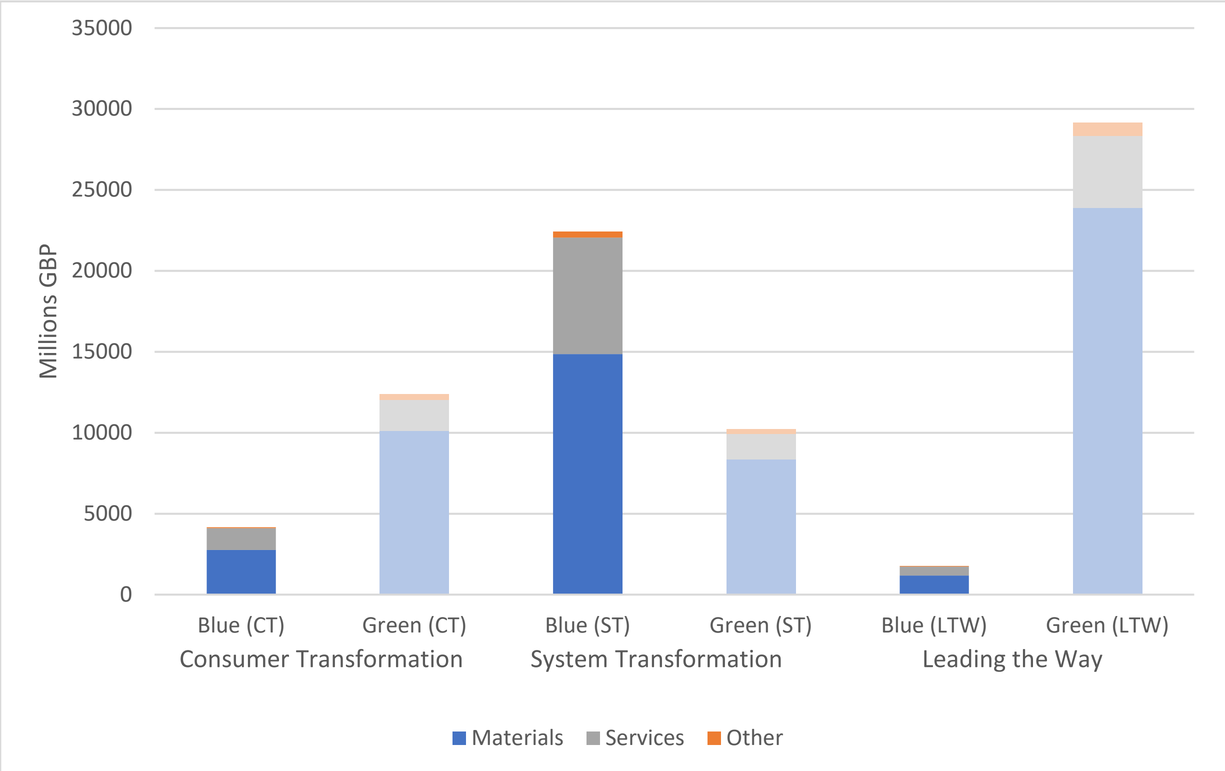


Figure 18: Cumulative Scale of Blue (and Green) Hydrogen Production Supply Chain by 2050

The proportions of the constituent parts in this analysis remain unchanged from the 2030 analysis, which is unlikely, but how the hydrogen economy and its constituent supply chains develop over the next 30 years is not known at this stage. The scale and variability to which the proportions and value of the supply chain components will change may be significant if elements are capacity constrained and basic materials become more expensive due to demand.

4.3.2.2 Green Hydrogen Production

Figure 19 illustrates the possible scale of the supply chain associated with green and blue hydrogen production in 2050.

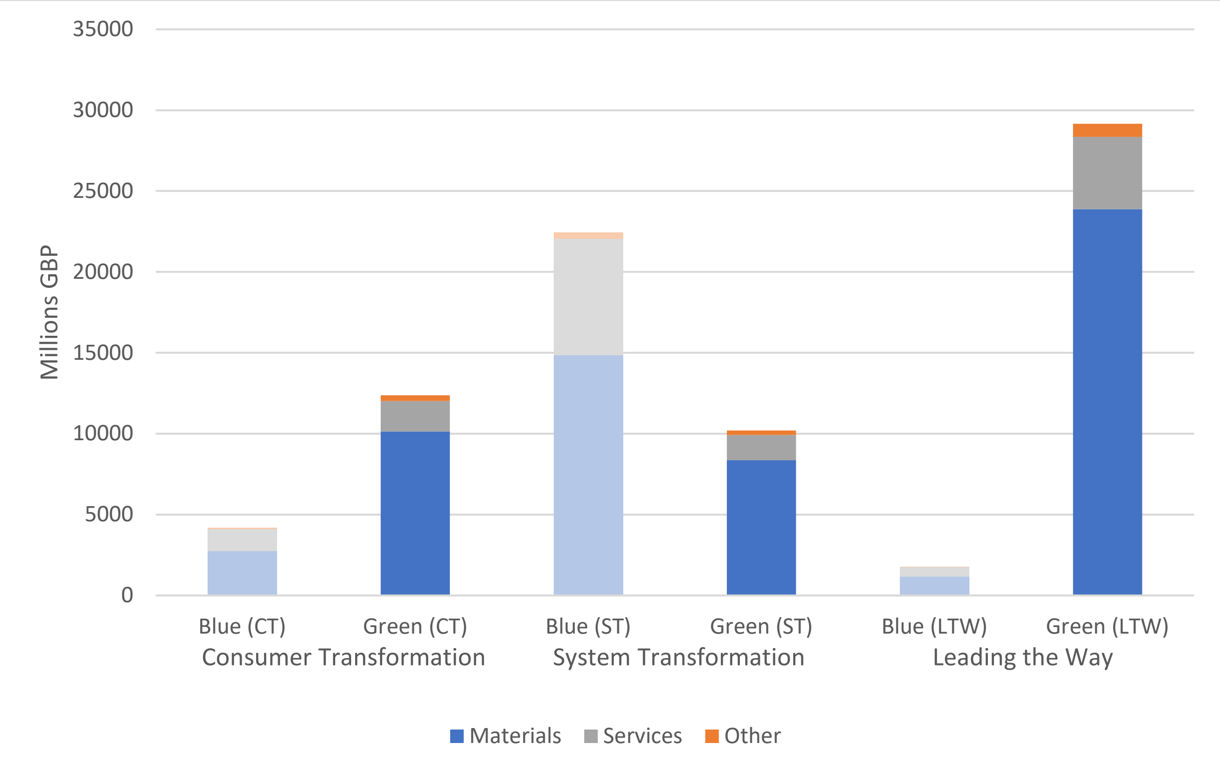


Figure 19: Cumulative Scale of Green (and Blue) Hydrogen Production Supply Chain by 2050

Again, the same methodology and basis used for analysis in 2030 has been used for 2050. The limits of the electrolysis plant remain the same. What is different is the price per kW used to estimate the scale of capital required to install the assets required to meet the production target. Costs are taken from the same source[18] but a 2050 cost is used. This cost is lower in 2050 than compared to 2030 due to assumed improvements in manufacturing techniques and a higher degree of automation helping to realise a lower cost of production. This is expected to affect the electrolyser stacks, particularly, and, therefore, there is a risk that the proportion of value attributed to the electrolyser packages is overestimated in the data presented. However, similarly to the blue hydrogen production deployment, a large number of the assets will be operational before 2050.

4.3.3 Hydrogen Storage

The volume of Hydrogen storage required is dependent on the scale and pattern of hydrogen supply and demand. This is highly uncertain and estimates of storage need vary significantly. The quantity of hydrogen storage considered in this work is that described in the FES, which is taken for all scenarios in 2030 and 2050 and in addition an assumption of storage required to support hydrogen used in transport. The main sensitivity in the estimate of storage costs are these very uncertain projections of storage requirement and therefore this analysis should be seen as illustrative only. This storage requirement stated in the FES is taken to be the storage required to smooth out seasonal variation in demand however it is acknowledged that geological storage may also be required for other uses such as power system balancing in a hydrogen turbine. The FES assumes that this storage is provided by salt caverns and, therefore, that is what has been assumed in this analysis although there is ongoing research to suggest that storage in depleted gas fields is also feasible however will likely incur different costs to those presented here. The stated quantity required in the FES is certainly within the theoretical capacity of the UK potential of 200TWh, assuming that cavern size is limited to 140-160GWh[26].

The evidence base for storage costs is very limited and estimates vary greatly, however using a GBP/GWh stored cost for salt cavern storage in a specific area from the hydrogen supply chain evidence base[27] allows a highly illustrative quantification of the total value associated with each of the adopted scenarios. This absolute cost includes the cost of the cavern construction along with the associated topsides for operation. Geology suitable for salt caverns can be found in 3 main onshore areas in the UK: Wessex Basin, Cheshire Basin and East Yorkshire. For illustrative purposes we have taken the conditions and cost of storage in East Yorkshire. In 2030 this is a reasonable assumption and some developers have already announced intention to store hydrogen in salt caverns in this area[28]. In 2050 it is likely that storage projects will be undertaken in other areas in the UK and cavern construction costs will vary for these other locations owing to, among other things, the depth of the salt deposit and associated storage pressure and the distance from an appropriate water source for solution mining.

The number of caverns required for each of the scenarios was calculated using a typical cavern size of 150GWh. For East Yorkshire this equates to the working capacity of a 300,000m^3 cavern with a maximum operating pressure of 270 bar$_a$. The cost of construction of a cavern of this size was taken from work completed by Amec Foster Wheeler for the Energy Technology Institute in 2013[29] and escalated to present day costs. The ETI report was also the source of information used to support the Hydrogen supply chain evidence base so it is therefore considered comparable.

To calculate the cost of topside infrastructure, the cost of cavern construction was deducted from the total storage cost. This topside cost was then split into more granular categories using cost data for topside infrastructure from the ETI report.

There is uncertainty around the location and configuration of caverns, particularly around the number of caverns per site. This affects the cost estimates, and the ratio of construction and topside costs. For example, a site with only one cavern would have higher topside costs per unit of hydrogen stored than a site with multiple caverns, as some of the topside costs can be shared between the caverns. A site located inland and far from a suitable water source for solution mining would have higher construction costs than a site located close to water, due to the cost of transporting water to the site.

As can be seen in Figure 20 there is a significant value associated with the construction of caverns alone - this cost does also not include the cost of the land or cushion gas required for stable cavern operation. These costs are subtracted from the total calculated stored costs to provide the adjusted costs displayed in Figure 21.

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26 J Williams et al. British Geological Survey (2020) Theoretical capacity for underground Hydrogen storage in UK Salt Caverns

27 Element Energy (2018) Hydrogen Supply chain evidence base

28 SSE (2021) https://www.sse.com/news-and-views/2021/07/sse-and-equinor-developing-plans-for-world-leading-hydrogen-storage-facility-in-yorkshire/

29 Energy Technologies Institute (2013) Hydrogen Storage and Flexible Turbine Systems WP2 Report – Hydrogen Storage

Scenario	2030		2050	
	Caverns	Cost M GBP	Caverns	Cost M GBP
Consumer Transformation	7	234	80	2,678
System Transformation	7	234	340	11,380
Leading the Way	14	469	100	3,347

Figure 20: Salt Cavern Requirement in 2030 and 2050

The adjusted cost using the figures quoted in the hydrogen supply chain evidence base are depicted below

Scenario	2030 (M GBP)	2050 (M GBP)
Consumer Transformation	1,169	14,163
System Transformation	1,169	60,193
Leading the Way	2,338	17,704

Figure 21: Salt Cavern Total Adjusted Stored Cost in 2030 and 2050

The split of costs associated with the topside infrastructure is depicted below in Figure 22

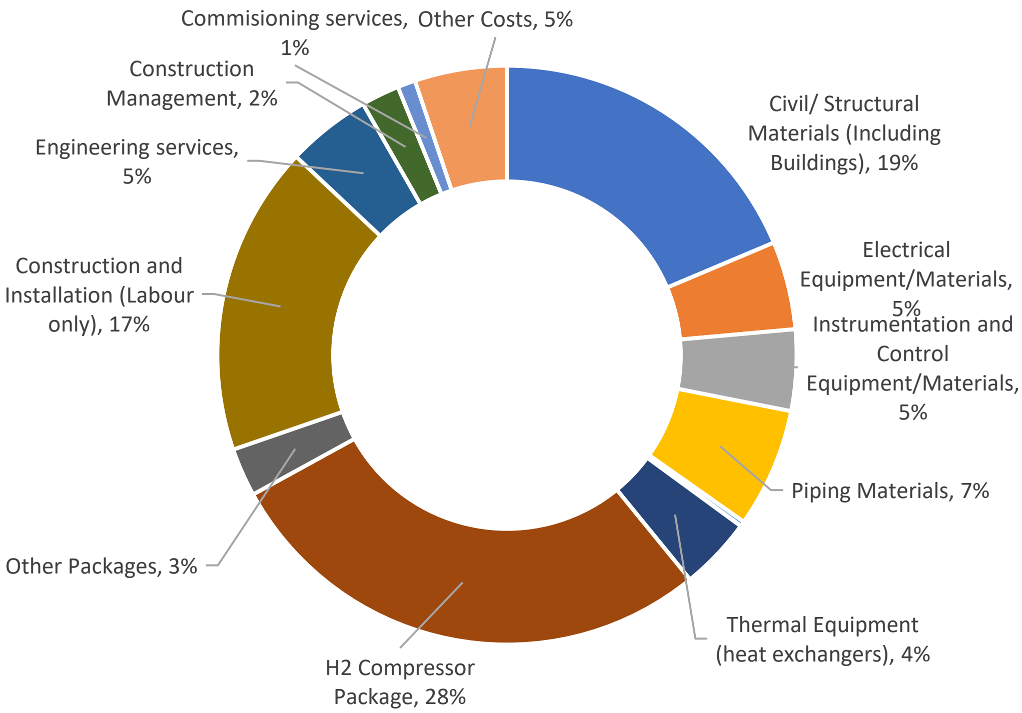

Figure 22: Cost Make up of Surface Facilities for Salt Cavern Storage

Compressor costs are the largest contributor to this overall cost. In this case compressors are based on a reciprocating type of compressor.

4.3.3.1 Above Ground Hydrogen Storage

Certain users of hydrogen will require above ground temporary storage and compression. This is particularly true for hydrogen destined for use in ground transport (Hydrogen refuelling stations for road vehicles and trains). The above ground high pressure storage is in addition to the storage requirement outlined in the FES which is predominantly salt cavern storage. This above ground storage requirement was, therefore, estimated based on the daily requirement for hydrogen used in ground transportation applications. This was based on 1 cycle per day i.e. 24 hours storage. The total value of the storage requirement was based on numbers published in the hydrogen supply chain evidence base[27] in GBP/kWh. This cost was then split into constituent components based on Wood internal reference data for similar applications.

The split of component costs is depicted in Figure 23.

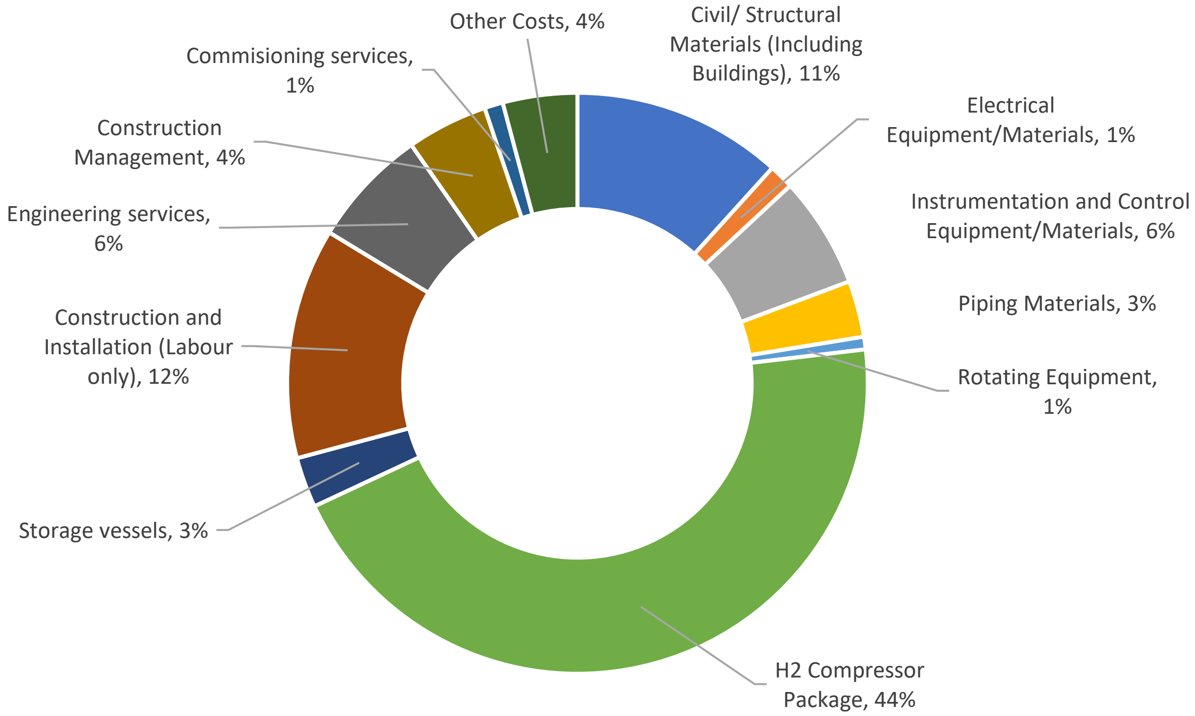

Figure 23: Cost Make up of Above Ground Storage Facilities

Again, hydrogen compressors contribute the greatest proportion of the cost from a materials standpoint and construction and installation from a services perspective. The total value for 2030 and 2050 is illustrated in Figure 24.

Scenario	2030 (M GBP)	2050 (M GBP)
Consumer Transformation	450	4,800
System Transformation	900	9,300
Leading the Way	150	6,750

Figure 24: Above ground compression and storage facilities cost in 2030 and 2050

The above is based on 1 cycle per day and the upper cost reported in the hydrogen supply chain evidence base (selected as a conservative assumption). There is a high degree of uncertainty in the in the assumptions made and thus the information presented here but does provide an illustration of the potential supply chain scale associated with this storage application. It is anticipated that composite, Type 4 pressure vessels will become more common place and cheaper over time as manufacturing methods improve and demand increases. This may, therefore, reduce the total cost stated above towards 2050.

4.3.4 Hydrogen Transport

The volume of hydrogen requiring transport across the UK and the method of transport will vary based on the type, size and location of the end market. Industrial users of hydrogen are likely to be located in industrial clusters close to hydrogen production facilities. Similarly, early adopters of hydrogen in the residential sector will likely be in hydrogen towns and cities rather than dispersed at random throughout the country.

Hydrogen destined for use in aviation and shipping is assumed to be based on the production of synthetic aviation fuel (aviation) and ammonia (shipping). These two production steps are assumed to be co-located with the hydrogen production assets, especially so for blue hydrogen plants where blue ammonia production units are fully integrated into a single facility. Therefore, hydrogen destined for this end use does not require transporting significant distance and is included within the industrial network.

Hydrogen destined for use in transportation i.e. fuel cell vehicles is not covered within the analysis. Hydrogen would either be transported to refuelling stations by industrial networks, through the repurposed natural gas distribution network or via truck (tube trailer) which is partially covered by the above ground storage analysis. However, this assumes a centralised production model. For scenarios utilising green hydrogen production it is equally possible that small scale decentralised production units could be deployed generating Hydrogen fuel across the country local to demand.

The assumptions and therefore the information presented in this section is highly uncertain and is included for illustrative purposes only to provide a sense of the potential scale of the supply chain.

4.3.4.1 Transport of Hydrogen to Industry

This analysis has assumed that dedicated low pressure hydrogen networks will be developed in the industrial clusters. This is especially true for blue hydrogen production that is anchored to the CCS clusters under development around the UK. Both blue and green (PEM) hydrogen production plants have the potential to produce hydrogen at pressure (30-60bara) and, as such, it assumed that additional compression is not required for these local networks. The precise route and size of a particular hydrogen network is not known at this point in time so to illustrate these local networks a sample network configuration is assumed based on a coverage area of 10km diameter. A number of these networks are then assumed for each of the adopted scenarios, depending on the demand for industrial hydrogen. In 2050 the network size is expanded further and the number of networks increased to reflect the greater demand and utilisation in the future. Under certain scenarios, in particular System Transformation, the natural gas network is repurposed for hydrogen and will likely then replace the need for these local networks but this has not been considered in this analysis.

The cost to build one local network has been calculated using estimates of GBP/km for the specified diameter using the equation provided in the Hydrogen Supply Chain evidence base[27]. This aligns with Wood's own internal data for onshore pipeline construction costs. The total cost in each scenario is calculated by multiplying the cost per network by the assumed number of networks. The breakdown of the total value to the constituent supply chain components is then undertaken using internal Wood data on pipeline projects.

Figure 25 and Figure 26 show the cumulative supply chain value associated with the installation of dedicated pipelines for industrial hydrogen use.

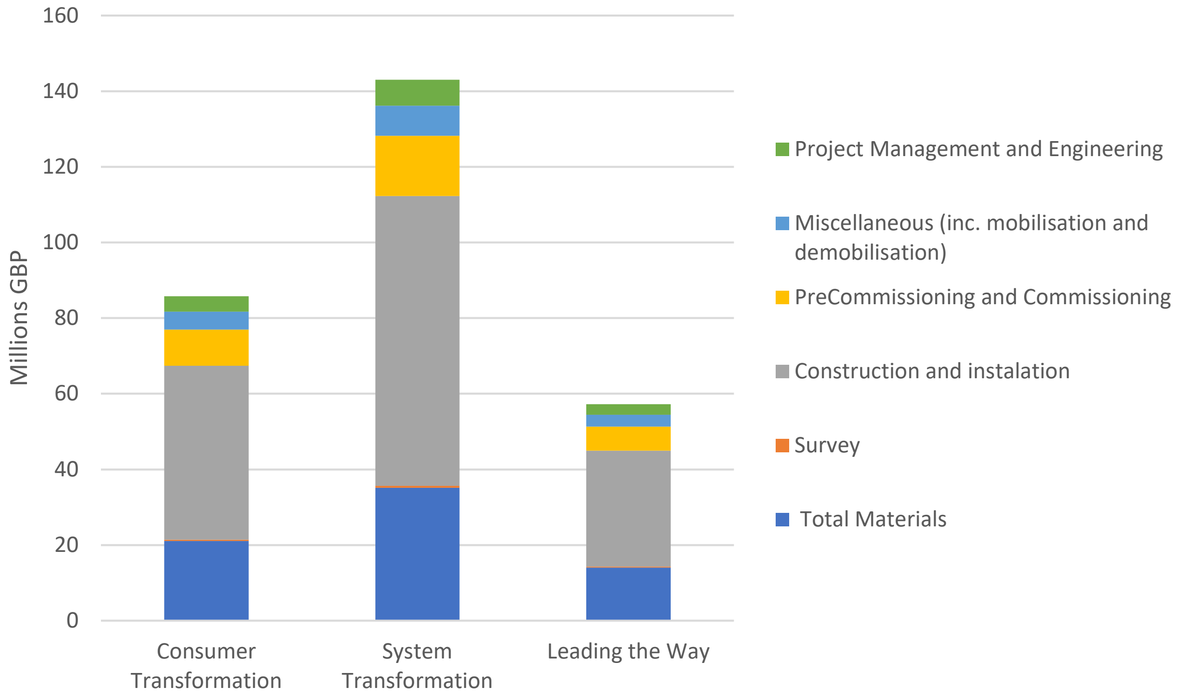

Figure 25: Installation of Pipeline Networks for Industrial Hydrogen Use in 2030

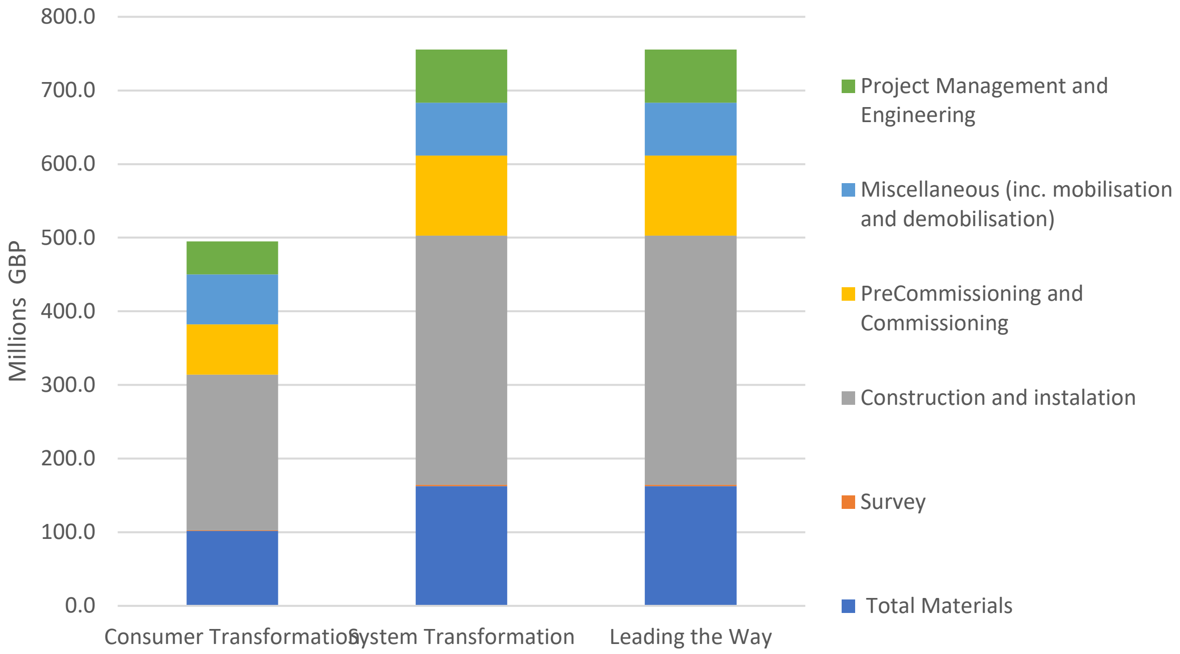

Figure 26: Installation of Pipeline Networks for Industrial Hydrogen Use in 2050

As is common with pipelines the greatest value component is the installation and construction of the pipeline rather than the materials which is piping equipment and materials (line pipe and valves etc).

4.3.4.2 Transport of Hydrogen to Residential Users

Bulk transport of hydrogen required for heating UK homes is analysed in 3 components:

1. Compression
2. High pressure transmission
3. Low pressure distribution to homes.

The quantity of hydrogen distributed to UK homes for, predominantly, heating purposes is taken directly from the Future Energy Scenarios. The government intends to take strategic decisions on the role of hydrogen for heat in 2026, so the demand for hydrogen for heat is dependent on the outcome of these decisions and could be zero. It is assumed that this hydrogen needs to be compressed for transmission. Depending on the level of hydrogen utilisation in UK homes, sections of the UK transmission system will need to be upgraded so that they are suitable for high pressure hydrogen storage and line pack storage needs. Low pressure distribution to homes is assumed to be undertaken in the natural gas distribution mains, which are repurposed for the use of hydrogen. Again, the extent of the refurbishment is linked to the level of utilisation of hydrogen by residential users. In 2030, residential demand for hydrogen is very low or zero. By 2050 the level of utilisation is either significant (System Transformation), moderate (Leading the Way) or low (Consumer Transformation). Costs of compression were calculated based on numbers published by Element Energy in the Hydrogen Supply Chain evidence base. This constituent supply chain value was derived from this headline cost number using Wood data on the build-up of a typical compressor station like those presented in Figure 27.

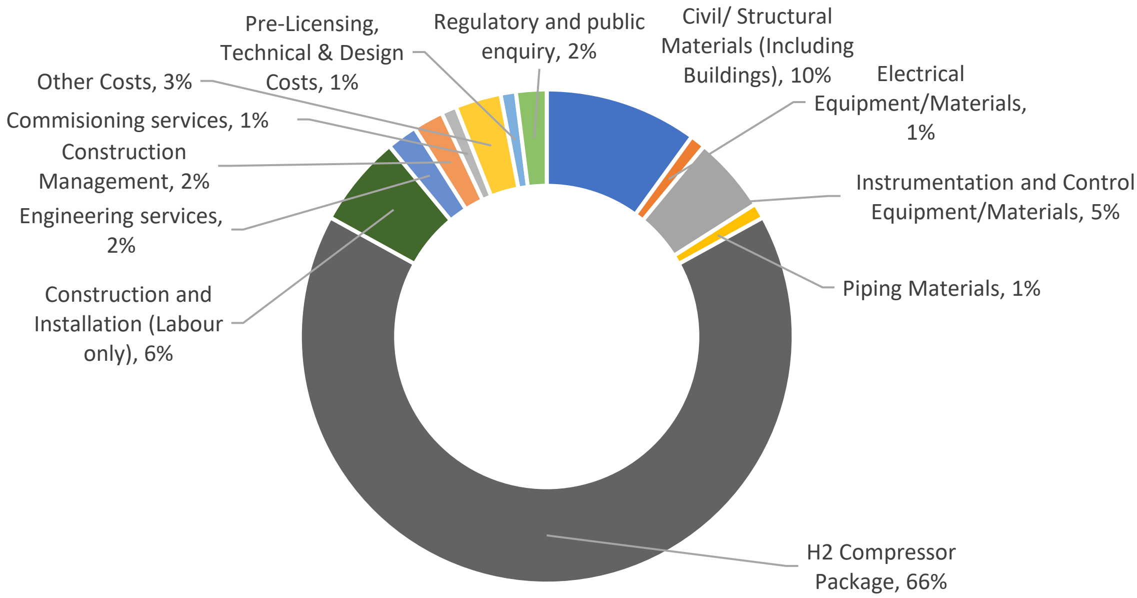

Figure 27: Cost makeup of Hydrogen Compression facility

Figure 28 depicts the cumulative supply chain values associated with compression of hydrogen for transmission by 2050.

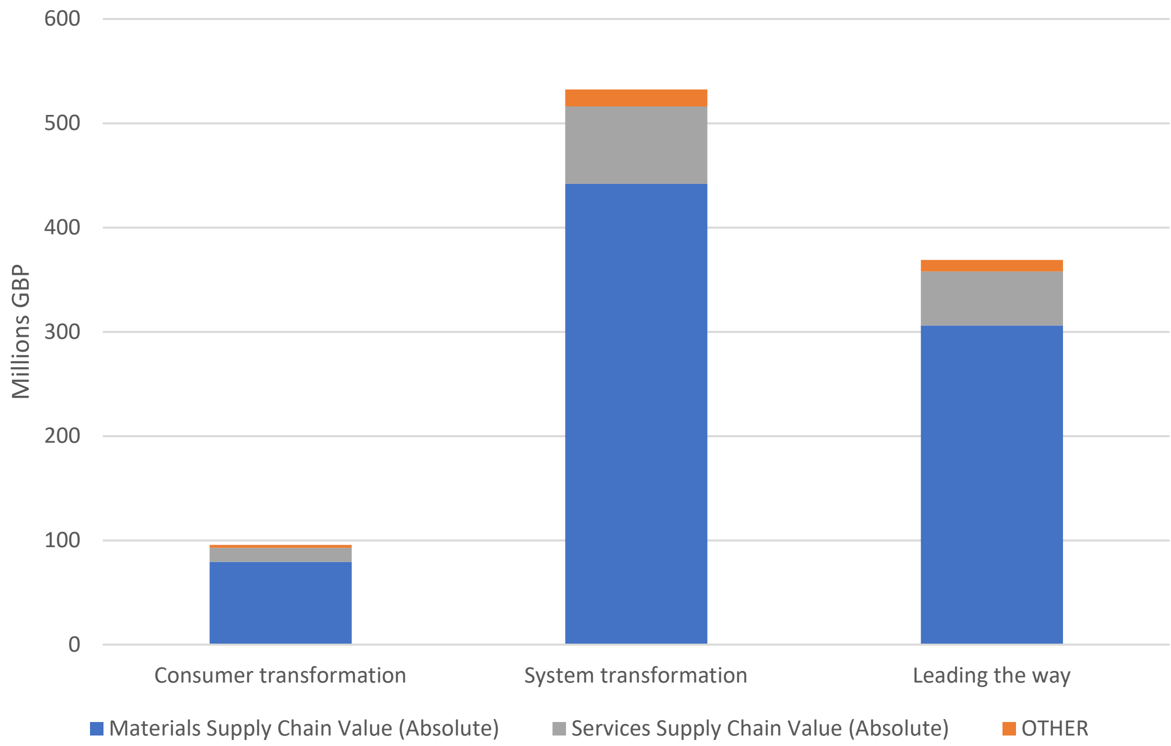

Figure 28: Cumulative Compression Requirement costs for Hydrogen Transmission by 2050

Hydrogen compressors dominate the cost make-up. This cost and build up is based on a reciprocating-type machine. It is hoped to utilise centrifugal type machines which, traditionally, offer a lower cost of compression. These machines are not currently commercially available although research and development is ongoing.

It is assumed that entirely new high pressure transmission system would be required to transport hydrogen to distribution networks. This is a conservative assumption but is consistent with assumptions supporting similar work published by others[27]. Replacement of the UK transmission system has been estimated assuming a length of 36 inch pipeline following the methodology outlined in section 4.3.4.1. The section length has been judged based on the level of residential hydrogen consumption i.e. for low consumption, only specific parts of the country will be utilising hydrogen in their homes. For the System Transformation scenario 7000km of pipeline is assumed to require replacement. This is a pessimistic assumption and its likely a proportion of the existing transmission may be repurposed, but it considered suitable for this illustrative example.

Figure 29 shows the possible cumulative value associated with replacement of the UK natural gas transmission system and its constituent supply chain value.

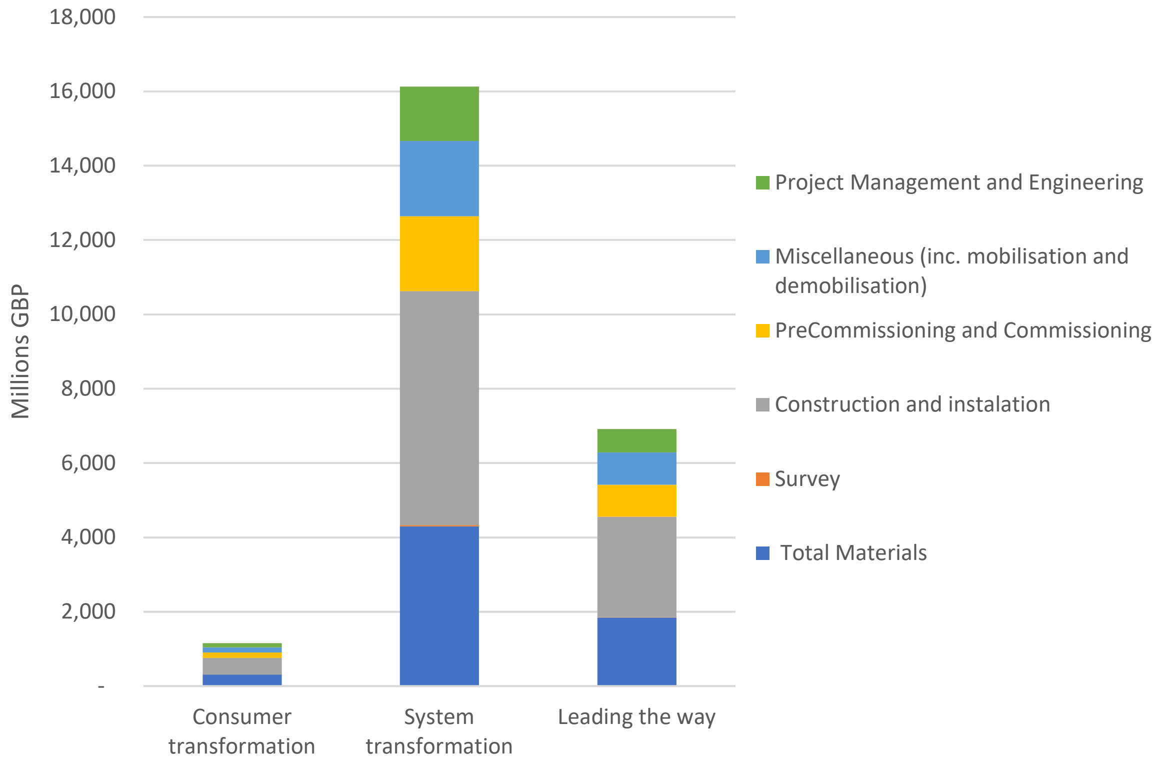

Figure 29: Transmission Pipeline Replacement Costs by 2050

The distribution of cost associated with repurposing the natural gas distribution system is presented in Figure 30. The cost of replacing the entire system. (~22.2 billion GBP), including its makeup, is published in the Hydrogen Supply Chain evidence base. The cumulative value requiring replacement under each scenario is roughly calculated from this figure based on a comparison of the present energy consumption of natural gas in UK homes for heating purposes against the estimated value of hydrogen consumption for the same purpose in each of the adopted energy scenarios. The cumulative value for System

Transformation, which assumes the greatest level of repurposing, is around 73% which equates to an investment 16.2 billion GBP by 2050 this is due to the assumption that there are some residual users of natural gas and, as with the other scenarios, a high degree of electrification. For Consumer Transformation and Leading the Way scenarios the cumulative values are 1.3 and 3.8 billion GBP respectively. There is uncertainty around the extent of repurposing that will be possible: if repurposing some parts of the distribution system proves to be challenging and some new pipelines are required instead, this could significantly impact the costs presented here.

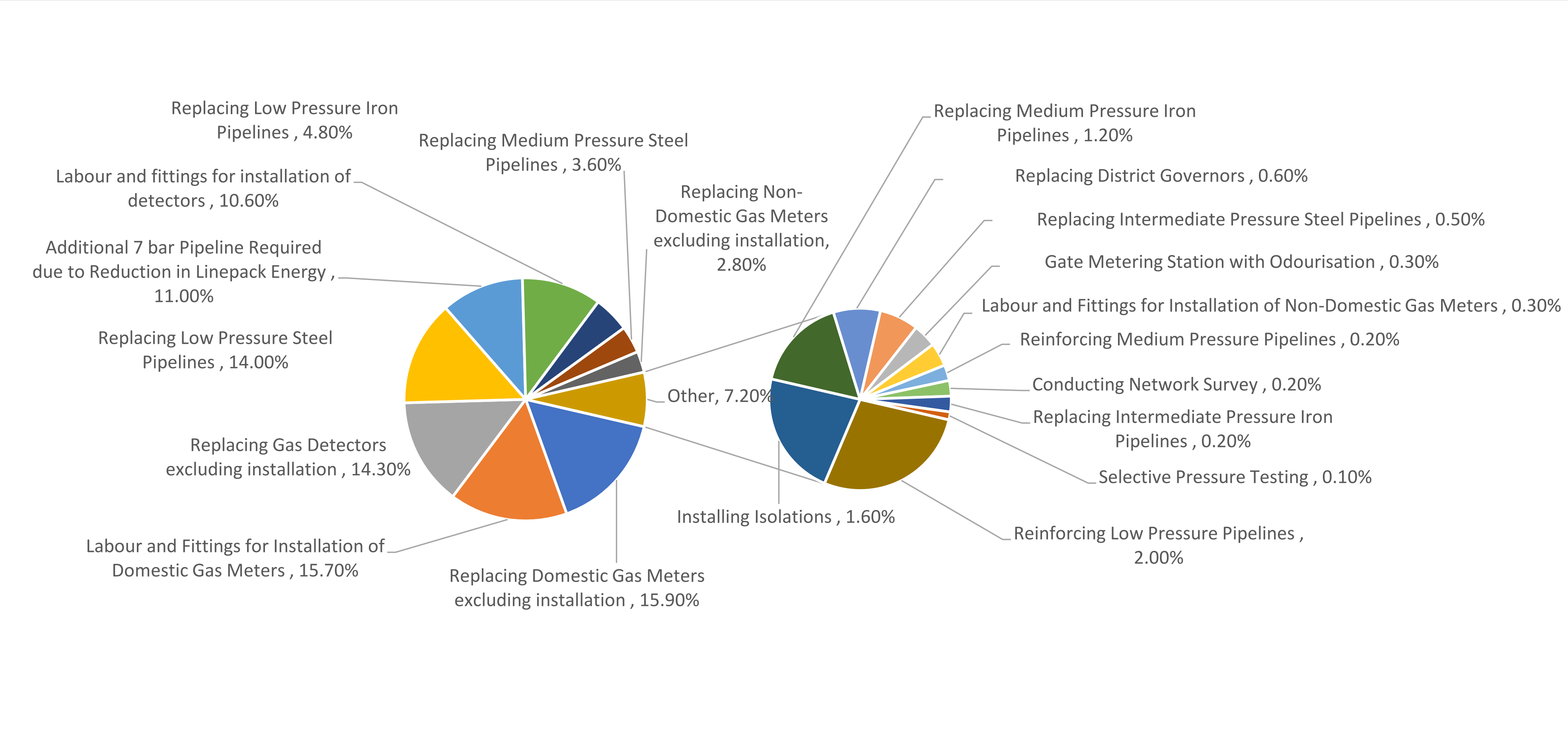

Figure 30: Cost distribution for Repurposing of the Gas Distribution Network 2050

4.3.5 Fuel Cells

The number of fuel cells required for fuel cell electric vehicles has been derived from the numbers of fuel cell electric vehicles estimated to be on UK roads for each of the adopted scenarios. These figures have been taken directly from the FES. This data is then categorised into light and medium/heavy duty vehicles. Data on the costs of manufacture of PEM fuel cells for automotive applications has been adapted from work completed by B.D. James at al.[30] This then allows a simplistic assessment of the potential supply chain value for automotive fuel cell manufacture for each of the adopted scenarios, as shown in Figure 31 and Figure 32.

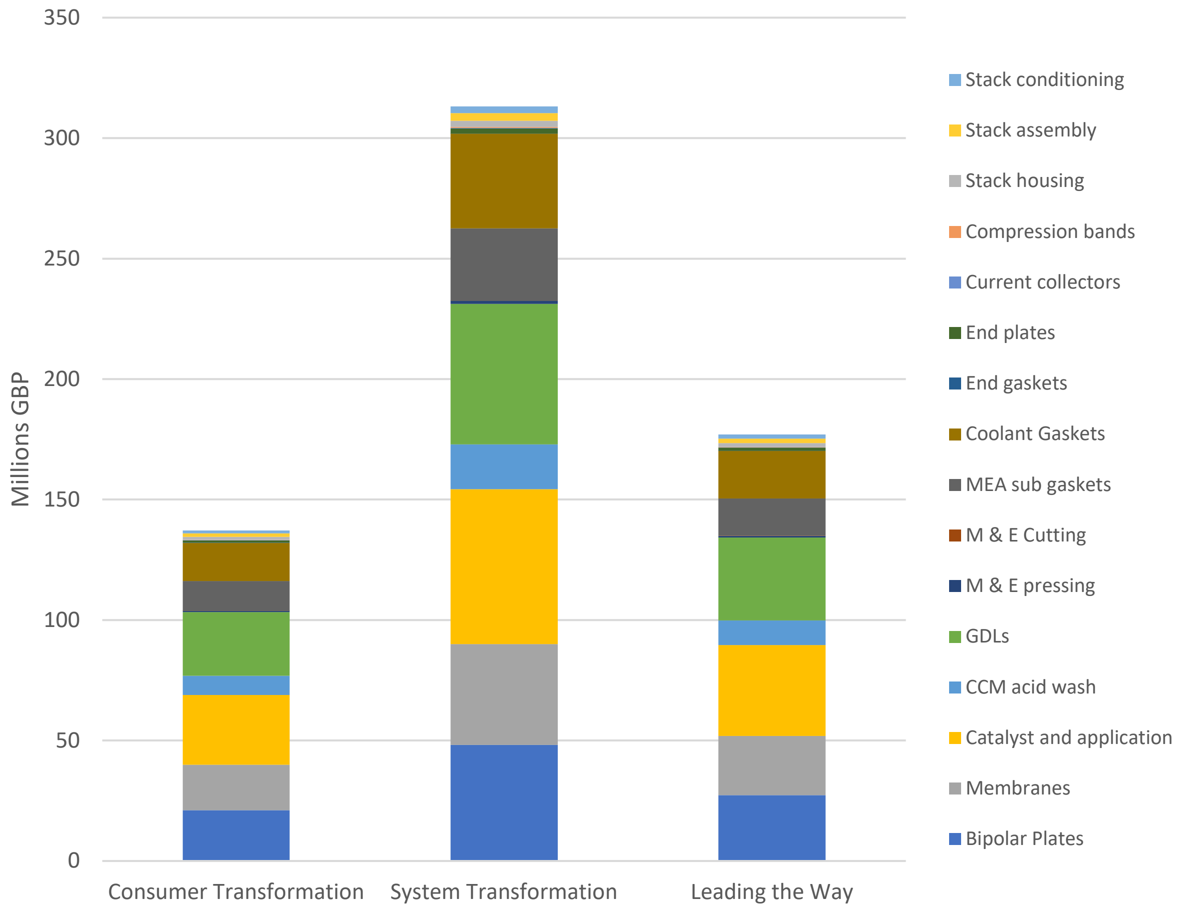

Figure 31: Fuel Cell Manufacturing Costs 2030

At lower numbers of manufacture the cost of production is higher. We have assumed a linear rate of manufacture between present day and 2030/2050 respectively. That rate dictates the price of manufacture used and therefore there is a risk that the numbers presented above are either over or underestimated depending on the actual rate of manufacture achieved. What is evident in the data across all scenarios is the growth in the contribution of catalyst and application component of the

30 B.D James at al. "Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2018 Update." Strategic Analysis December 2018

manufacturing supply chain. This is not so much growth but is the shrinking of the other elements of manufacture at higher rates of production

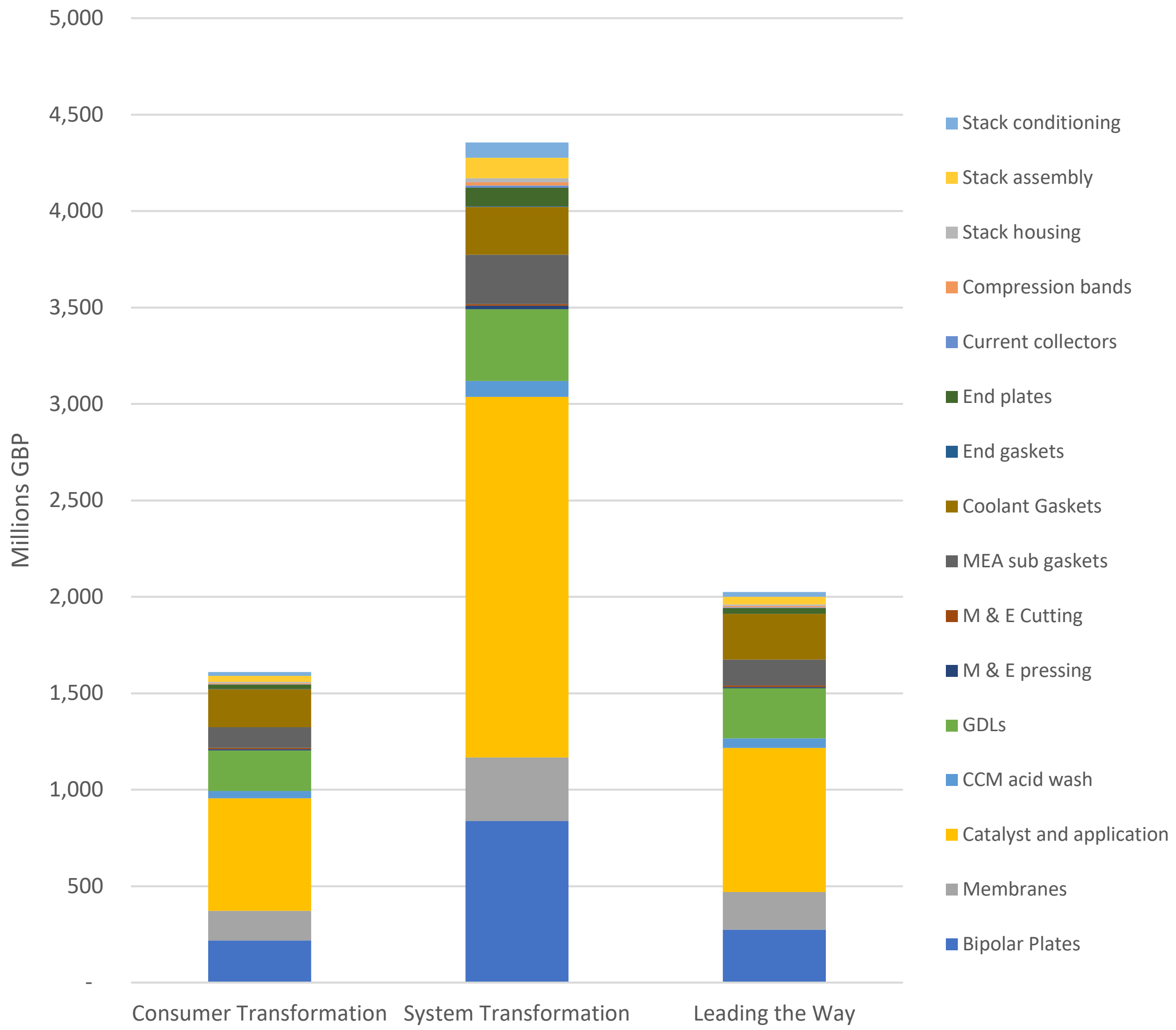

Figure 32: Fuel Cell Manufacturing Costs 2050

Abbreviations used in Figure 31 and Figure 32 are as follows:

- MEA: Membrane Electrode Assembly.
- M & E: Membrane and Electrode
- GDL: Gas diffusion Layer
- CCM: Catalyst Coated Membrane

5 Potential Economic Benefits of Hydrogen Supply Chain Development

Analysis detailed in previous sections provides estimates of the potential scale of the hydrogen supply chain to meet UK demand in both 2030 and 2050, based on the three scenarios developed. The main objective of this part of the work was to develop a more granular understanding of the potential for jobs and economic benefits from specific parts of the supply chain, to complement existing analysis on the total jobs and economic benefits across the hydrogen value chain.

5.1 UK Supply Chain Opportunities and Associated Economic Impact

5.1.1 Analytical Framework

The supply chain structure presented in Figure 6, has been divided into eight categories for economic impact analysis, as shown in Figure 33.

Supply Chain Segment	Detailed Categories	Economic Impact Categories
Hydrogen Manufacturing Supply Chain	Materials and Components for Production of Blue Hydrogen Manufacturing Equipment.	1. Blue hydrogen production equipment manufacture
	Production of Blue Hydrogen Manufacturing Equipment	
	Prouction of Blue Hydrogen Ancillary Equipment/Consumables	
	Materials and Components for Production of Green Hydrogen Manufacturing Equipment.	2. Green hydrogen production equipment manufacture
	Production of Green Hydrogen Manufacturing Equipment	
	Prouction of Green Hydrogen Ancillary Equipment/Consumables	
	Blue Hydrogen Manufacturing Plant Construction	3. Blue hydrogen manufacturing plant construction
	Green Hydrogen Manufacturing Plant Construction	4. Green hydrogen manufacturing plant construction
	Blue Hydrogen Manufacturing	5. Hydrogen manufacture
	Green Hydrogen Manufacturing	
Hydrogen Transport, Distribution and Storage	Pipelines	6. Hydrogen transport
	Truck/Train/Ship Transport	
	Salt Caverns	7. Hydrogen storage
	Storage Tanks	
	Fuelling Stations	
Manufacture of Fuel Cells	Fuel Cell Components	8. Fuel cell and component manufacture
	Fuel Cells	
Support Functions	Professional Services	Included in categories above, as appropriate, as defined in the supply chain analysis
	R&D/Education	
	Ancillary Services	
Development of Hydrogen Infrastructure	Concept Engineering and Consultancy	Included in categories above, as appropriate, as defined in the supply chain analysis
	Engineering, Procurement, and Construction (EPC)	
	Detailed Component Design	
	Specialist hydrogen shipping design	Included in categories above, as appropriate, as defined in the supply chain analysis
Installation and Commissioning of Hydrogen Infrastructure	Hydrogen production plant installation	
	Pipeline installation	
Operation and Maintenance of Hydrogen Infrastructure	Logistics	Not included in the supply chain or economic impact analysis, due to lack of appropriate data
	Maintenance and Service	
	Health & Safety	
	Software and IT Support	

Figure 33: Segmentation of the Supply Chain for Economic Impact Analysis

The scale of the hydrogen economy supply chain under the different scenarios for 2030 and 2050, as presented earlier in this report, defines the scale of manufacturing capacity, infrastructure and manufacturing outputs required to meet the different scenarios in both 2030 and 2050 but it does not consider the time periods for capacity and infrastructure development. It is, however, considered important to present annual data in the analysis of economic impact to indicate the scale of (turnover) and employment within the supply chain. The approach taken to prepare annual data is detailed below.

Estimating Annual Activity up to 2030

It is assumed that developing 2030 capacity is spread evenly over a period of seven years (2023 to 2029). This is a stylised assumption for the purposes of this analysis, but it is recognised that there is likely to be different levels of activity in different years depending on the pace of rollout of hydrogen. For example, a model that shows different activities being carried out at different times for construction of a hydrogen manufacturing facility, based on the experience of Wood plc, is presented in Figure 34. This reflects expected timescales in the early years of developing hydrogen facilities, but it is expected that these times will get shorter as more facilities are designed and built.

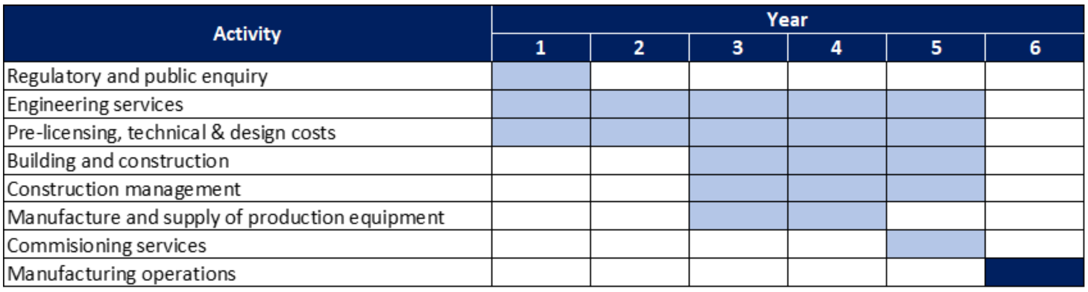

Figure 34: Projected Timescales – Construction of Hydrogen Manufacturing Facility

Estimating Annual Activity between 2030 and 2050

It is assumed that:

- The manufacturing plants and infrastructure established in the period to 2030 will still be in operation in 2050. Therefore, the number of manufacturing plants and scale of infrastructure in 2030 is deducted from the total figures for 2050, as presented in Section 4, above.
- The jobs and GVA associated with operating plants built during the 2020s is included in the 2050 data for hydrogen manufacture
- Fuel cells, predominantly for transport applications, are assumed to have a 20 year lifetime. Therefore, no replacement of fuel cells in use in 2030 are included in the 2050 analysis.
- The additional capacity required to meet the needs of the scenarios in 2050 is developed at a consistent level over the twenty year period. This is, again, a stylised assumption for the purposes of this analysis, but it is recognised that you could have different levels of activity in different years depending on the pace of rollout of hydrogen.

Calculating Economic Impact

The costs detailed in Section 4 for each part of the hydrogen supply chain are considered to provide an approximation of the turnover of the supply chain and its constituent parts. These figures can be used to calculate employment and gross value added (GVA) figures using appropriate published data (turnover per employee and GVA per employee) from the Office for National Statistics[31]. We have used data for relevant two digit SIC Codes as this is the best available. Direct GVA data only is presented. Indirect and induced GVA, could also be calculated using appropriate multipliers[32], but this study has focused specifically on direct GVA.

5.2 Potential Economic Impact for 2030

This section defines the scale of activity required to deliver the capacity defined in 2030 but does not include any assumptions about UK suppliers market share, so it presents total economic impact and should not be interpreted as indicating specific economic benefits for the UK.

5.2.1 Total Impact

The estimated potential total turnover to fully deliver UK hydrogen supply chains of the scale defined for each scenario ranges from £7.9 to £9.3 billion, as presented in Figure 35. These figures show the total scale of the opportunity.

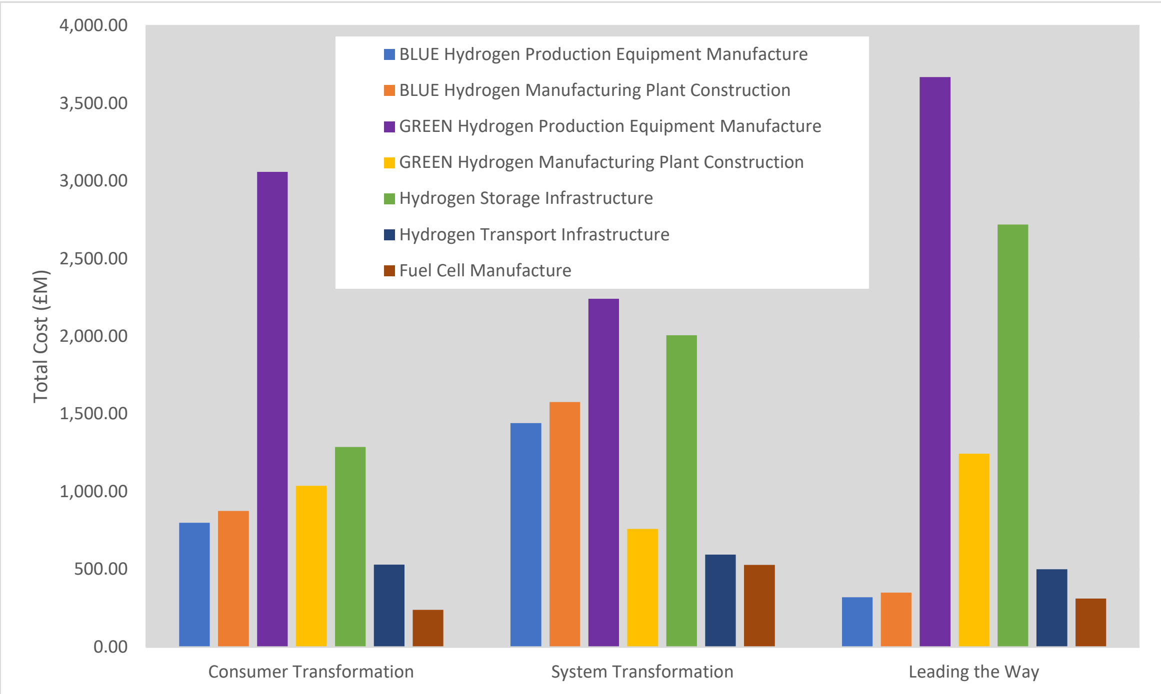

Figure 35: Scale of Activity (Turnover) to Deliver 2030 Hydrogen Capacity

Notes:

- The scale of hydrogen manufacture is excluded from this figure as it is assumed that it commences in the latter part of the period to 2030, therefore, cumulative data over the 2023-2030 period is not available.

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31 https://www.ons.gov.uk/businessindustryandtrade/business/businessservices/datasets/uknonfinancialbusinesseconomyannualbusinesssurveysectionsas

32 These multipliers are defined at https://www.evaluationsonline.org.uk/evaluations/help/guidance.htm. They can be sourced from https://www.gov.scot/publications/about-supply-use-input-output-tables/. This source is used as it gives the greatest level of detail for multipliers for specific industries (ref, e.g. Economic Impact of the University of Oxford, Methodological Appendix, Biggar Economics, November 2016)

- As already indicated, the evidence base for storage costs is very limited and estimates vary greatly. Using a GBP/GWh stored cost for salt cavern storage in a specific area from the hydrogen supply chain evidence base allows a highly illustrative quantification of the total value associated with each of the adopted scenarios.

Figure 35 shows that green hydrogen production equipment manufacturing and the development of hydrogen storage infrastructure in each scenario account for the highest costs.

The average annual employment from 2023 to 2029 to establish the 2030 hydrogen supply capacity is estimated at between 6,100 and 7,100 full time equivalent staff, as shown in Figure 36 for each scenario. As this is annual data it includes 2030 data for hydrogen manufacture. This analysis does not consider UK market share and exclude exports so are not directly comparable to jobs estimates from other sources e.g. BEIS analysis based on EINA methodology – the focus of this analysis is the breakdown of jobs by category, rather than the total jobs.

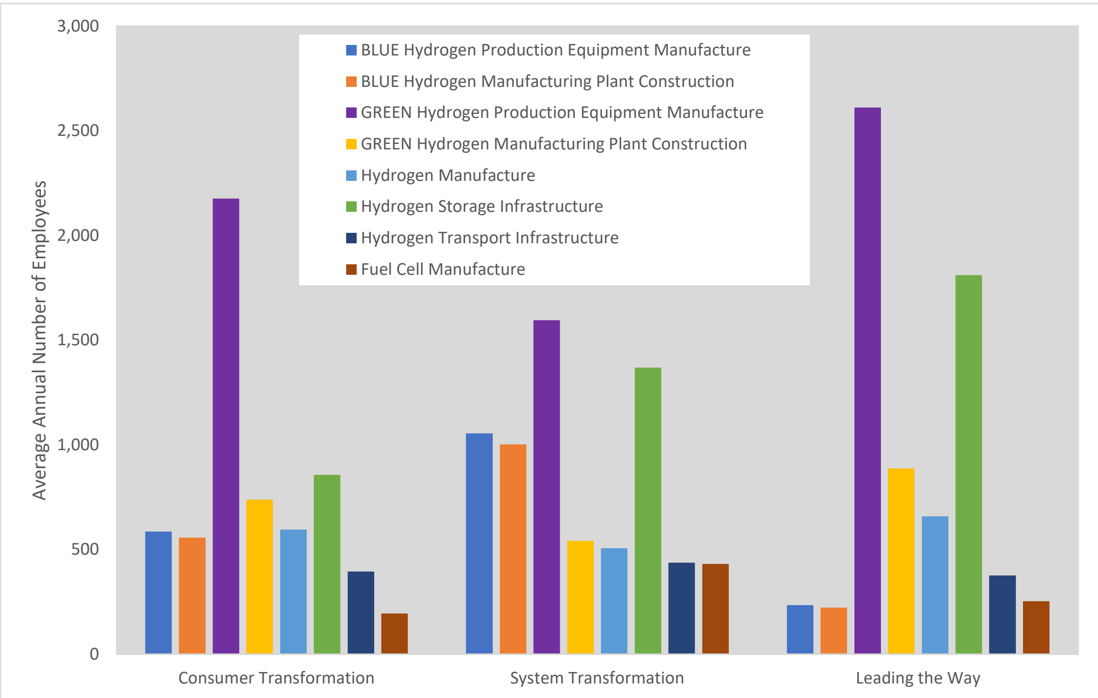

Figure 36: Estimated Annual Employment to Deliver 2030 Hydrogen Capacity

This again shows the importance of green hydrogen production equipment manufacture and the development of hydrogen storage infrastructure in each scenario. Here, the 2030 figure for hydrogen manufacture is also included.

The average annual direct GVA over the period from 2023 to 2029 to establish the 2030 hydrogen supply capacity is estimated at between £575 million and £665 million, as shown in Figure 37 for each scenario. Again, this analysis does not consider UK market share and exclude exports so are not directly comparable to GVA estimates from other sources – the focus of this analysis is the breakdown of GVA by category, rather than the total GVA.

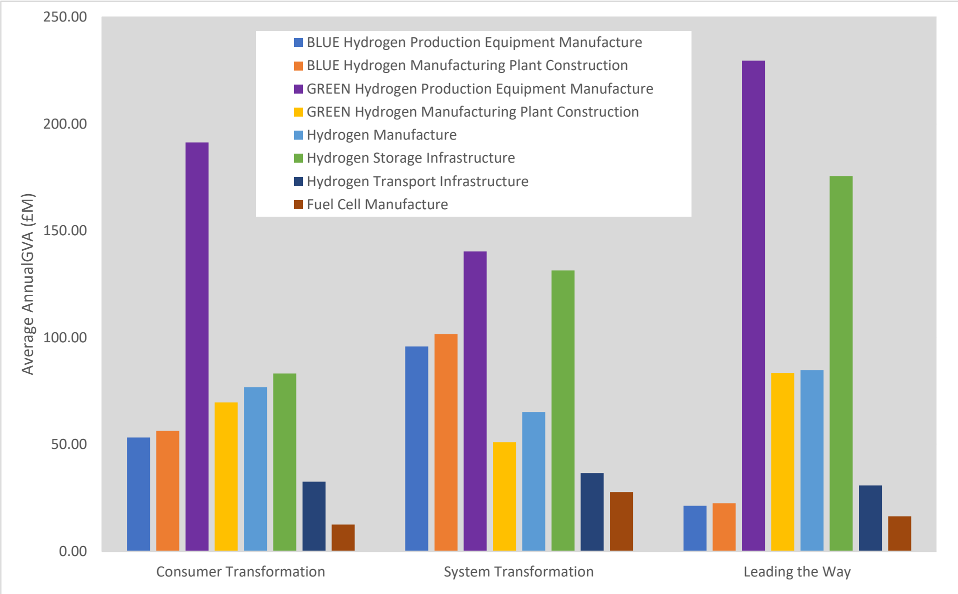

Figure 37: Estimated Annual Direct GVA to Deliver the 2030 Hydrogen Capacity

5.2.2 Detailed Impact Analysis by Category

Detailed analysis of the potential economic impact for the major categories shown in Figure 35 to Figure 37 is included in this section.

5.2.2.1 Manufacture of Blue Hydrogen Production Equipment and Plant Construction

The scale (total turnover in £M) of different categories within the manufacture of blue hydrogen production equipment and plant construction ranges from £670 million to £3,000 million across the three scenarios, as shown in Figure 38.

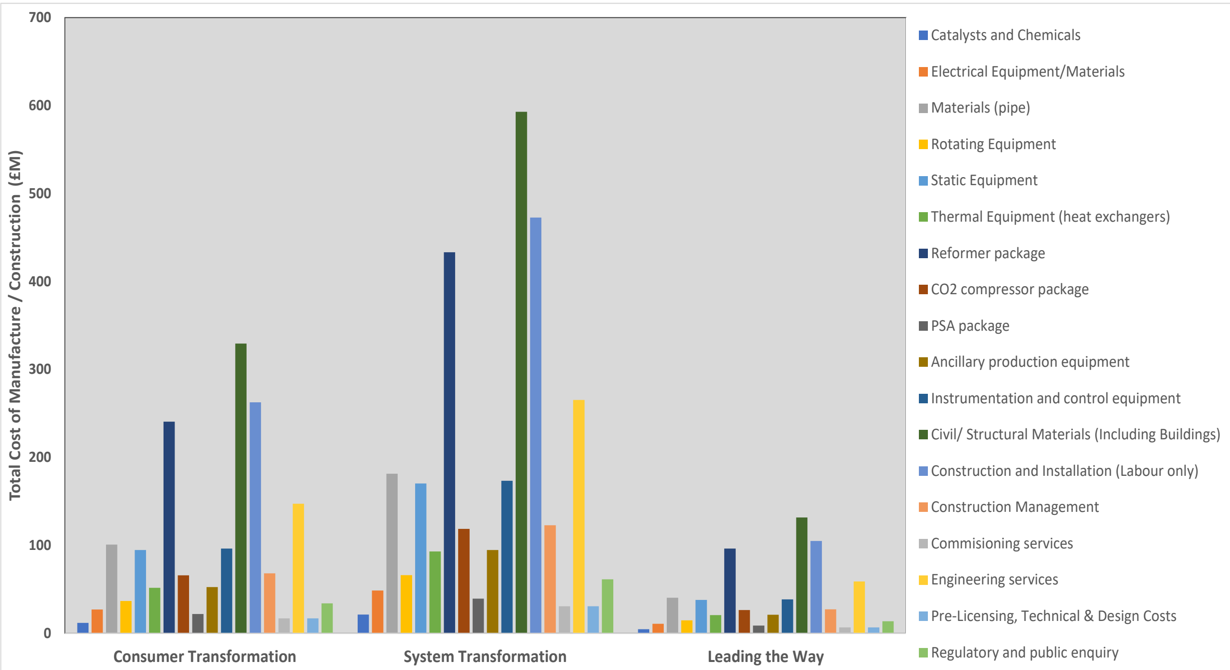

Figure 38: Total Turnover (£M) to Deliver Blue Hydrogen Manufacturing Capacity in 2030

This shows, in each scenario, that the largest turnover is incurred for:

- Civil and structural materials (including buildings)
- Construction and installation labour
- Reformer package manufacture
- Engineering services

The average annual employment over the period from 2023 to 2029 in different categories within the manufacture of blue hydrogen production equipment and plant construction ranges from 460 to 2,060 across the three scenarios, as shown in Figure 39.

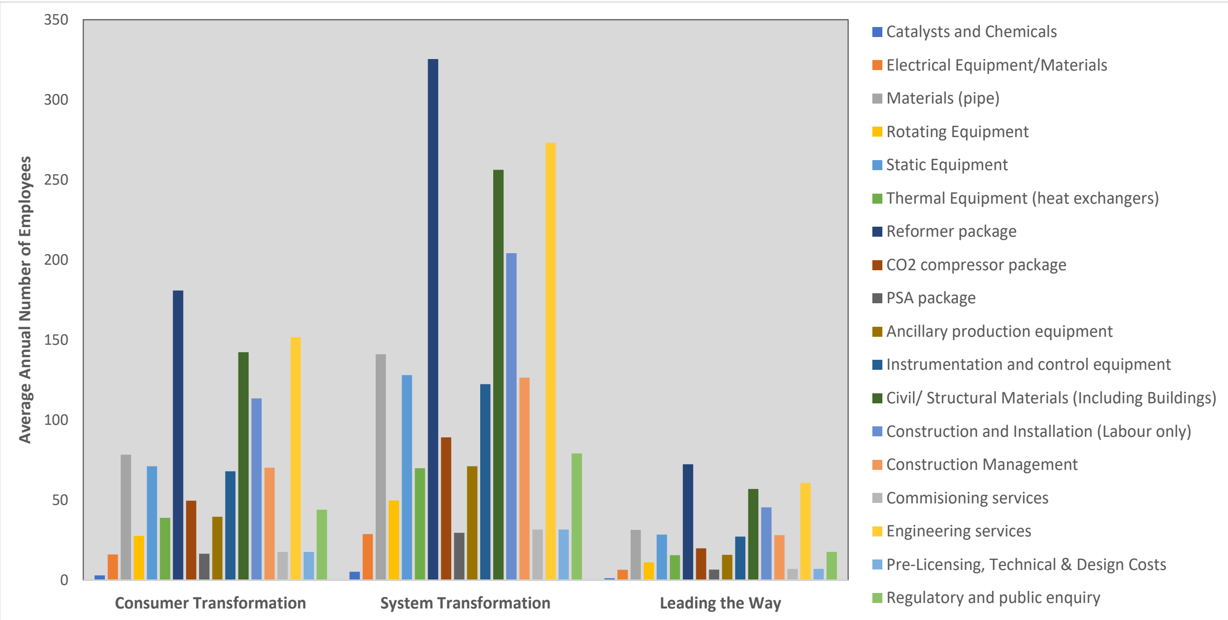

Figure 39: Average Annual Employment to Deliver Blue Hydrogen Manufacturing Capacity in 2030

This shows, in each scenario, that the largest average annual employment is for:

- Reformer packages
- Engineering services
- Civil and structural materials (including buildings)
- Construction and installation labour

It is noted that average annual employment in reformer package manufacture and engineering services are highest, although these do not incur the highest turnover, as shown in Figure 38. This is due to turnover per employee data for construction activities being higher than for manufacture of special purpose machinery (reformer packages) and engineering services. This effect, where the turnover and employment data are not consistent, will be seen across all segments of the hydrogen supply chain due to sector by sector variations in turnover per employee data, based on published Office of National Statistics data.

The average annual GVA in different categories within the manufacture of blue hydrogen production equipment and plant construction ranges from £44 million to almost £200 million across the three scenarios, as shown in Figure 40.

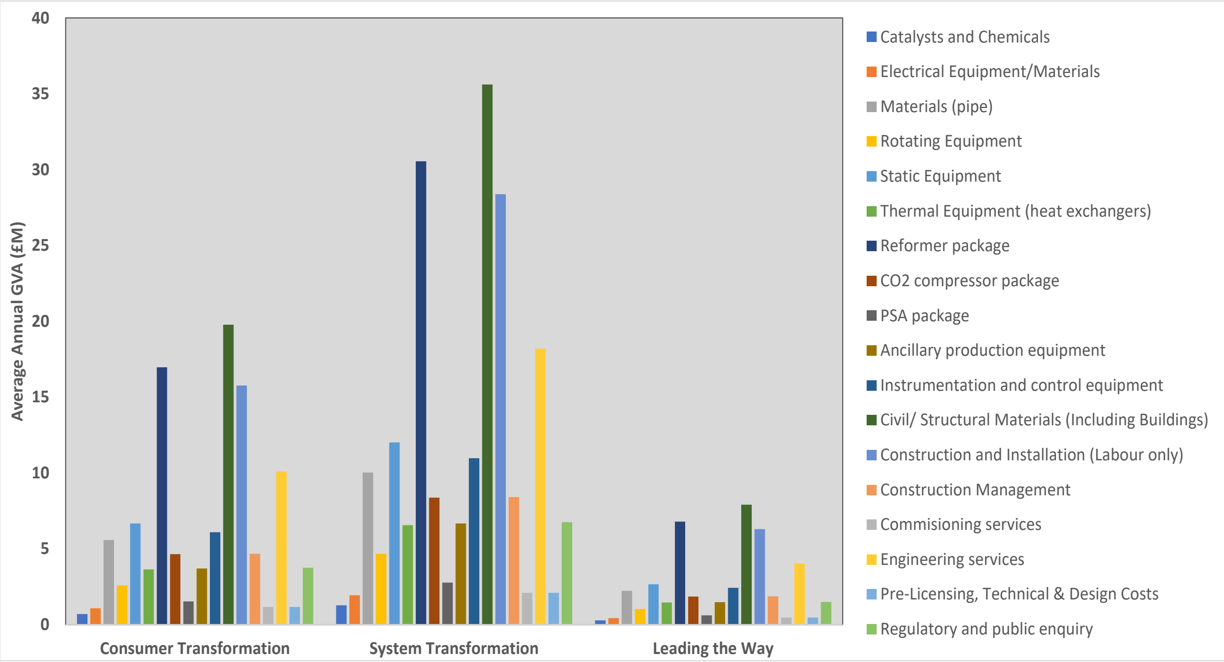

Figure 40: Average Annual GVA to Deliver Blue Hydrogen Manufacturing Capacity in 2030

This shows, in each scenario, that the largest average annual GVA is for:

- Civil and structural materials (including buildings)
- Reformer package manufacture
- Construction and installation labour
- Engineering services

As can be noted, this is a different order than for both turnover and annual employment. This is due to GVA per employee data, used to calculate GVA being variable from sector to sector. This effect will, again, be seen across all segments of the hydrogen supply chain due to sector by sector variations in GVA per employee data, based on published Office of National Statistics data.

5.2.2.2 Manufacture of Green Hydrogen Production Equipment and Plant Construction

Similar analyses to those above can be presented for the manufacture of green hydrogen production equipment and plant construction. Here the scale (turnover in £M) of different categories ranges from £3,000 million to £4,900 million across the three scenarios, as shown in Figure 41. This is significantly higher than for blue hydrogen due to the output of blue and green hydrogen assumed in each scenario.

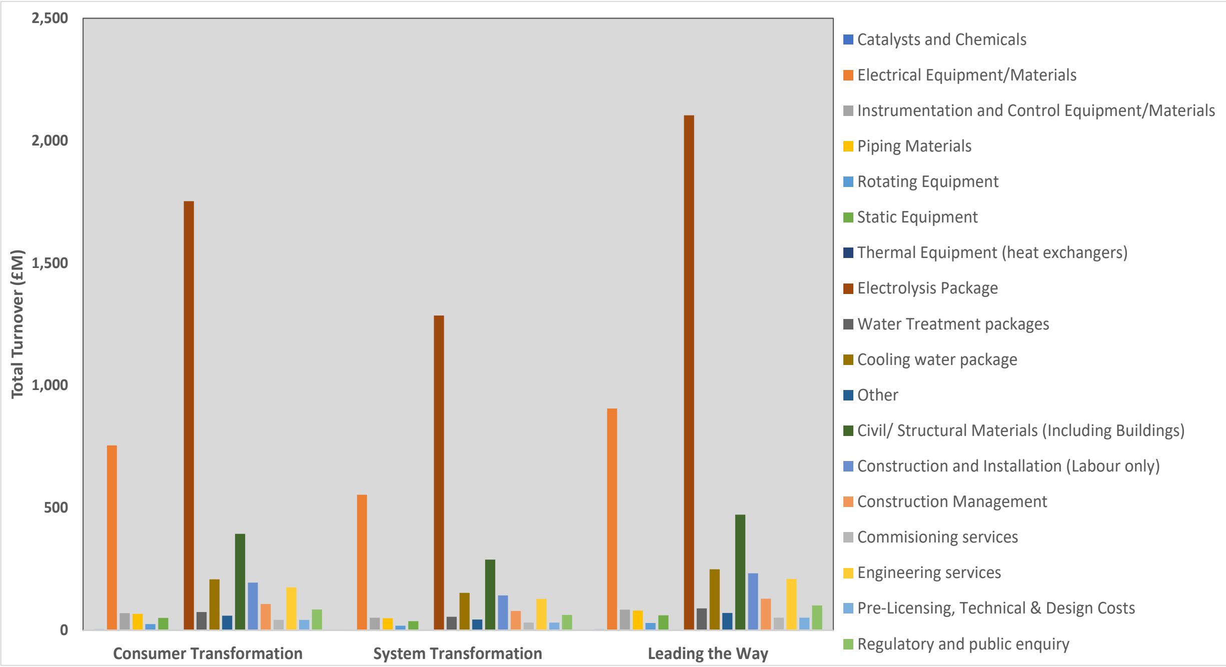

Figure 41: Total Turnover (£M) to Deliver Green Hydrogen Manufacturing Capacity in 2030

This shows, in each scenario, that the largest turnover is incurred for:

- Electrolysis package manufacture
- Electrical equipment and materials manufacture
- Civil and structural materials (including buildings)
- Cooling water package manufacture

This highlights the large scale of major equipment categories. The relative scale of civil and structural materials (including buildings) and construction and installation labour are much lower here than in the case of blue hydrogen manufacturing plant construction (see Figure 35) – due to higher cost of manufacturing equipment and lower cost of construction per unit of capacity.

The average annual employment in different categories within the manufacture of green hydrogen production equipment and plant construction ranges from 2,100 to 3,500 across the three scenarios, as shown in Figure 42.

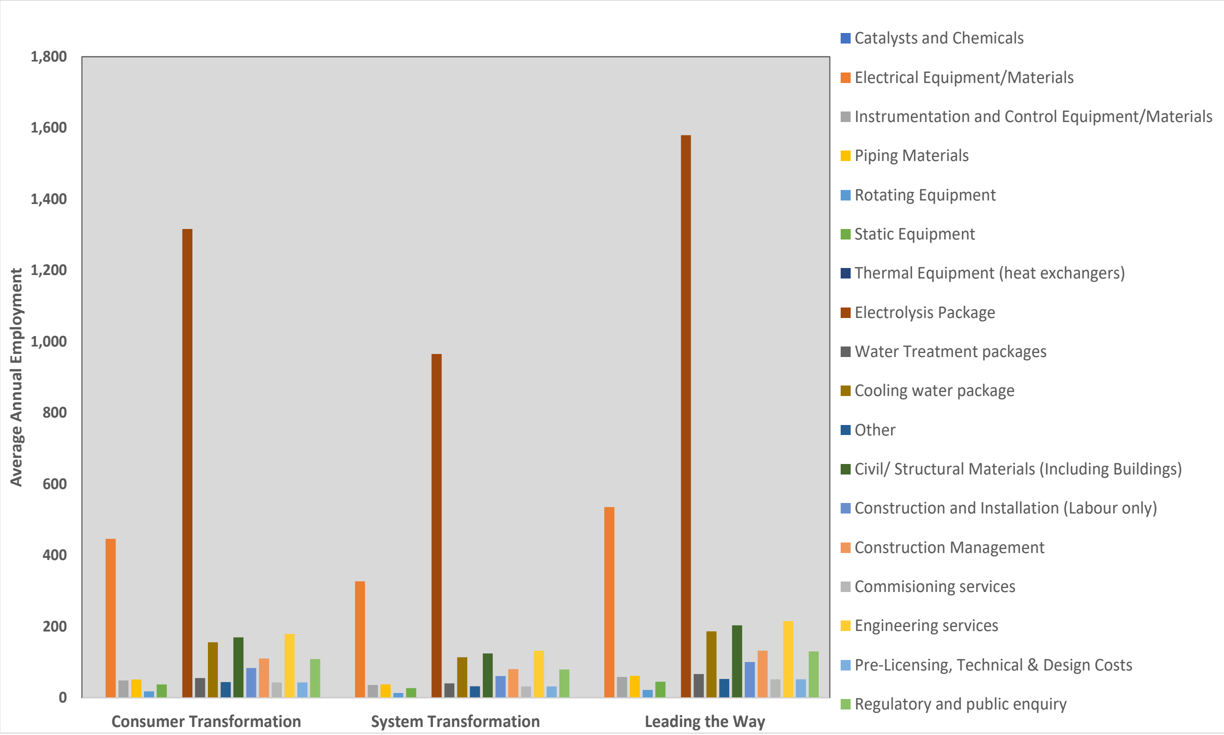

Figure 42: Average Annual Employment to Deliver Green Hydrogen Manufacturing Capacity in 2030

This shows, in each scenario, that the largest average annual employment is for:

- Electrolysis package manufacture
- Electrical equipment and materials manufacture

Here engineering services is the third largest category in terms of average annual employment.

The average annual GVA in different categories within the manufacture of green hydrogen production equipment and plant construction ranges from £190 million to £310 million across the three scenarios, as shown in Figure 43.

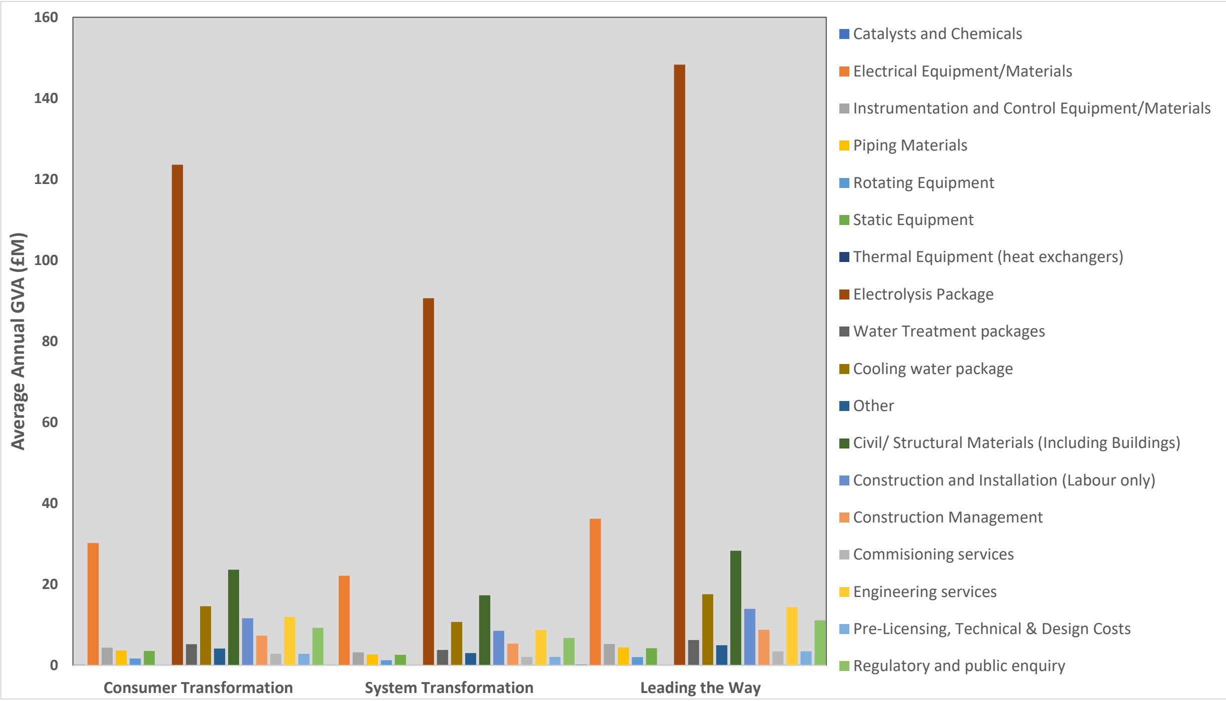

Figure 43: Average Annual GVA to Deliver Green Hydrogen Manufacturing Capacity in 2030

This shows, in each scenario, that the largest average annual GVA is for:

- Electrolysis package manufacture
- Electrical equipment and materials manufacture

This, again, highlights the attractive economic impact of electrolysis package manufacture and electrical equipment and materials manufacture.

5.2.2.3 *Hydrogen Manufacture*

The scale of hydrogen manufacturing plant operations in 2030 is summarised in Figure 44.

		Consumer Transformation	System Transformation	Leading the Way
BLUE Hydrogen	Plant operations cost - per annum (£M)	17	28	7
	Employment - per annum	72	121	32
	GVA per annum (Direct) (£M)	9	16	4
GREEN Hydrogen	Plant operations cost - per annum (£M)	120	89	144
	Employment - per annum	524	386	626
	GVA per annum	67	50	81
Total Hydrogen Manufacture	Plant operations cost - per annum (£M)	137	117	151
	Employment - per annum	596	507	659
	GVA per annum	77	65	85

Figure 44: Economic Impact of Hydrogen Manufacturing Plan Operation in 2030

Here, the employment and GVA multipliers are assumed to be the same for blue and green, so the difference is driven by the assumed capacity of blue/green in each scenario and the assumed operational cost.

5.2.2.4 *Hydrogen Transport in Repurposed Natural Gas Distribution Network*

Each scenario in 2030 assumes 2% of the natural gas distribution network is repurposed for hydrogen. This is an illustrative figure to reflect the development of hydrogen for heat in residential homes and plans for the first hydrogen towns by 2030 as proposed in the National Grid Future Energy Scenarios[8]. The scale of this task, in terms of total turnover and average annual employment, are summarised in Figures 45 and 46.

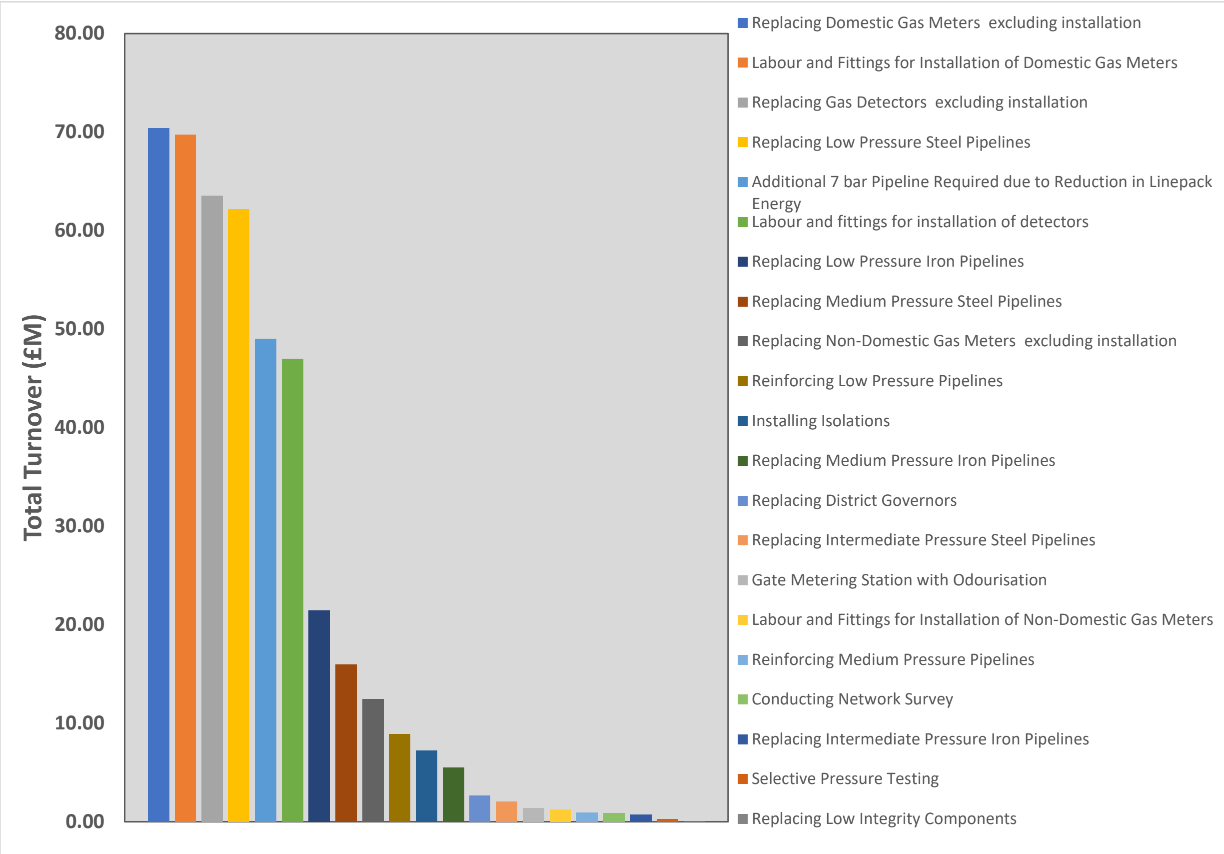

Figure 45: Total Turnover for Activities in Repurposing Part of the Natural Gas Distribution Network

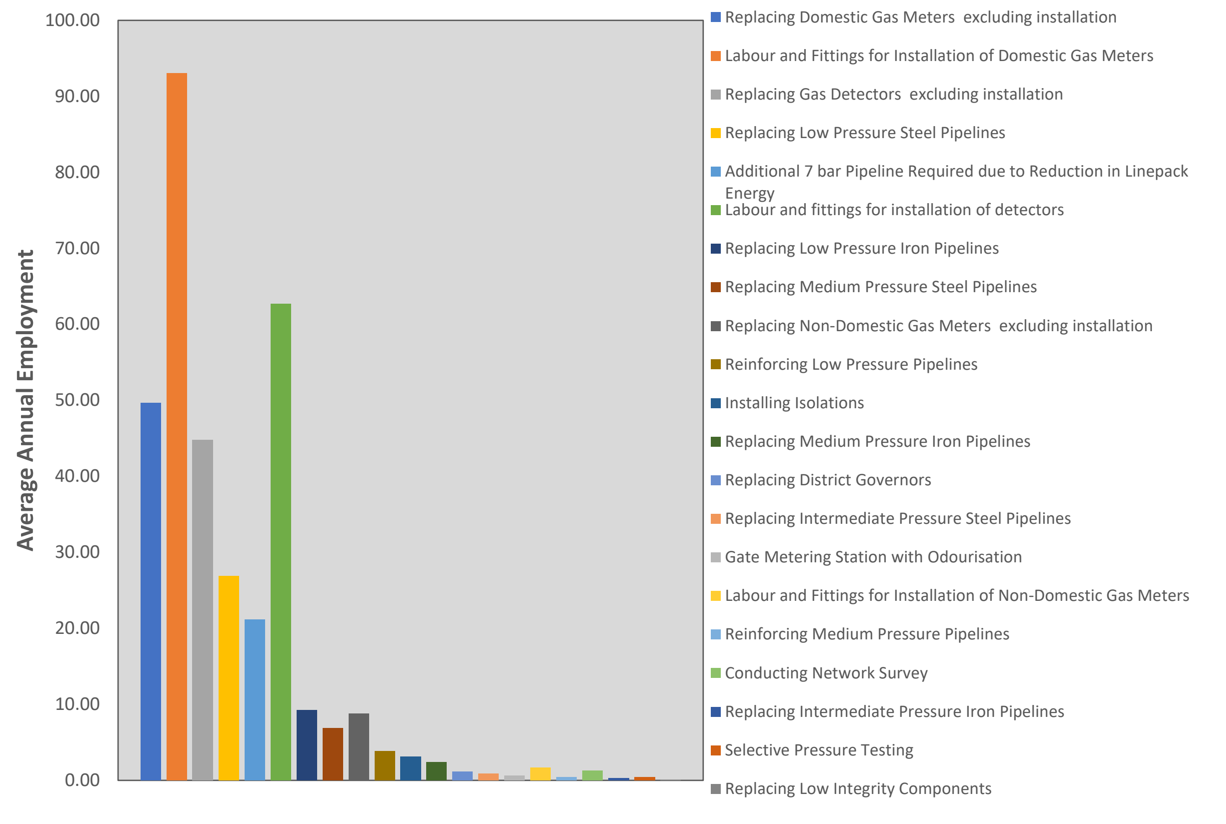

Figure 46: Average Annual Employment for Repurposing Part of the Natural Gas Distribution Network

This shows that the largest activities, in terms of both turnover and average annual employment, are:

- Replacing domestic gas meters, excluding installation
- Labour and fittings for installation of domestic gas meters
- Replacing gas detectors, excluding installation
- Replacing low pressure steel pipelines
- Additional 7 bar pipeline required due to reduction in linepack energy
- Labour and fittings for installation of detectors

5.2.2.5 Hydrogen Storage (Salt Caverns)[33]

Salt caverns are the key source of hydrogen storage capacity. Development of 2030 underground storage capacity can be summarised as follows:

33 As already indicated, the evidence base for storage costs is very limited and estimates vary greatly. The use of a GBP/GWh stored cost for salt cavern storage in a specific area from the hydrogen supply chain evidence base allows a highly illustrative quantification of the total value associated with each of the adopted scenarios.

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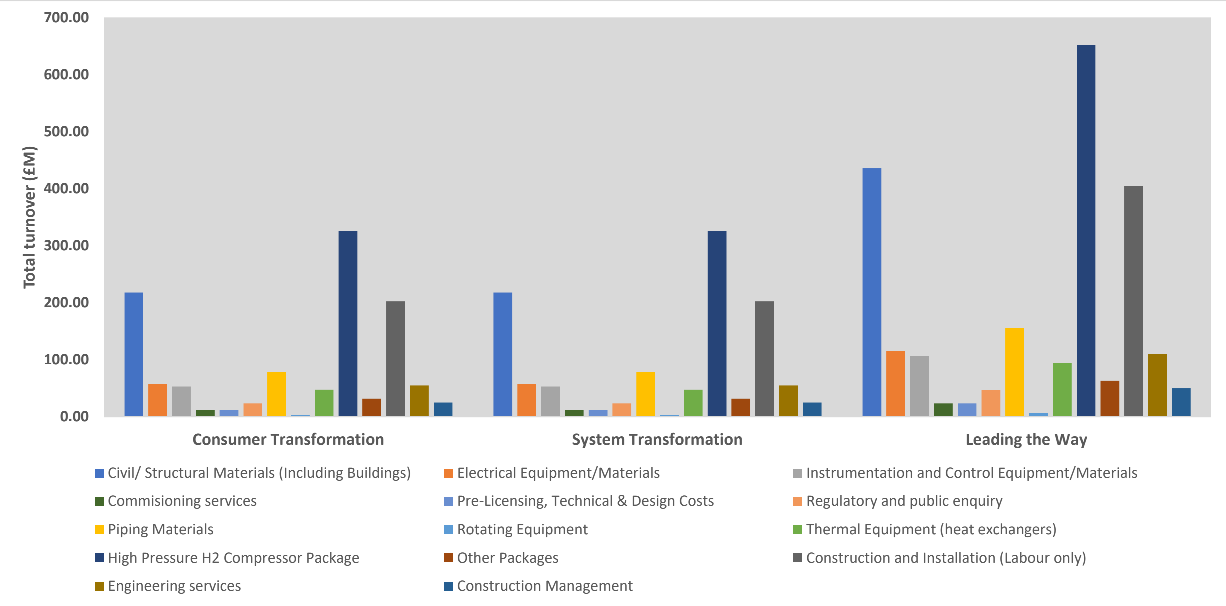

Figure 47: Total Turnover to Deliver 2030 Underground Hydrogen Storage Capacity

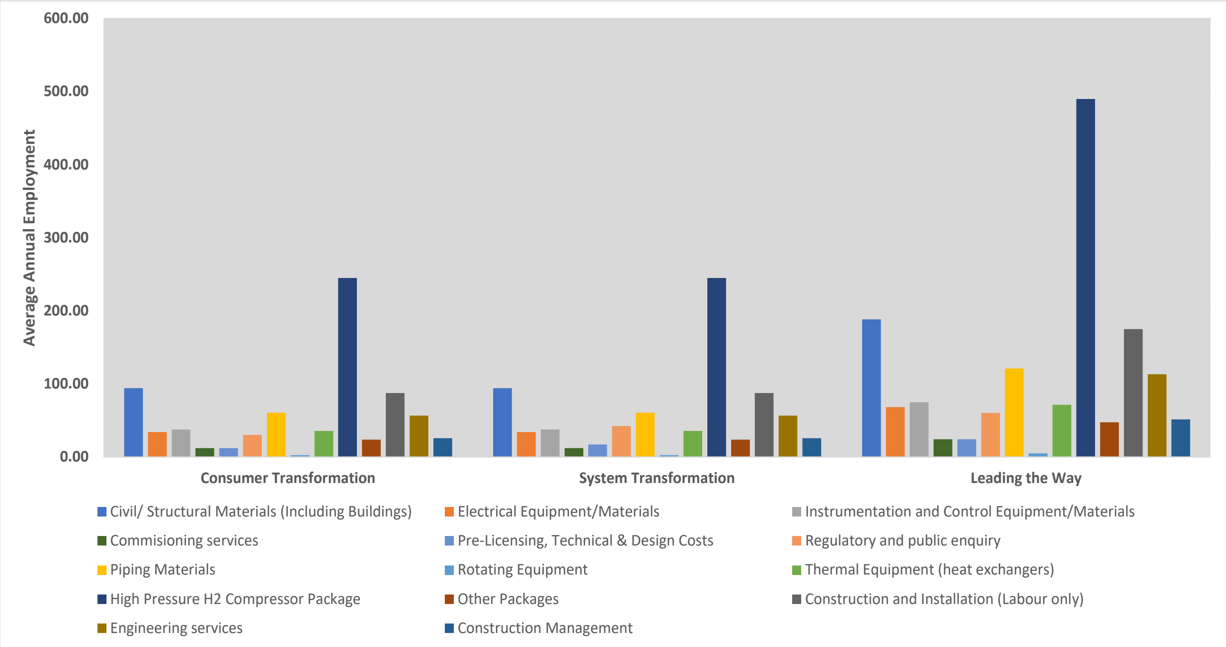

Figure 48: Average Annual Employment to Deliver 2030 Underground Hydrogen Storage Capacity

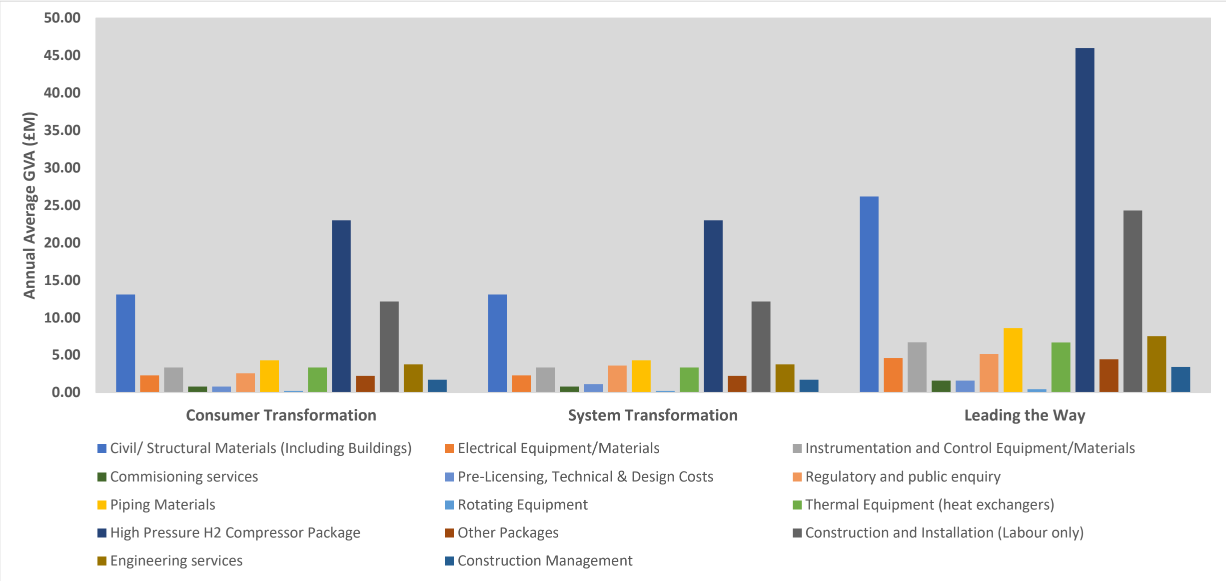

Figure 49: Average Annual GVA to Deliver 2030 Underground Hydrogen Storage Capacity

These show that the largest economic activity, under all three measures, is in:

- High pressure H2 compressor package manufacture
- Civil/ structural materials (including buildings)
- Construction and installation (labour only)

However, the high pressure H2 compressor package manufacture is more attractive in terms of average annual GVA and, particularly, average annual employment due to higher turnover per employee and GVA per employee data for construction compared to equipment manufacture, as already highlighted.

5.2.2.6 Fuel Cell Manufacture

The scale of activity to manufacture fuel cells in the period to 2030 can be summarised as follows:

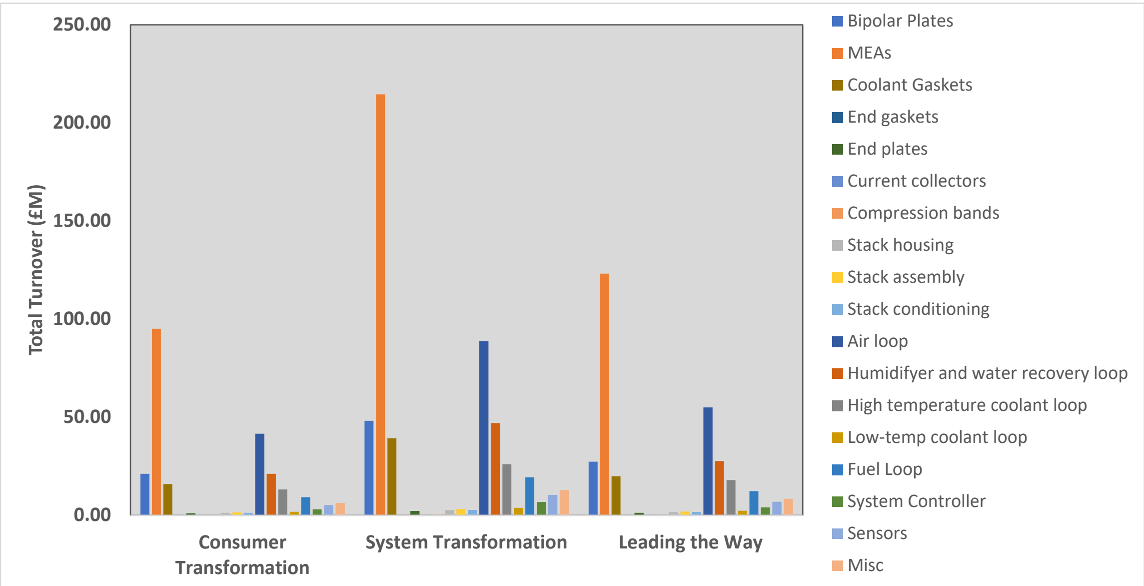

Figure 50: Total Turnover (£M) to Manufacture 2030 Fuel Cell Demand

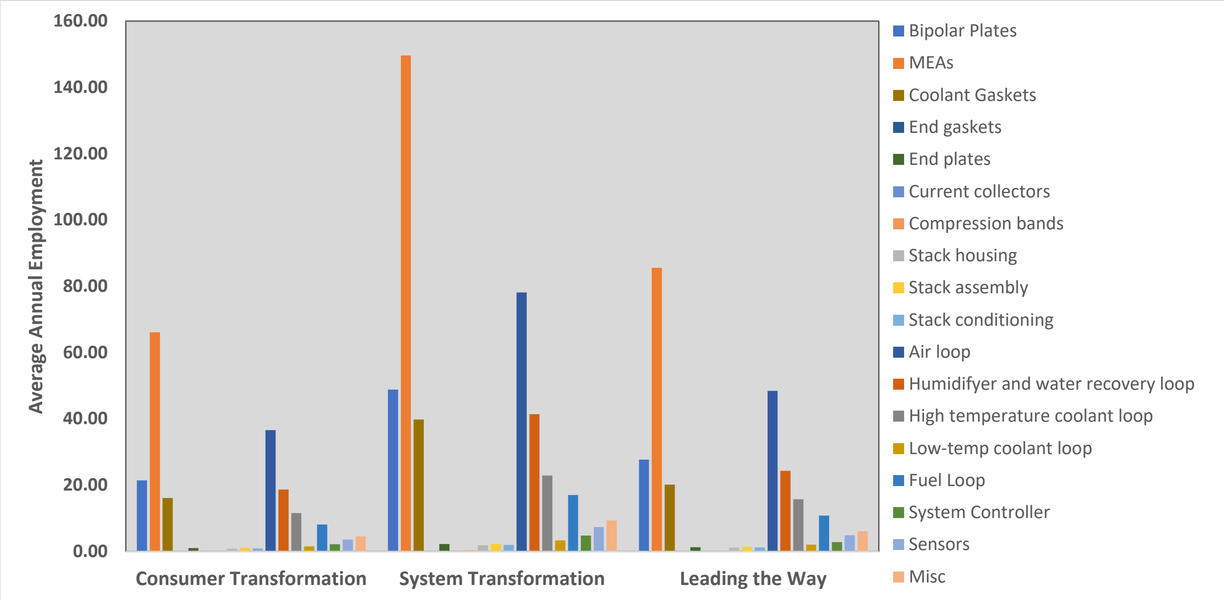

Figure 51: Average Annual Employment to Manufacture 2030 Fuel Cell Demand

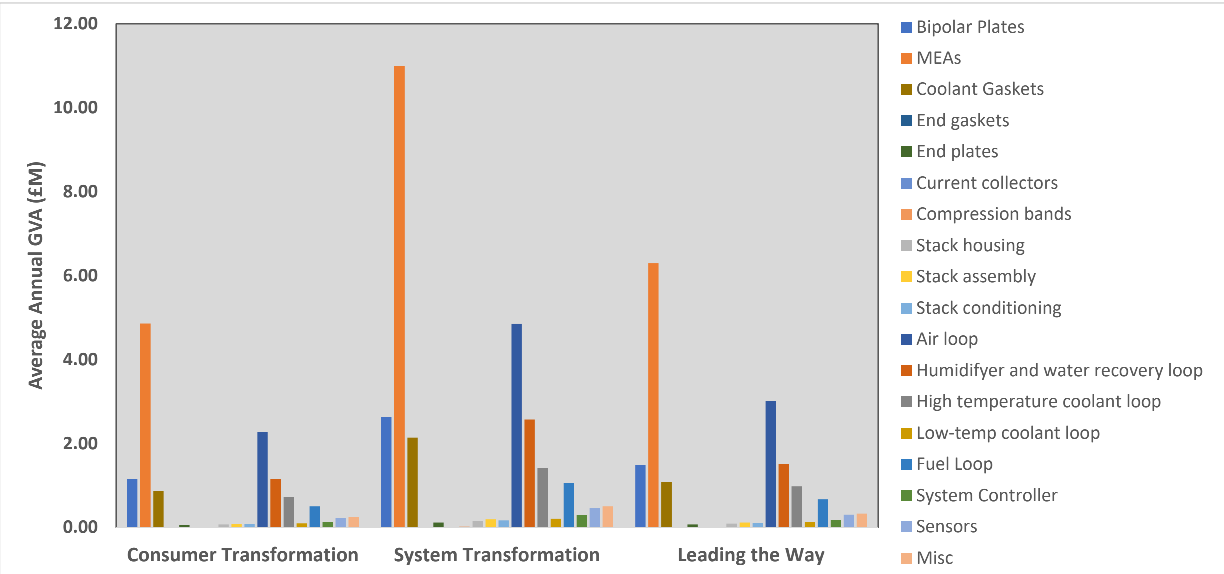

Figure 52: Average Annual GVA to Manufacture 2030 Fuel Cell Demand

Under all three metrics, membrane electrode assemblies, balance of plant air loops and balance of plant humidifier and water recovery loops offer the largest economic impact.

5.2.3 Potential UK Market Share

As already highlighted, this section has reviewed the scale of activity, but has not considered the market share that could be captured by UK companies, so does not translate directly into economic benefits for the UK. UK market shares are discussed in section 8, following assessment of UK supply chain capability.

5.3 Potential Economic Impact for 2050

The estimated total economic benefit (jobs/GVA) of delivering hydrogen supply chains of the scale defined in each scenario are presented below. Again, these show the total scale of supply chain activity to deliver the 2050 UK hydrogen economy and do not consider UK company market share.

5.3.1 Total Impact

The estimated total economic impact to fully deliver UK hydrogen supply chains of the scale defined for each scenario for 2050 ranges from £33.5 to £124 billion, as presented in Figure 53. These figures show the total scale of the opportunity.

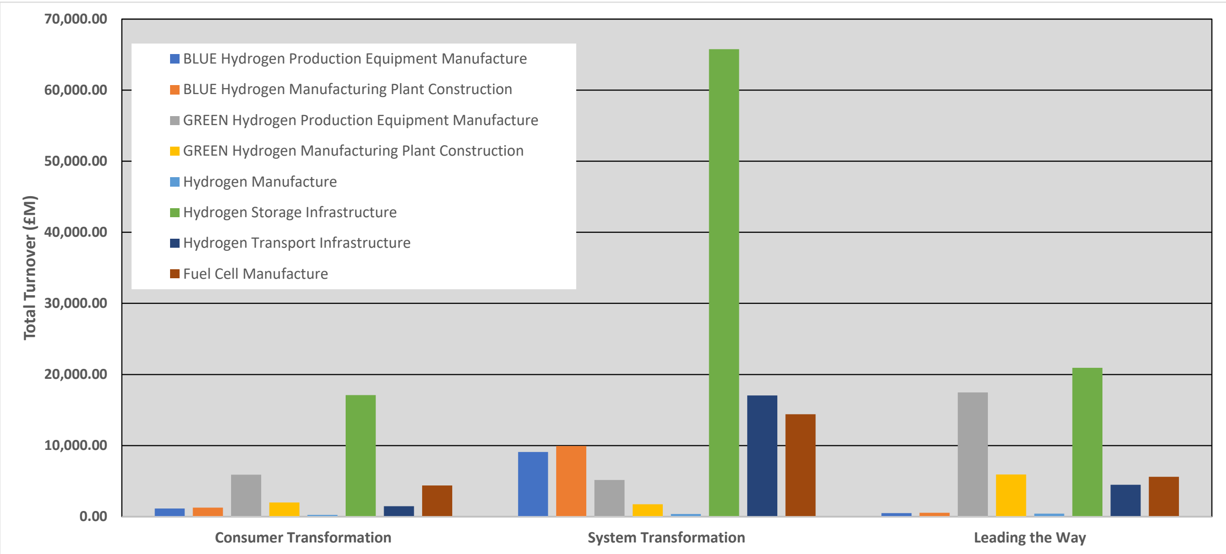

Figure 53: Scale of Activity (Turnover) to Deliver 2050 Hydrogen Capacity

Again, the uncertainty associated with storage requirements and costs, as per previous comments, should be noted here.

The scale of hydrogen manufacture is excluded from this figure as it is a plant operational cost, rather than a manufacturing asset or infrastructure development cost.

Figure 53 shows the dominance of hydrogen storage infrastructure in each scenario and green hydrogen production equipment manufacture in two of the scenarios.

The average annual employment between 2030 and 2050 to establish the 2050 hydrogen supply capacity is estimated at between 9,000 and 27,500, as shown in Figure 54 for each scenario. As this is annual data it includes 2050 data for hydrogen manufacture. This compares to an annual average of between 6,100 and 7,100 between 2023 and 2030 to deliver the 2030 hydrogen economy. In the same way as for 2030, this analysis does not consider UK market share and exclude exports so are not directly comparable to jobs estimates from other sources e.g. BEIS analysis based on EINA methodology – the focus of this analysis is the breakdown of jobs by category, rather than the total jobs.

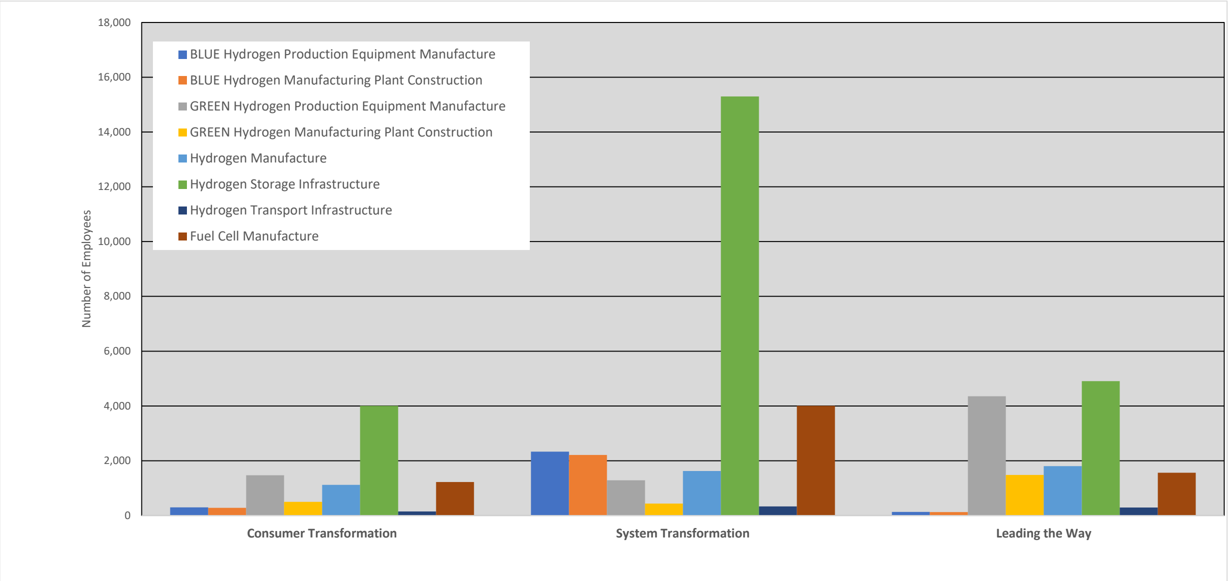

Figure 54: Estimated Annual Employment to Deliver 2050 Hydrogen Capacity

The importance of hydrogen storage infrastructure in each scenario and green hydrogen production equipment manufacture in two of the scenarios is again shown.

The average annual direct GVA to establish the 2050 hydrogen supply capacity is estimated at between £878 million and £2,900 million, as shown in Figure 55 for each scenario. This compares to an annual average of between £575 million and £664 million to deliver the 2030 hydrogen economy.

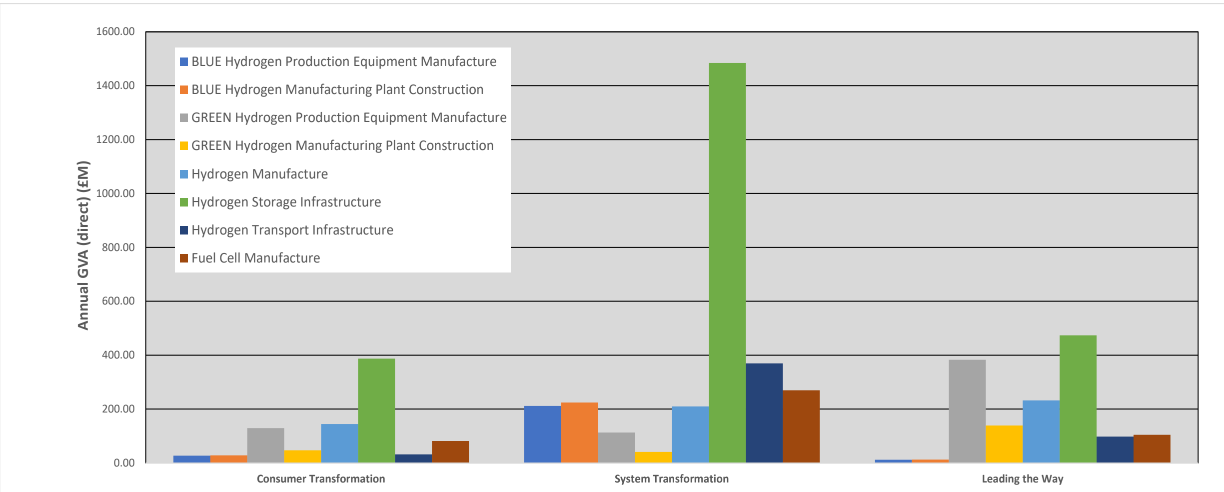

Figure 55: Estimated Annual Direct GVA to Deliver the 2050 Hydrogen Capacity

5.3.2 Detailed Impact Analysis by Category

Detailed analysis of the potential economic impact for the major categories in 2050, in the same way as presented above for 2030, using the same multipliers, is included in this section. Therefore the conclusions for 2030 on the relative scale of turnover, average annual employment and average annual GVA for different categories also hold for 2050.

5.3.2.1 *Manufacture of Blue Hydrogen Production Equipment and Plant Construction*

The scale (turnover in £M) of different categories within the manufacture of blue hydrogen production equipment and plant construction ranges from £858 million to £19,000 million across the three scenarios, as shown in Figure 56.

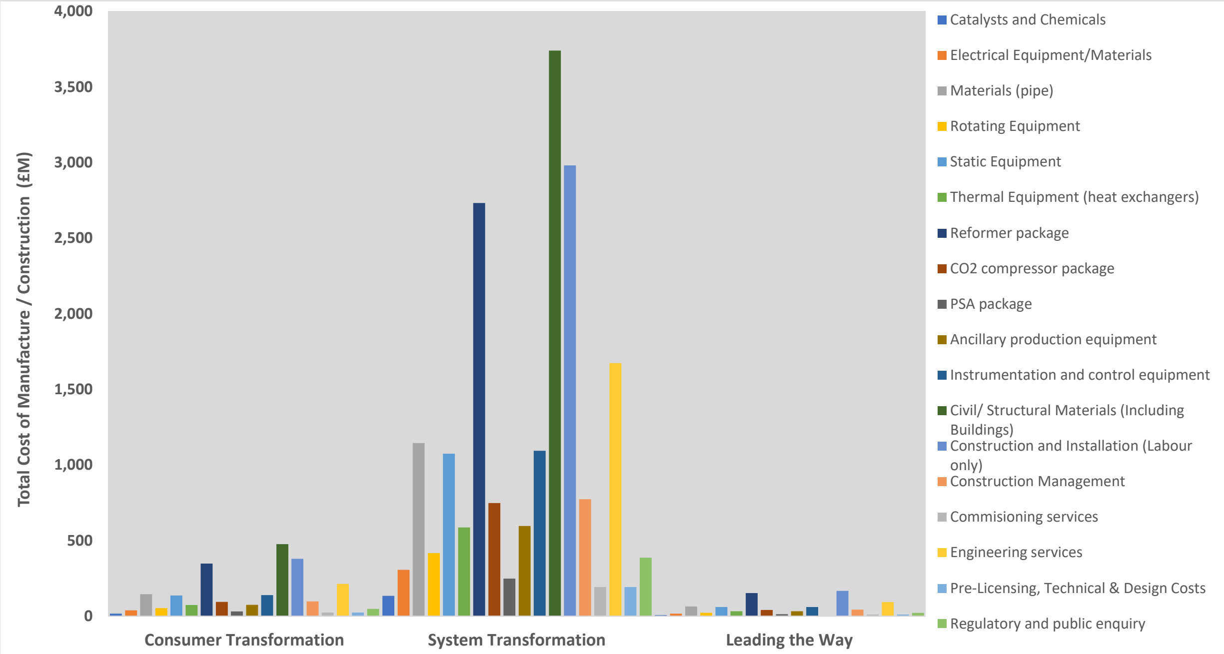

Figure 56: Total Turnover (£M) to Deliver Blue Hydrogen Manufacturing Capacity in 2050

This shows, in each scenario, that the largest turnover, as in the 2030 scenarios, is incurred for:

- Civil and structural materials (including buildings)
- Construction and installation labour
- Reformer package manufacture
- Engineering services

The average annual employment in different categories within the manufacture of blue hydrogen production equipment and plant construction ranges from 255 to 4,550 across the three scenarios, as shown in Figure 57.

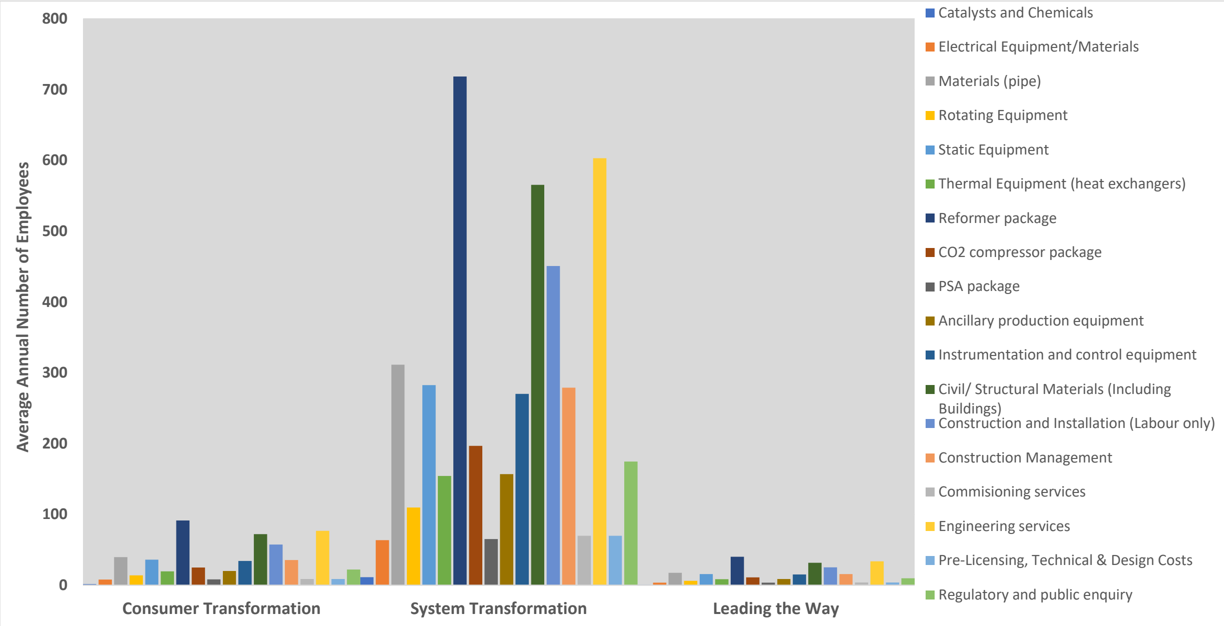

Figure 57: Average Annual Employment to Deliver Blue Hydrogen Manufacturing Capacity in 2030

The average annual GVA in different categories within the manufacture of blue hydrogen production equipment and plant construction ranges from £24 million to over £430 million across the three scenarios, as shown in Figure 58.

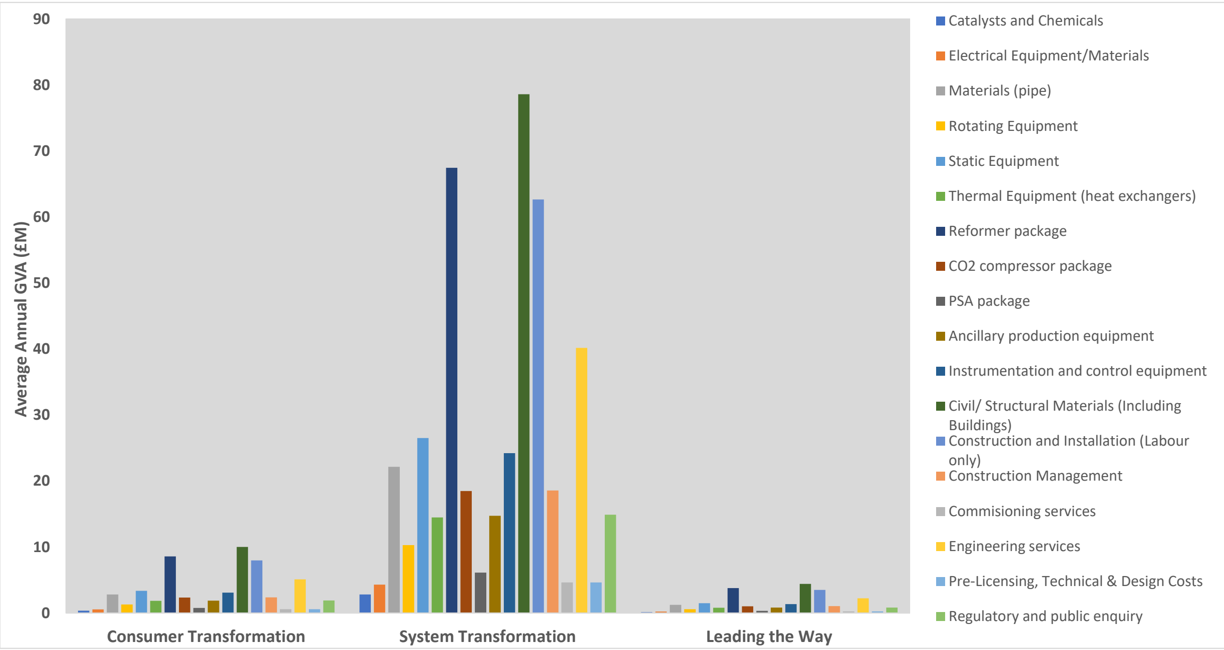

Figure 58: Average Annual GVA to Deliver Blue Hydrogen Manufacturing Capacity in 2030

5.3.2.2 *Manufacture of Green Hydrogen Production Equipment and Plant Construction*

Similar analyses to those above can be presented for the manufacture of green hydrogen production equipment and plant construction. Here the scale (turnover in £M) of different categories ranges from £6,900 million to £23,400 million across the three scenarios, as shown in Figure 59. This compares with between £3,000 million to £4,900 million across the three scenarios for 2030.

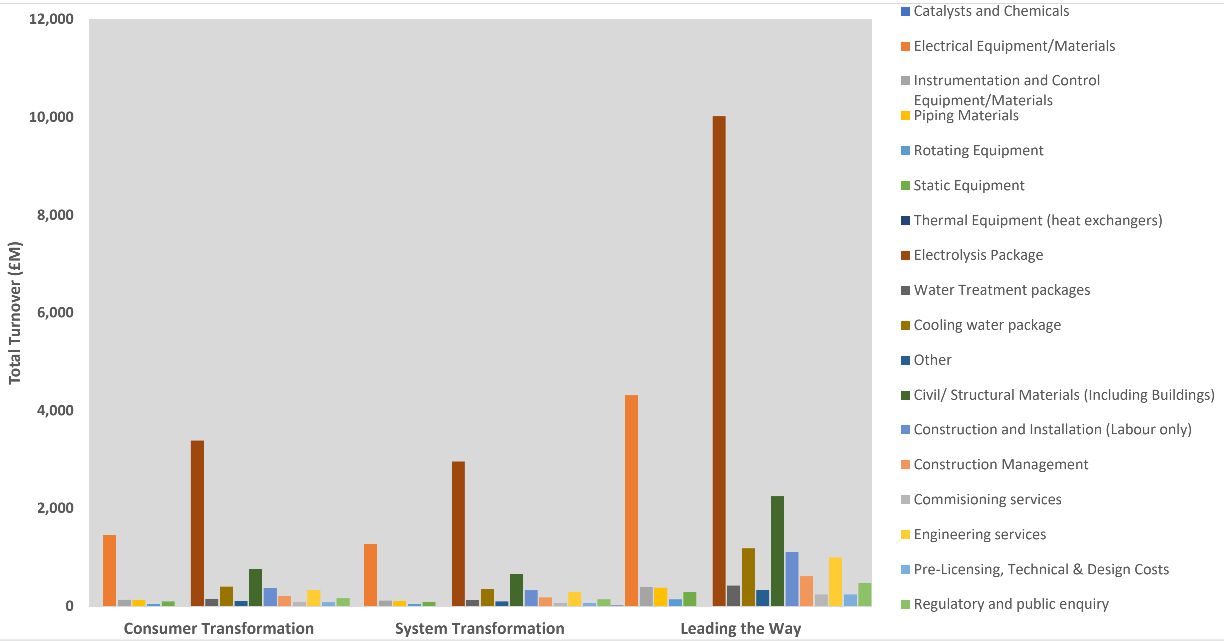

Figure 59: Total Turnover (£M) to Deliver Green Hydrogen Manufacturing Capacity in 2050

This shows, in each scenario, that the largest turnover is incurred for:

- Electrolysis package manufacture
- Electrical equipment and materials manufacture
- Civil and structural materials (including buildings)
- Cooling water package manufacture

Similarly, the relative scale of civil and structural materials (including buildings) and construction and installation labour are much lower than in the case of blue hydrogen manufacturing plant construction (see Figure 56).

The average annual employment in different categories within the manufacture of green hydrogen production equipment and plant construction ranges from 1,720 to 5,830 across the three scenarios, as shown in Figure 60. This compares to between 2,140 and 3,500 for the period to 2030, showing that for two of the scenarios the 2030 level of employment is sufficient to deliver 2050 capacity.

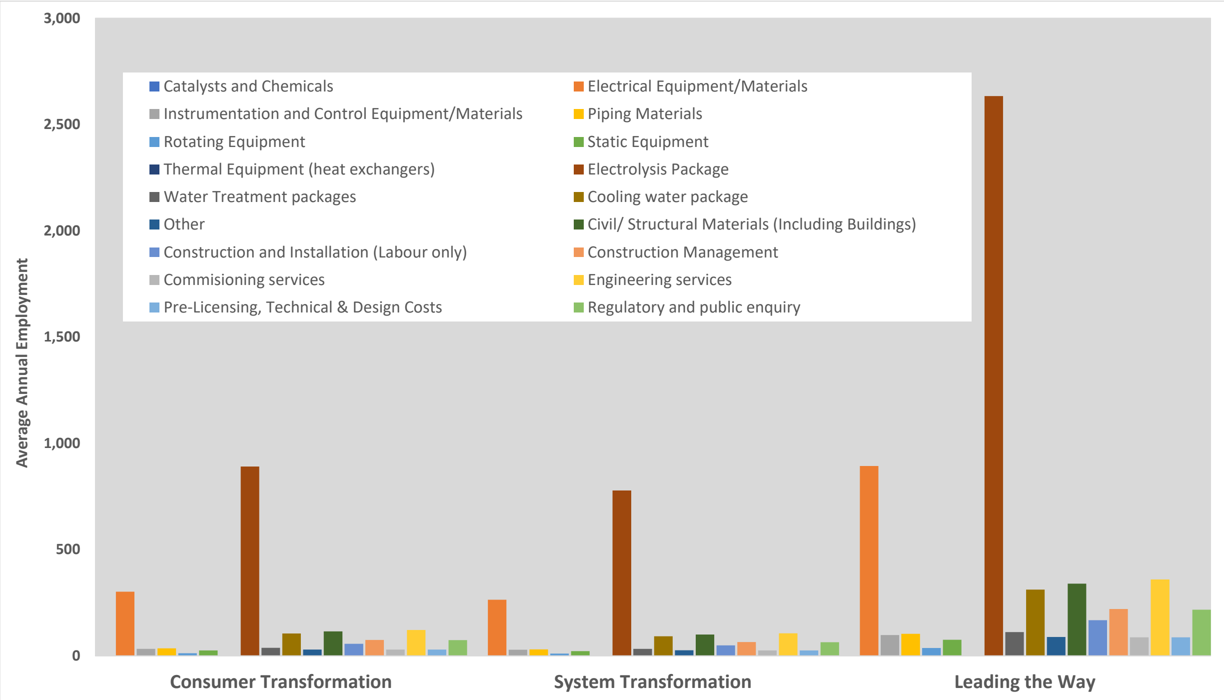

Figure 60: Average Annual Employment to Deliver Green Hydrogen Manufacturing Capacity in 2050

The average annual GVA in different categories within the manufacture of green hydrogen production equipment and plant construction ranges from £154 million to £522 million across the three scenarios, as shown in Figure 61.

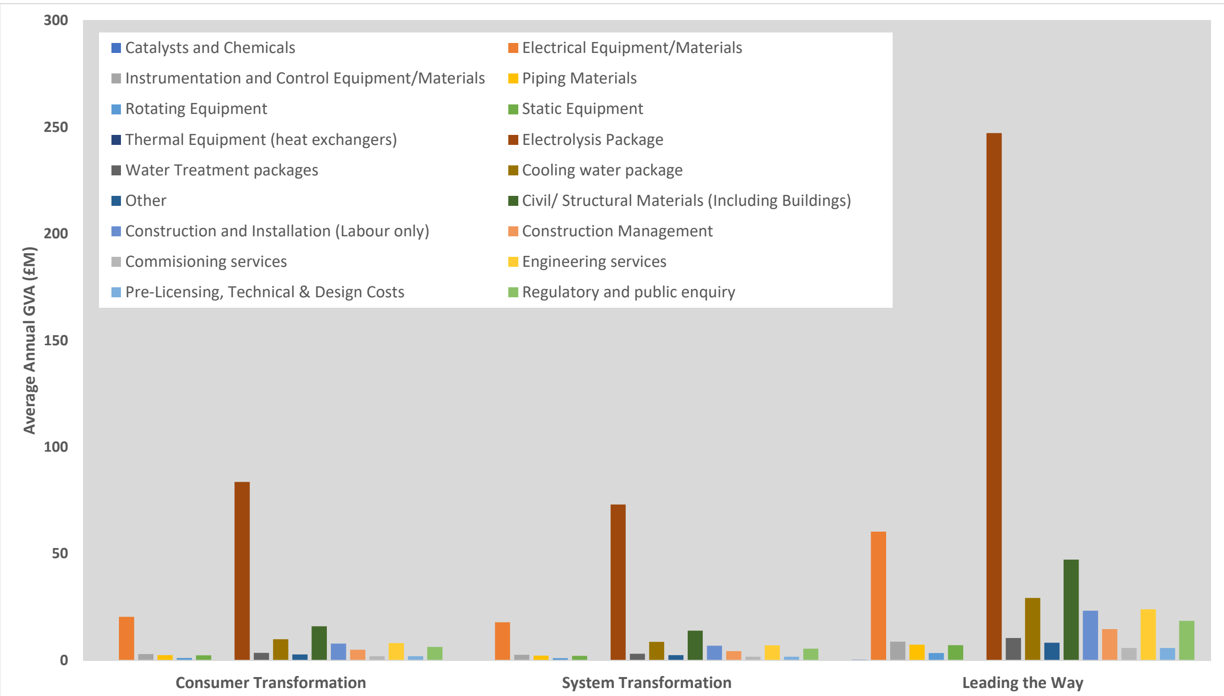

Figure 61: Average Annual GVA to Deliver Green Hydrogen Manufacturing Capacity in 2050

5.3.2.3 Hydrogen Manufacture

The scale of hydrogen manufacturing plant operations in 2050 is summarised in Figure 62.

		Consumer Transformation	System Transformation	Leading the Way
BLUE Hydrogen	Plant operations cost - per annum (£M)	37	155	22
	Employment - per annum	161	675	96
	GVA per annum (Direct) (£M)	21	87	12
GREEN Hydrogen	Plant operations cost - per annum (£M)	221	219	393
	Employment - per annum	961	953	1708
	GVA per annum	124	123	220
Total Hydrogen Manufacture	Plant operations cost - per annum (£M)	258	374	415
	Employment - per annum	1122	1628	1804
	GVA per annum	145	210	232

Figure 62: Economic Impact of Hydrogen Manufacturing Operations in 2050

5.3.2.4 Hydrogen Transport in Repurposed Natural Gas Distribution Network

In 2050 it is assumed that different illustrative percentages of the natural gas distribution network are repurposed for hydrogen, ranging from 6 to 73%, reflecting the development projected in the National grid Future Energy Scenarios[8]. The scale of this task, in terms of total turnover and average annual employment is summarised for the 73% case in Figure 63 and Figure 64.

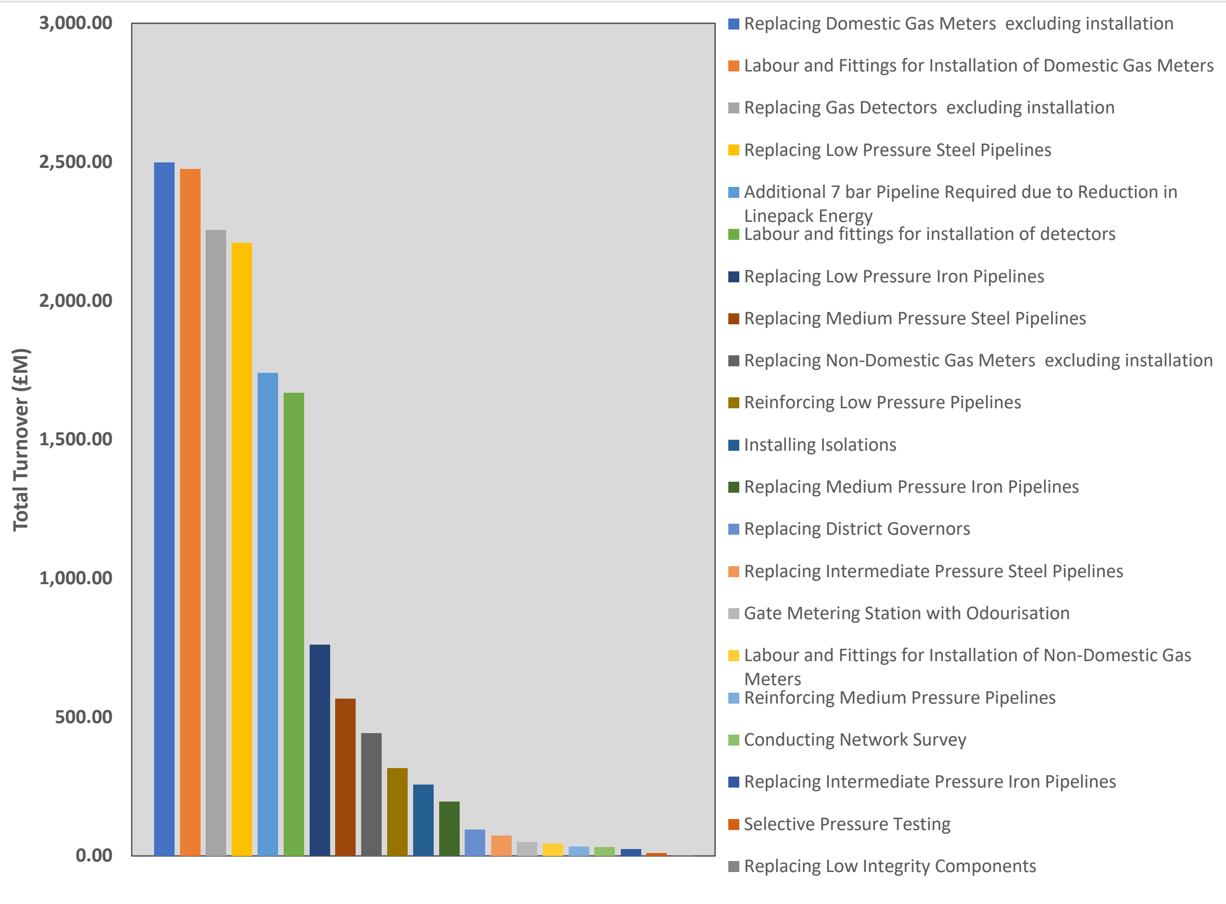

Figure 63: Total Turnover of Activities for Repurposing 73% of the Natural Gas Distribution Network

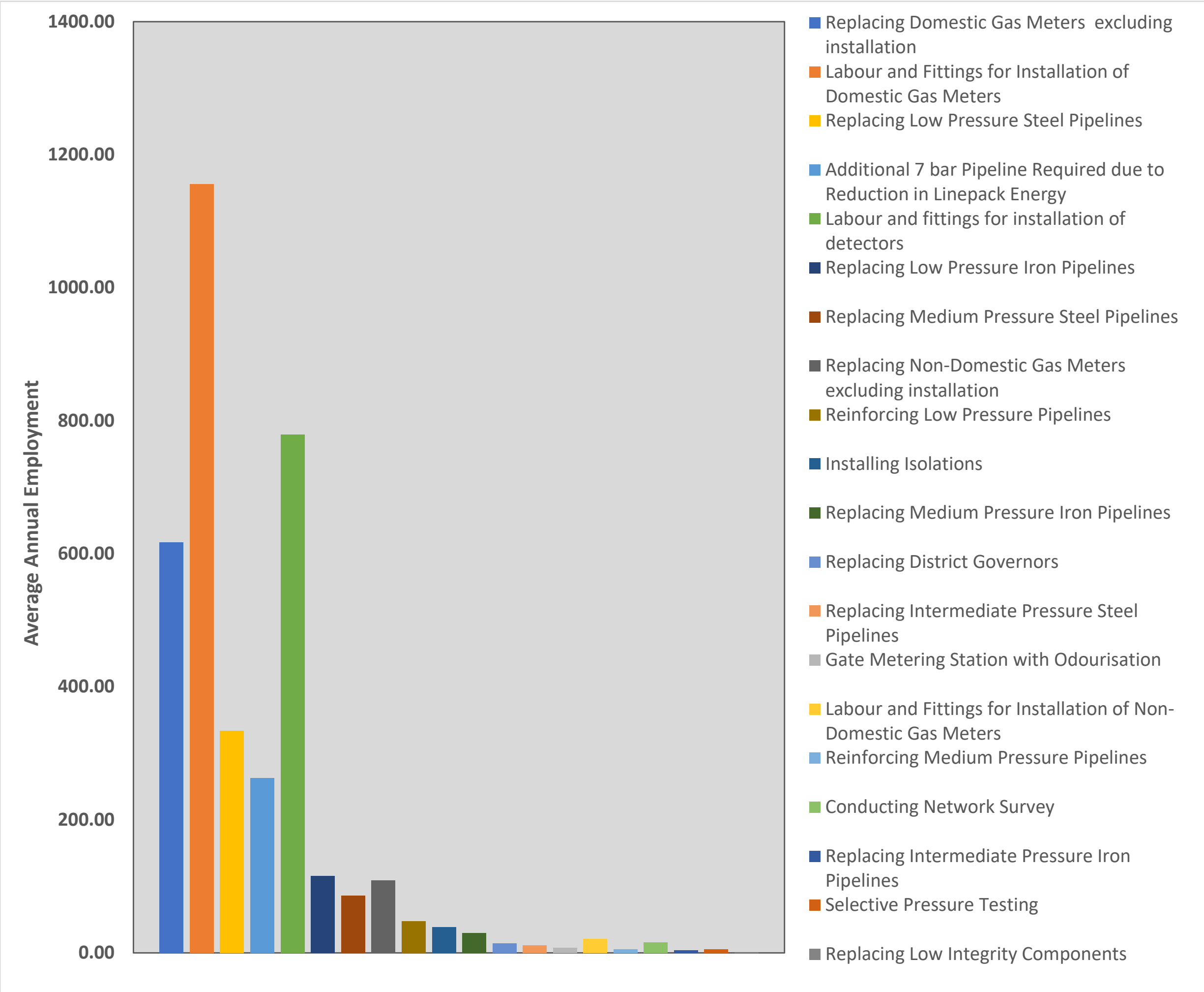

Figure 64: Average Annual Employment for Repurposing 73% of the Natural Gas Distribution Network

This shows the relative scale of different activities and highlights the key economic activities are:

- Replacing domestic gas meters, excluding installation
- Labour and fittings for installation of domestic gas meters
- Replacing gas detectors, excluding installation
- Replacing low pressure steel pipelines
- Additional 7 bar pipeline required due to reduction in linepack energy
- Labour and fittings for installation of detectors

5.3.2.5 Hydrogen Storage (Salt Caverns)[33]

Hydrogen storage is a major part of the 2050 hydrogen infrastructure, as shown in Figure 49. This analysis assumes salt caverns are the main type of storage used. Development of the 2050 underground storage capacity under the three scenarios is shown in Figure 65. A total turnover between 12,600 million and 57,700 million is required, segmented as shown in the figure.

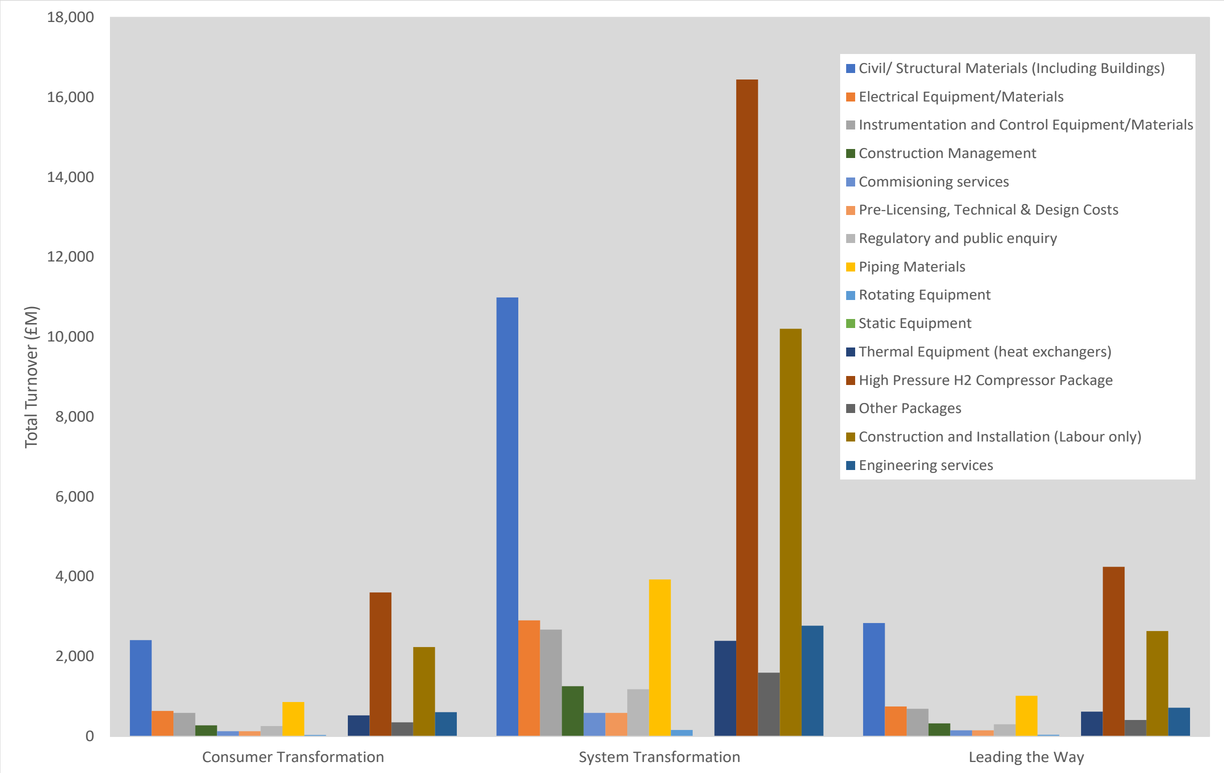

Figure 65: Total Turnover to Deliver 2050 Underground Hydrogen Storage Capacity

Average annual employment to deliver this storge capacity is estimated at between 2,900 and 13,400 as shown in Figure 66 and average annual GVA shown in Figure 67.

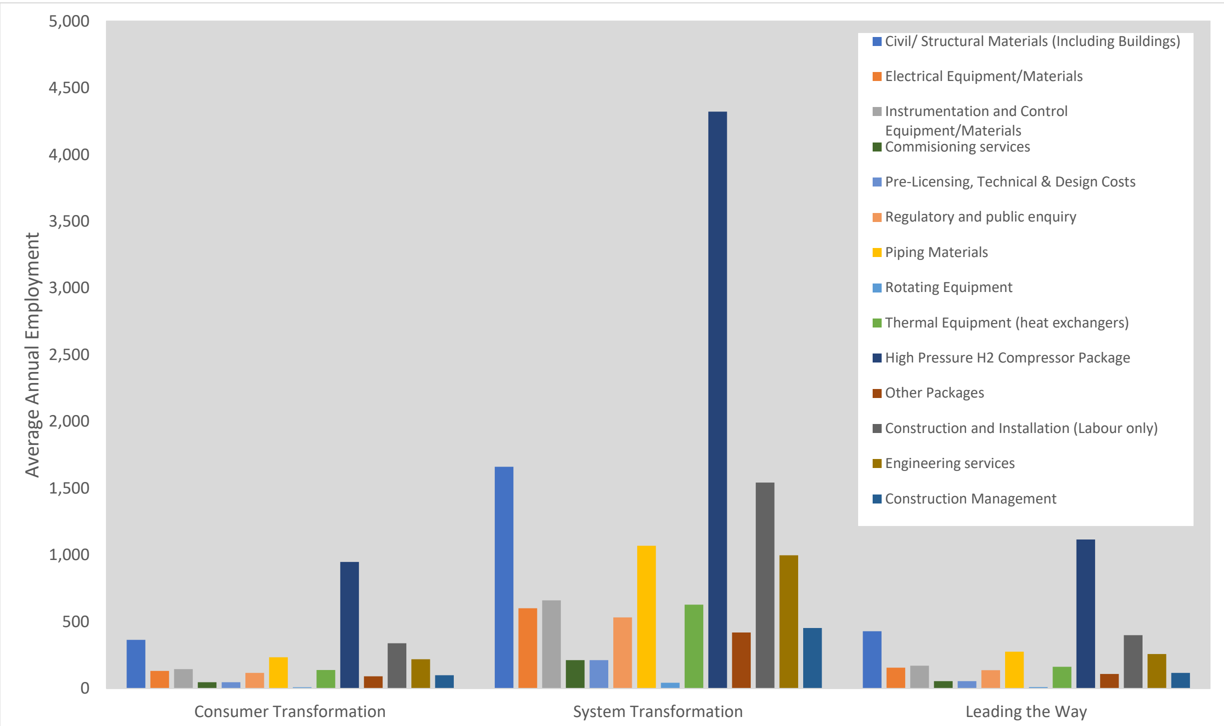

Figure 66: Average Annual Employment to Deliver 2050 Underground Hydrogen Storage Capacity

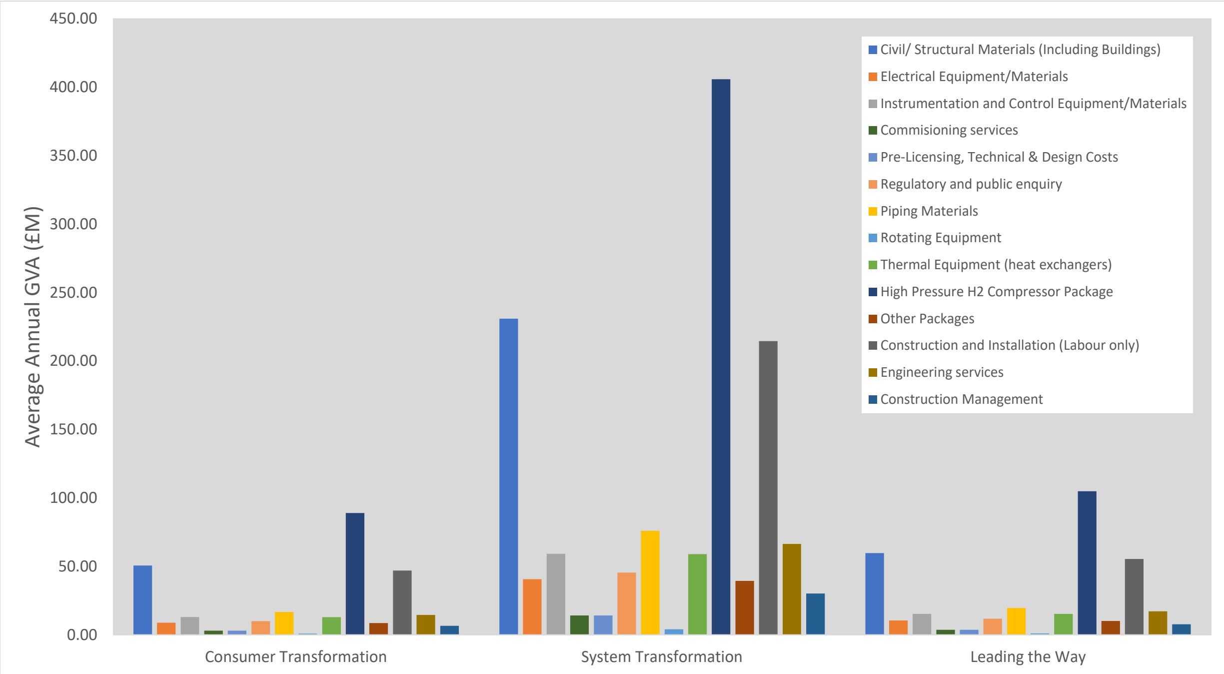

Figure 67: Average Annual GVA to Deliver 2050 Underground Hydrogen Storage Capacity

Figure 65 to Figure 67 show that the largest scale activities here are high pressure H2 compressor package manufacture, civil/ structural materials (including buildings) and construction and installation (labour only).

5.3.2.6 Fuel Cell Manufacture

The scale of activity to manufacture fuel cells in the period to 2050 can be summarised as follows:

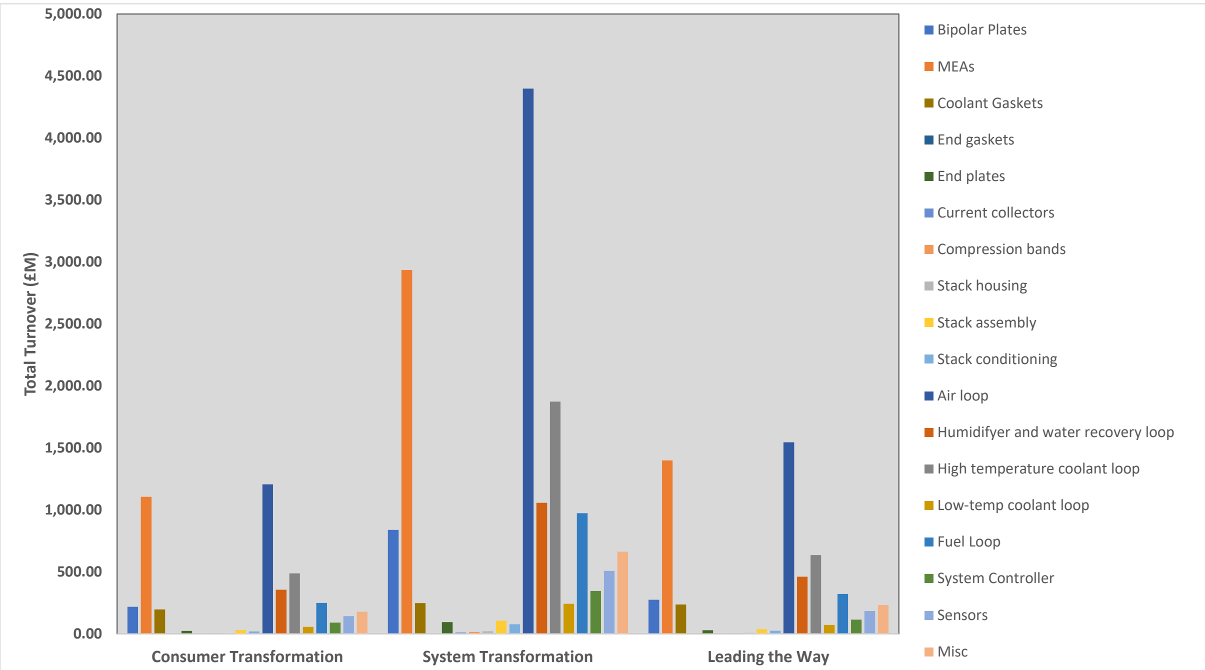

Figure 68: Total Turnover (£M) to Manufacture 2050 Fuel Cell Demand

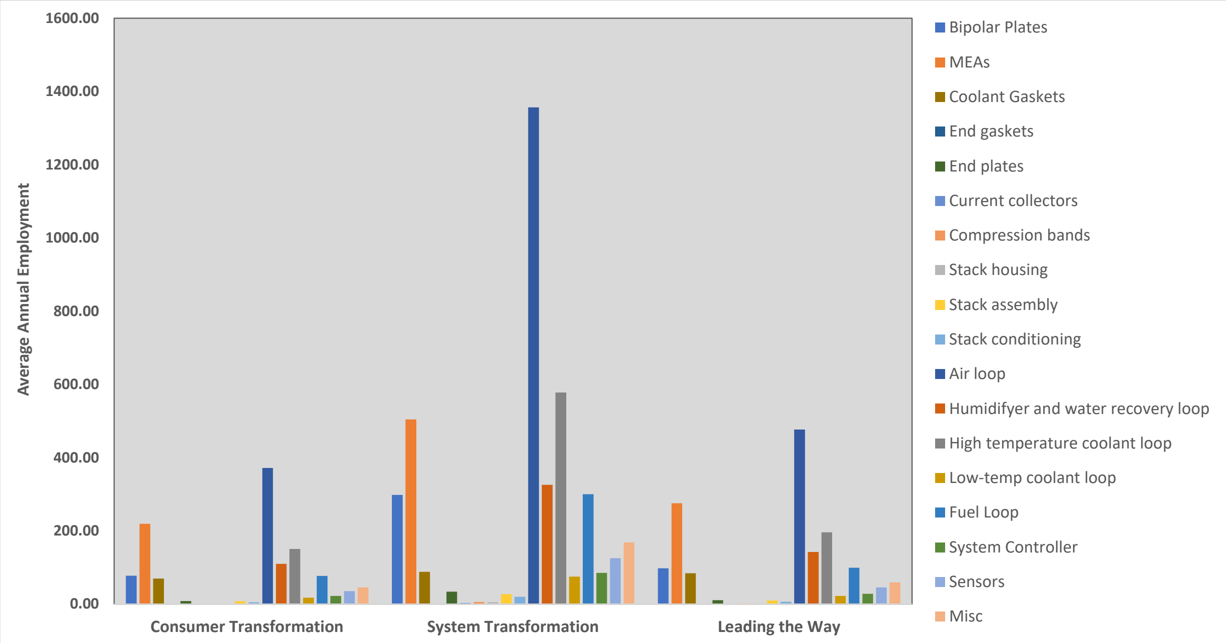

Figure 69: Average Annual Employment to Manufacture 2050 Fuel Cell Demand

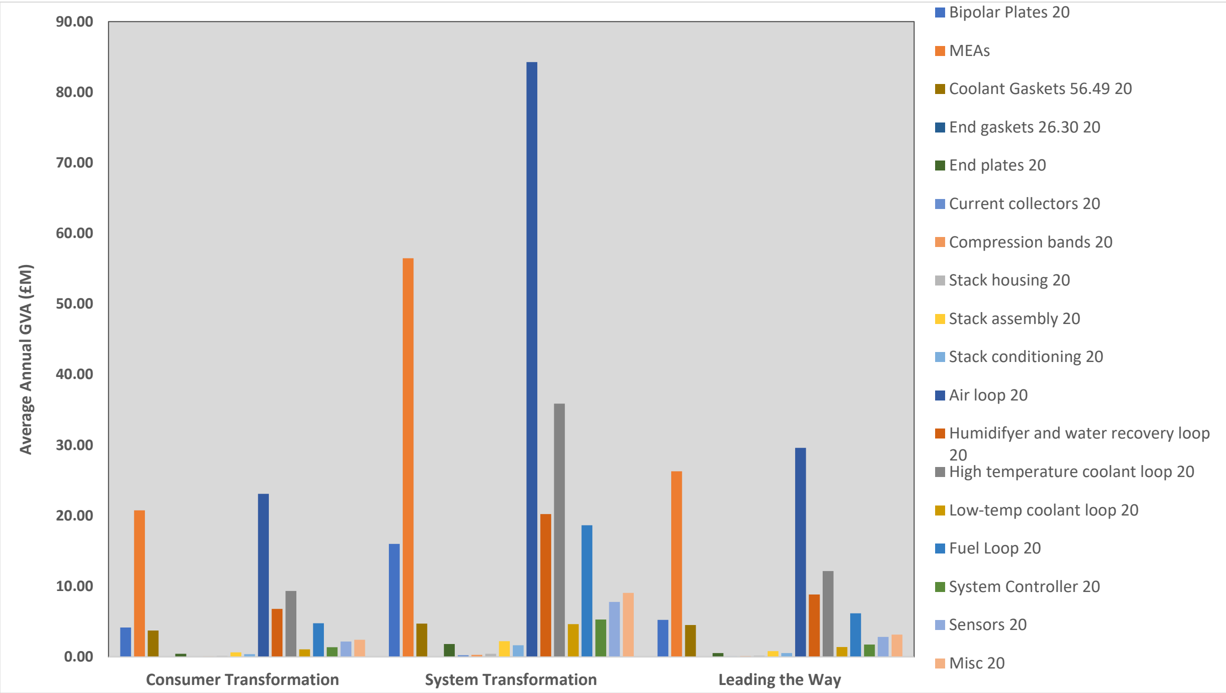

Figure 70: Average Annual GVA to Manufacture 2050 Fuel Cell Demand

Under all three metrics, membrane electrode assemblies, balance of plant air loops and balance of plant high temperature coolant loops offer the largest economic impact.

5.3.3 Potential UK Market Share

As with the 2030 analysis, this section has reviewed the scale of activity, but has not considered the market share that could be captured by UK companies, so does not translate directly into economic benefits for the UK. UK market shares are discussed in section 8, following assessment of UK supply chain capability.

6 Current Supply Chain Capabilities

The analysis of supply chain extent and capability has been performed by Wood, using our in-house Supply Chain team. This team is normally in contact with vendors to obtain prices for active projects in the fields of oil & gas, oil refining, petrochemicals and power generation, and, therefore, Wood has a detailed in-house listing of suppliers for different equipment and material types. This has formed the primary basis for this first pass evaluation of capability in the hydrogen field. For equipment or services where a limited number of manufacturers / suppliers were identified, further research was conducted through a desktop-based search using resources such as the Energy Industries Council (EIC) Supply Map.

Appendix F contains summary tables for supply chain capability in the following areas:

- Common equipment and services applicable across categories
- Blue hydrogen production
- Green hydrogen production
- Hydrogen storage
- Hydrogen transportation
- Fuel cells for transportation

The analysis uses a RAG (Red-Amber-Green) assessment configuration to highlight areas of strength and weakness related to the number of suppliers, range of capabilities, and relevant experience. Definitions used for the assessment are shown in Figure 71.

Rating	1	2	3
Number of major suppliers	More than 5	3 to 5	Fewer than 3
Capability	Sufficient knowledge	Some but requires investment	Low with high investment required
Experience	Fully experienced in this delivery	Some experience	Lack of experience

Figure 71: Supply Chain Assessment Criteria and Scoring

When reviewing the availability of UK-based suppliers, it is important to recognise the international nature of modern supply chains. Very few manufacturers are based solely in one country and most source their components from a range of different nations. Many international suppliers will have a UK-registered subsidiary or local stockist that can supply UK projects and manage the process of importing their products from a variety of countries where they manufacture. Whilst the greatest benefits for the UK economy accrue where a UK-based company manufactures within the UK, our analysis recognises that some benefit is also gained through the use of a UK stockist, including employment of administration and warehouse staff. Therefore, the tables in Appendix F include a set of columns for "UK Suppliers / Stockist - Distributer / Agent" in addition to the column covering UK manufacturers and the global marketplace.

Figure 72 shows a typical example of the assessment output that is included within Appendix F.

Blue H2 Production											
			UK Manufacturers			UK Suppliers / Stockist - Distributer / Agent			Foreign Supplier / Manufacturer		
			Number of Major Manufacturers	Capability	Experience	Number of Major Suppliers	Capability	Experience	Number of Major Manufacturers	Capability	Experience
Burners	Part of reformer package -standard offering	Standard materials	1	1	1	1	1	1	1	1	1
Catalysts	standard established catalysts used in gas reforming	Standard materials	2	1	1	1	1	1	1	1	1
Columns	Packed columns used for Absorbers and strippers with the Carbon capture process. Scale is dependant on size of plant but is not expected to be abnormally large or require specialist metallurgy		1	1	1	1	1	1	1	1	1
Dampers	Part of reformer package -standard offering		1	1	1	1	1	1	1	1	1
Desuperheaters	Standard bulks		2	1	1	1	1	1	1	1	1
Ducts	Part of reformer package -standard offering		1	1	1	1	1	1	1	1	1
Packages - Main equipment supplier	Key packages specific to blue hydrogen production:	various									
	Reformer	various	3	1	1	2	1	1	2	1	1
Reactor vessel	standard pressure vessels up to 30barg with design temp of around 500oC -size will be dependent on design and capacity. Not expected to be anything abnormally large	Will be a range but will include exotic material linings such as Hastelloy in certain applications	1	1	1	1	1	1	1	1	1
Reactor/heat exchanger	Pressure vessels up to 30barg with design temps of around 500oC also internals - nothing especially large but will vary depending on design of plant	Will be a range but will include exotic material linings such as Hastelloy in certain applications	1	1	1	1	1	1	1	1	1
Solvents	Amine or similar based on chosen technology provider		1	1	1	1	1	1	1	1	1

Figure 72: Typical example from Supply Chain Assessment

6.1 UK Hydrogen Supply Chain Capability

The Supply Chain RAG analysis in Appendix F provides a picture of supplier availability, both in terms of UK manufacturers and for UK-companies that are registered to act as suppliers or stockists for equipment and material manufactured in other countries.

Hydrogen production is not a new business. Hydrogen has been used extensively in oil refining over the last 60 years to remove contaminants such as sulphur from crude oil (hydrotreating), breaking of long-chain hydrocarbons into shorter chains (hydrocracking) and to saturate hydrocarbon rings, reducing reactivity and improving fuel properties (hydrogenation). The number and capacity of hydrogen production facilities in the UK is relatively small now compared to where we need it to be, if low carbon hydrogen is to provide a significant proportion of future energy needs, but in most areas the technology is not new.

The types of equipment and materials required for conventional hydrogen production and distribution are also not new. The product level categorisation in Appendix D breaks the components of hydrogen production, storage and transmission down to the component level. For the majority of the equipment items, materials and services, the suppliers for hydrogen plants will be the same as the suppliers for any refinery, petrochemical or power generation project. In terms of the number of UK manufacturers, there is a healthy production line for most of the fabricated items and the tables in Appendix F provide a positive indication of the UK manufacturing industry. For most categories, more than 5 active suppliers were readily identified. Some specific categories or service types were, however, recognised as gaps, as described in the following pages.

For this report, the analysis of the capability and experience for the UK supply chain has been based on a desktop assessment using in-house references and online materials. Whilst this approach provides a good starting point, we are aware that there will be other companies operating in these areas that we did not identify and we welcome further information on these companies. We also recognise that this is not an ideal method to assess the capacity and willingness of individual companies to expand significantly or the level of investment support they might require. It is, therefore, recommended that a follow-up study should be considered, in which individual companies could be surveyed directly on their expansion plans to support the UK's energy transition. A survey of this nature would likely be best conducted through a representative trade association.

6.1.1 Common Equipment & Services Applicable Across Categories

The RAG analysis for common equipment and services shows good coverage by UK manufacturers for the majority of equipment and material types. The exceptions are amongst some of the more specialist categories, such a packaged equipment and high integrity valves.

Emergency Shutdown ESD Valves and Pressure Relief Valves

These specialist valves are fundamental to protection of the process plant from overpressure and manufacturers need to demonstrate high integrity in design and manufacture. The valves used on hydrogen plants are the same as those used throughout the oil & gas and refining industries. The market has consolidated significantly over time and there are few UK suppliers that would be able to supply to the future hydrogen market. The only UK-based ESD valve manufacturer identified was BEL Valves, whilst UK manufacturers of relief valves included Broady, Gresswell, ESME and Severn Valve. There is significant competition from within Europe, particularly Italy, Germany, France and Spain, which has sufficient capacity to supply to the UK market. Whilst UK manufacturers should be able to hold their market share, this is not expected to be an area for significant growth.

Dehydration Packages

As the solvents typically used for capturing CO_2 are water-based, the resultant CO_2 stream is saturated with water: a highly corrosive mixture. This stream needs to be dehydrated to ensure that the export system can be constructed of non-exotic materials. Dehydration packages would also be utilised for treating hydrogen after geological storage. Dehydration can be achieved either through contact with a circulating tri-ethylene glycol (TEG) stream, or by using molecular sieve / adsorbent beds that operate and regenerate in a cyclical manner. Both systems are usually supplied as standard skid-mounted packaged units.

Our team did not identify any UK-based suppliers of dehydration packages. However, there are sufficient suppliers within continental Europe, and internationally, to cover the expected expansion in hydrogen and carbon capture projects. The technology is not particularly challenging to develop and manufacture and so a company anticipating a growing UK business and wishing to establish a UK manufacturing unit could credibly enter this market.

Molecular Sieves / Adsorbent Bed Materials

Molecular sieve and adsorbent bed materials are supplied in bulk as small beads to dehydration package manufacturers and are used to fill the adsorbent vessels. Two UK suppliers of molecular sieve material were identified. The technology is not challenging and there are a large number of international competitors providing these materials.

Piping Materials

In order to supply material / pipe for hydrogen service, suppliers much follow the established codes; currently this is ASME B31.12, which allows for the use of steel grades up to X52 for hydrogen service without qualification. However, most pipeline designers / installation contractors will want to use higher grades so that thinner wall thickness can be used. Lower wall thickness can make a significant difference to the overall volume and cost of material over a large length of piping. X52 (L360) is a low strength material, typically X65 (L450) or higher would be used.

To use >X52 grades the material needs to be qualified and to do this you have to produce material in accordance with the code requirements, then conduct a laboratory test in a hydrogen environment to prove that your material meets the requirements. This would be a minimum prerequisite for a steel mill to be able to effectively engage with potential clients. If mills have not developed materials and qualified these as per the code, potential buyers will not purchase from them.

Within the UK, there are two manufacturers of carbon steel pipe with significant capacity: Liberty Steel Group and Tata Steel. Liberty's production route is through the longitudinal submerged arc welding (LSAW) process, forming pipes from steel plate material, which is bent around and then welded along the seam. The company's manufacturing range is from 2" to 20" with wall thicknesses from 8.7 - 51mm (grade and diameter dependent), steel grades up to X80 and a yearly production capacity of around 200,000 tonnes. Tata's production route is the high frequency induction (HFI) process, forming pipes from steel coil (strip) material. This company's manufacturing range is from 8" to 20" with wall thicknesses from 5 - 20mm (grade and diameter dependent), steel grades up to X70 and a yearly production capacity of around 220,000 tonnes.

Qualifying material is not cheap and takes time, costing tens of thousands of GBP per grade. It is a pre-investment activity that a supplier must engage in before it can, effectively, bid for contracts. This creates a potential barrier to supply in the hydrogen market unless the manufacturers have completed their material qualification for the full range of grades.

Materials Testing

Qualification of carbon steel materials for hydrogen service requires a laboratory capable of analysing hydrogen fracture mechanics in a pressurised environment. Wood is aware of one reputable testing facility in the UK, The Welding Institute (TWI). However, TWI sits within a small pool of globally recognised peers: we are aware of three comparable organisations in Europe and three in North America. If the scale of the hydrogen market is growing and an increased number of suppliers need to qualify their products for hydrogen service, then expanded materials testing facilities will be required.

6.1.2 Blue Hydrogen Production

Much of the equipment used for blue hydrogen production is typical for oil refining. Our RAG analysis shows good coverage by UK manufacturers for most equipment and material types. The exceptions are amongst the more specialist categories, such as the main reformer and reforming catalysts.

Blue Hydrogen Process Licensors

The costs associated with 'Pre-Licensing, Technical and Design' in Section 4.3.1.1 include the basic engineering for the licensed technology package. The three main processes for industrial-scale production of hydrogen are SMR, ATR and POx as described previously. The number of process technology licensors in the field numbers less than a dozen, but three are UK companies: Wood, Shell and Johnson Matthey. Using the RAG assessment, 3 suppliers is classified as amber but, in reality, the

UK has a strong foothold in the process licensing market for hydrogen that could be developed as the global market expands.

Figure 73 indicates the main Process Licensors for blue hydrogen technology and the technologies they offer.

Process Licensor	Country	Technology
Air Liquide	France	SMR
Haldor Topsøe	Denmark	SMR, ATR
Johnson Matthey	UK	ATR
Linde	Germany	SMR, ATR, POx
Lummus	USA	SMR, ATR
Shell	UK / Netherlands	POx
Technip	France	SMR
Wood	UK	SMR

Figure 73: Major Process Licensors for Blue Hydrogen Technology

Reformer Packages

Reformers are large-scale, specialist units that form the heart of the hydrogen production process and are manufactured and installed as packages. They are, typically, supplied as proprietary equipment by the licensor of the process, since the performance and guarantees for the overall plant are linked directly to the design and performance of the reformer itself. The designs contain specific intellectual property (IP) belonging to the licensors, which is closely guarded, hence, there are a very limited number of manufacturers across Europe. Wood currently uses approved manufacturers in Poland, Spain, Italy, Portugal and Spain, but none in the UK.

The barriers for new entrants into this market are very high. The most likely way a manufacturing facility could be established in the UK would be through an existing manufacturer developing an additional site in the UK, importing their existing know-how and quality assurance processes. However, efforts could be made to encourage more UK supply of materials into the reformer manufacturing process. For example, Johnson Matthey has already begun the process of investigating which higher-value elements of the reformer could reasonably be provided from UK suppliers.

Reforming Catalysts

Catalysts for natural gas reforming come from a few niche suppliers. The market is not large as the fixed-bed catalysts should last for years in the reformer tubes if they are protected against poisoning. Catalyst efficacy does decline slowly over a period of time, such that changeout may be required at some point during the life of the plant, but for the most part, the reformer is filled with catalyst at the start of life and no annual replacement is required.

Several UK-based catalyst suppliers have been identified (i.e. Johnson Matthey, BASF and Magma Group) that have the potential to supply into the reformer market, but very few actually supply this limited market at present. Catalyst makes up a small proportion of the reformer cost but is critical to the performance of the plant, therefore licensors will tend to stick with reliable suppliers and catalysts that have been thoroughly tested. There is a significant barrier to new market entrants.

CO_2 Compressor Packages

Carbon dioxide (CO_2) is removed from a blue hydrogen plant either downstream of the shift reactor (pre-combustion) or from the flue gas exiting the combustion section of the reformer (post-combustion). In either case, the CO_2 is captured using a solvent-based absorption process and is regenerated at moderate or low pressure. The CO_2 then needs to be compressed for either transmission via pipeline or liquefaction for export via road tanker / ship. The same equipment will be required that is used for carbon capture systems in other power and industrial applications.

CO_2 compression packages are typically supplied skid-mounted, complete with mechanical drives, control systems, lube oil and seal oil systems. Several UK-based manufacturers were identified in our analysis (Gas Compressors Ltd, Bauer Kompressoren UK Ltd, Atlas Copco UK), but the choice is not broad, and it is not clear that they are able to supply to the output pressure and capacity desired for the future market. This is an area where early investment and clarity on the scale of the future market may benefit UK manufacturers in expanding their sales.

6.1.3 Green Hydrogen Production

There is a limited range of equipment, materials and services specific to green hydrogen production. Most categories are covered within the Common Equipment and Services table in Appendix F. The main gap identified is related to electrolyser packages.

Electrolyser Packages

Of the suppliers of commercially available electrolysers for hydrogen production at greater than 1 MW capacity, there are approximately 20 global suppliers of either PEM or alkaline electrolyser packages, but only one of these is based in the UK: ITM. ITM has invested in increasing both production capacity at its facility in Sheffield and the maximum size of its standard offering. However, given the scale of ambition for construction of green hydrogen plants over the next two decades in the UK, Europe and globally, further expansion in the range of suppliers can be justified.

Our RAG analysis rates the number of suppliers as green (more than 5) but recognises a lower level of capability and experience. There are a number of UK-based electrolyser suppliers that can supply electrolysers at a smaller scale or for other non-hydrogen production processes (e.g. AFC Energy, Amalyst, Ceres, Clean Power Hydrogen Group (CPH2), Supercritical Solutions). These may have the capability to expand their production into large-scale hydrogen production, but this could not be confirmed in a desk based study.

6.1.4 Hydrogen Storage and Transportation

Many of the components of hydrogen storage and transportation facilities are covered within the Common Equipment and Services table in Appendix F. Specific gaps identified in this category are described below.

Salt Cavern Design & Engineering Consultancy

Unless it becomes practicable to re-use exhausted gas reservoirs for the diurnal or seasonal storage of hydrogen, then salt caverns might be the best alternative for balancing out swings in production and demand. The UK has a small number of salt caverns that are used for storage of natural gas or liquefied petroleum gas (LPG). Understanding the subsurface geology of the salt structures and designing a salt cavern that can withstand the cycle of operating pressures within a storage facility is a specialist discipline that is not widely held in UK consultancies. Salt cavern storage is more widely used in continental Europe, particularly in Germany and France and, hence, more experience and capability can be found in European consultancies.

If there is a clear demand for salt cavern storage in UK locations, then this will provide an opportunity for UK-based consultancies to develop the appropriate skill sets, seeding these with knowledgeable individuals from overseas consultancies or academic institutions.

Hydrogen Compressors

Hydrogen that is used to recharge fuel vehicle tanks is, typically, stored and transported at very high pressures in tube trailers or pressurised bullets, so that storage volumes are reduced. These systems usually use low-capacity reciprocating compressors that can fill a store to high pressure over a moderate length of time. The UK has a broad range of manufacturers that can provide compressors for hydrogen and other services, competing against international companies. UK manufacturing companies identified for compression include Howden, Pure Energy, Peter Brotherhood, Belliss & Morcom and Reavell / Gardner Denver.

Based on the future hydrogen demand profiles described in Section 4.1, the volume of hydrogen that will need to be transported around the UK will be much greater than it is now. Natural gas transmission systems make broad use of centrifugal compressors, which have higher volumetric capacity, although at lower maximum discharge pressures. We have not identified any suppliers of large capacity hydrogen compressors, either in the UK or internationally. This provides a potential opportunity for UK-based compressor manufacturers to expand their range of services.

6.1.5 Fuel Cells for Transport Applications

This analysis has focused on the use of fuel cells for transport applications (light, medium and heavy vehicles) rather than static fuel cells designed to provide electric power to commercial or residential users. The UK Hydrogen Fuel Cells Association (UKHFCA) [34] lists a number of UK suppliers of fuel cells and designers of vehicles for use with fuel cells.

The UK (and Europe) has focused on battery electric vehicles as a solution to zero-emission transport for cars and vans, whilst hydrogen has, typically, been seen as a more credible solution in Japan and South Korea. Production lines for fuel cells have not yet been established in the UK. The lack of production facilities for hydrogen-powered transport in the UK creates a barrier to the production of fuel cells now, but also creates an opportunity for future investment. The Advanced Propulsion Centre UK (APC) has produced a roadmap for the development of automotive fuel cells highlighting the challenges and opportunities for UK technology developers [35]. There are also opportunities for manufacturer of fuel cell components, such as the Gas Diffusion Layers (GDLs) and Membrane Electrode Assemblies (MEAs) offered by Johnson Matthey.

For heavy goods vehicles and trains, where more space is available for the hydrogen storage tank, a lower on-board storage pressure can be used for hydrogen. This simplifies the design and fuel loading

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34 UKHFCA website, http://www.ukhfca.co.uk/

35 APC technology development roadmaps, see https://www.apcuk.co.uk/media-type/roadmaps/

systems and, hence, hydrogen fuel cells are less challenging. The production of fuel cells aligned with production lines for next generation HGVs and trains provides an opportunity for new manufacturing facilities in the UK.

6.1.6 Summary – Key Strengths and Gaps

6.1.6.1 Supply Chain Strengths

The UK has a well-established supply chain for equipment and services for the Oil & Gas, oil refining and petrochemical industries. The technology and skills required to support the hydrogen economy are the same. Hence, the established suppliers should be able to compete effectively to supply hydrogen production, storage and transportation projects against global competition.

Three of the main hydrogen reformation technology licensors are UK-based companies. As reformation processes move from 'grey' hydrogen (with no carbon capture) to blue hydrogen (with integrated carbon capture), these companies are in an excellent position to provide engineering design services within a global market.

The UK is home to ITM, one of the primary suppliers of electrolyser modules for production of green hydrogen. ITM has a manufacturing base in Sheffield, with a production capacity of 1 GW per annum and plans to expand capacity by an additional 1.5 GW per annum by the end of 2023.

6.1.6.2 Supply Chain Gaps

A number of supply chain gaps were observed in this evaluation where UK supply chain capability is weak and these are summarised below.

- Reformers – no suppliers of industrial scale reformers were identified. These are complex packaged items that are fundamental to achieving the guaranteed process performance of the overall plant. Therefore, licensors will continue to use well-known existing fabricators.
- Line pipe – UK manufacturers of line pipe are not yet qualified for production of the full range of grades of pipe for hydrogen service. This may prevent them for bidding to supply hydrogen projects and will require pre-investment by the suppliers to demonstrate that their products meet performance criteria.
- Electrolyser packages – There is only one recognised UK-based supplier of industrial-scale electrolyser packages for hydrogen services. Other electrolyser package manufacturers exist, but do not currently support large-scale hydrogen production.
- Hydrogen compressors – UK manufacturers are able to supply small-capacity, high-pressure reciprocating hydrogen compressors for charging storage tanks on vehicles. However, there is a shortage of suppliers able to support large-capacity, medium-pressure centrifugal compressors required for hydrogen transmission systems. This appears to be a general gap in the global supply chain, which could be filled by UK manufacturers that are already designing and supplying centrifugal compressors for hydrocarbon service.
- CO_2 compressors – There are limited UK suppliers that can provide CO_2 compressor packages for transport of CO_2 away from blue hydrogen plants for permanent storage. Since the key attribute is an understanding of rotating machinery and fluid thermodynamics, these companies are the same as companies supplying hydrocarbon service in the Oil & Gas industry.

- High integrity valves – This is a well-developed market that has seen widespread consolidation. The number of UK manufacturers is small, but they should be able to compete effectively in the new hydrogen market.
- Packaged dehydration units – No UK manufacturers of dehydration packages were identified. However, there is no reason to believe that these could not be produced domestically if the right investment opportunities existed.

6.2 Global Hydrogen Supply Chain Capability

As noted above, the market for hydrogen production equipment, and for the vast majority of the individual components, is a mature market with a broad range of international suppliers that are available to supply UK projects. Even where purchasers decide to limit the range of suppliers based on British or international standards, or if they choose to exclude low-cost manufacturing centres, there is still a strong, competitive market and UK manufacturers will face the same pressure as for current refinery or petrochemical projects.

Potential areas of weakness in the global marketplace that might be filled by UK suppliers are limited, but a few have been highlighted above.

A SWOT analysis and identification of priority development opportunities are included in Section 7.

6.3 Constraints and Barriers Affecting Development of the Hydrogen Economy

Constraints and barriers to development of the hydrogen economy that are linked to the hydrogen supply chain, the relevant business environment and the wider environment have been identified through a stakeholder workshop[36] and desk research, then assessed to a limited extent within the constraints of this study. These can be summarised as follows.

6.3.1 Supply Chain Constraints and Barriers

Supply chain constraints, their impact and potential mitigation options are detailed in Figure 74.

[36] A key input to this section was a workshop with the Hydrogen Advisory Council Sector Development Group.

Constraint	Impact on Supply Chain	Potential Mitigation
The extensive and disparate nature of the supply chain makes it difficult to identify how it will develop, limiting the potential to pursue business opportunities with confidence	Supply chain investment is inhibited due to difficulties in identifying and making the case for attractive opportunities	Separately address different elements of the supply chain (under wider framework)
Lack of confidence in the availability and capability of the required constuction resources to build hydrogen economy infrastructure	Supply chain investment inhibited as it is not clear that manufacturing plant and infrstructure will be available when needed	Mapping of construction capability Investment in skills development
Lack of CO2 shipping infrastructure to support blue hydrogen manufacturing	Blue hydrogen manufacturing investment inhibited as there is no readily available solution for carbon dioxide emissions	Prepare holistic sector development programme and investment plan
Lack of hydrogen shipping infrastructure to support international trade	Supply chain opportunities related to exporting inhibited	Prepare holistic sector development programme and investment plan
Lack of hydrogen infrastructure to support end user market developments	Supply chain investment is inhibited due to difficulties in identifying and making the case for attractive opportunities	Prepare holistic sector development programme and investment plan
Limited focus on developing hydrogen application supply chains, affecting business cases for hydrogen supply chain development	Supply chain investment is inhibited due to difficulties in identifying and making the case for attractive opportunities	Prepare holistic sector development programme and investment plan
Unproven supply chain capability inhibiting the ability of companies to pursue technology development	Slow development and introduction of technology	Demonstration projects

Figure 74: Identification and Analysis of Supply Chain Constraints

These all reflect the embryonic nature, complexity and wide scope of the hydrogen supply chain and highlight a lack of clarity and confidence in how the supply chain will develop. This, in turn affects how individual companies, which have proven approaches to business development will pursue opportunities and how UK industry can win a significant share. How can investment decisions be made regarding specific products or services when it is not clear how relevant supply chains and markets will develop? Leadership in the development of the UK hydrogen supply chain and prioritisation of areas for growth and investment is, therefore, required

6.3.2 Constraints and Barriers in the Business Environment

The identification and analysis of constraints and barriers in the business environment, was structured using the four factors in Porter's Diamond Model[37], a diamond-shaped framework that focuses on explaining why certain national industries are competitive internationally, while others might not. These factors are:

- Strategy, structure and rivalry of companies in the sector

[37] The Competitive Advantage of Nations, Michael E Porter, Harvard Business Review, March – April 1990

- Factor conditions - the natural, capital and human resources available
- Demand conditions – domestic and export demand and the complexity of demand
- Related and supporting industries - industries that supply, distribute, or are otherwise related to the industry being examined

The constraints and barriers identified in the business environment are presented in Figure 75.

Factor	Constraint	Impact on Supply Chain
Demand Conditions	Lack of established market infrastructure, activity and demand	Limited supply chain drivers
	Lack of clarity on priorities for domestic market demand	Supply chain development inhibited
	Overseas market attitude to UK hydrogen that may have come from non-renewable sources	No export market
	Global competition for supply chain investment	Lack of UK supply chain development
	Lack of demand in transport - linked to technology readiness of vehicles	Supply chain development inhibited
	Major challenge to certify automotive (fuel cell) hydrogen specification fully	Supply chain development inhibited
	Lack of regulations and standards for hydrogen combustion in transport	No clarity on market need
	Hydrogen transport options for international trading unclear	Lack of rationale for sector / supply chain development
	Hydrogen fired gas turbines not commercially available	Delay in power generation market development
Factor Conditions	Lack of confidence that the required infrastructure will be established	Lack of rationale for sector / supply chain development
	Lack of UK rail testing facilities for hydrogen traction	Product demonstration and supply chain development inhibited
	Decision on conversion of NTS to hydrogen vs new-build hydrogen backbone needed	Supply chain development inhibited
	Access to hydrogen based on clusters	Need to have a geographical approach to end use
	Regulations, codes, and standards either not in place or not appropriate	Supply chain development inhibited
	There are no UK certification facilities for hydrogen components	Cost of entry and certification for new components is prohibitive for UK manufs
	Actual or perceived safety risks re ammonia and/or hydrogen storage and combustion	Limiting development and commercialisation
Firm Strategy	Lack of global hydrogen supply chain companies	Lack of focal points / drivers for supply chain development
	Lack of investment in UK manufacturing sector	Supply chain development inhibited
	Limited exploitation/commercialisation of strong R&D portfolio	Supply chain development inhibited
	Lack of insurance and certification for new supply chain players	No confidence in capabilities
Related Industries	Need engagement and buy-in across related key sectors - e.g. finance, insurance, etc.	Development and operation of the supply chain affected

Figure 75: Identification and Analysis of Constraints in the Business Environment

A number of these support and extend the supply chain barriers and constraints identified above and are, predominantly, due to the early stage of development of the hydrogen economy and supply chain and its complexity. They reflect a desire for clarity and certainty within a business environment that is also at its early stages. Potential mitigation actions included preparation holistic sector development programme and investment plan, as highlighted in Figure 66, investment in relevant infrastructure, and development of appropriate regulations and standards.

6.3.3 Constraints and Barriers linked to Wider Environmental Factors

The wider political and economic context has been reviewed and the main constraints and barriers identified are:

- Political
  - The Hydrogen Strategy and recent Energy Security Strategy define high level targets for hydrogen capacity and manufacture but these do not provide the clarity and direction at the level of detail that industry needs to support investment decisions. This issue is exacerbated by the complexity and wide scope of the hydrogen supply chain. The recently published Hydrogen Investor Roadmap[38] may offer some of the clarity and detail required. The government has also announced recent investment schemes for future energy technologies[39].
  - The way in which the UK Government's regional cluster approach will catalyse supply chain investment that leads to national capability is not well understood
- Economic
  - The lack of a short term business case for decarbonisation

These issues reflect and support the constraints and barriers discussed above but are not specific to development of the hydrogen economy. They are also noted in the wider development of a net zero industrial economy[40].

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38 Hydrogen Investor Roadmap, UK Government, April 2022, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067408/hydrogen-investor-roadmap.pdf

39 Investment for Energy Technologies of the Future, UK Government, April 2022, https://www.gov.uk/government/news/government-unveils-investment-for-energy-technologies-of-the-future

40 For example, see Development of Scotland's Net Zero Roadmap for Industry (https://snzr.co.uk/)

7 SWOT Analysis of the UK Hydrogen Supply Chain

7.1 SWOT Analysis

A SWOT analysis of the UK hydrogen supply chain based on a review of the evidence gathered in this study has been completed, as presented below.

Strengths

- UK hydrogen, energy security and decarbonisation strategies offering strategic direction
- Government commitment to commercial development projects, such as the UKRI Industrial Decarbonisation Challenge and the BEIS Cluster Sequencing Programme, is ahead of European and global competitors, giving UK companies an opportunity to establish capabilities earlier than their companies in other countries.
- Credible plans for the development of commercial scale production of low-carbon hydrogen in all six of the UK industrial clusters supported by UKRI, forming a strong foundation for growth towards 2030 targets.
- Access to suitable, permanent CO_2 stores, critical for development of blue hydrogen production, which forms an integral part of UK industrial cluster development, especially in Scotland, with access to significant North Sea storage capacity.
- Significant cavern capacity for hydrogen storage
- Significant offshore wind energy availability for the manufacture of green hydrogen and a strong commitment to develop generating capacity (e.g. recent ScotWind offshore wind leasing activities[41])
- Great enthusiasm from companies to develop industrial low-carbon hydrogen projects, as demonstrated by the eight applications submitted to be BEIS Cluster Sequencing Programme Track-1, Phase-2 projects in the East Coast Cluster, Scottish Cluster or Hynet.
- A broad range of reputable suppliers of equipment, materials and services for the oil & gas, oil refining, petrochemical and power industries with products that are suitable for application in a hydrogen economy, as identified in this study, as defined in Section 6.
- Internationally recognised UK capability in electrolysis technologies, as defined in Section 6.
- UK-based technology providers are amongst the few recognised blue hydrogen production plant licensors, as defined in Section 6.
- Industry and government commitment to develop fuel cell technologies for automotive applications (e.g. Automotive Transformation Fund (ATF) and Advanced Propulsion Centre (APC) activities)

Weaknesses

- A lack of clarity and confidence in how the supply chain, which is complex with numerous interdependencies and wide in scope will develop

41 https://www.crownestatescotland.com/news/scotwind-offshore-wind-leasing-delivers-major-boost-to-scotlands-net-zero-aspirations

- Although some key UK companies are well aware of the future opportunities pipeline it is unlikely that the majority of UK manufacturers and service providers that could benefit from development of hydrogen supply chains have good knowledge of the future growth in blue and green hydrogen and the opportunities this will afford. Greater awareness of these will be needed in order to raise ambition levels.
- There is a shortage of qualified producers of line pipe steel for on-site hydrogen piping and regional hydrogen pipelines. There are two main manufacturers in the UK. Pre-investment in material qualification will be required to ensure they can successfully supply line pipe for all applications in a future hydrogen economy.
- There is a shortage of UK manufacturers of specialist high-integrity valves and packaged equipment. In a field where reliability and proven experience is more critical than price, new entrants will find it difficult to establish a competitive position against established international competition.
- Shortage of suppliers able to support large-capacity, medium-pressure compression required for hydrogen transmission systems
- Limited UK suppliers that can provide CO2 compressor packages for transport of CO2 away from blue hydrogen plants for permanent storage

Opportunities

- Widespread conversion of natural gas distribution systems and domestic and commercial premises to run on hydrogen instead of natural gas to address demand for low-carbon hydrogen. This will require significant skilled labour for the conversion process.
- The UK has one strong manufacturer of commercial-scale electrolysers, but also a number of smaller electrolyser producers that could expand their product range and service lines to include hydrogen production.
- The UK has one of the few globally-recognised institutions for qualification of materials for hydrogen-service. With the right investment, services could be expanded to take advantage of the likely growth in demand.
- There is no existing market for the supply of high capacity, centrifugal hydrogen compressors. Early commitment to developing manufacturing assets and infrastructure in the UK could facilitate investment in a new range of compressors by UK suppliers, giving them an advantage for future market growth.
- UK-based consultancies could establish capabilities in the conceptual design and engineering of salt caverns, drawing on knowledge imported from Europe or from academic institutions.

Threats

- The European Union ‘Fit for 55’ legislative package and member country plans focus heavily on green hydrogen with limited transition via blue hydrogen. Several member countries have similarly ambitious targets for early deployment of green hydrogen which may make European locations more favourable for investment in electrolyser production.
- Confidence of companies to invest in supply chains could be affected if government strategy and policy does not give companies sufficient confidence.
- Policies incentivising the use of hydrogen may not be viewed as sufficiently attractive to catalyse investment in hydrogen production, transport and storage infrastructure.

- There is a significant risk that UK companies will not be represented in the supply chains of projects if international engineering, procurement and construction (EPC) contractors are selected to deliver UK projects as they will likely default to their proven international supply chains.
- Availability of high-quality water supplies could restrict development of green hydrogen projects, particularly in areas of current water scarcity.
- Increased demand for renewable electricity for homes and industrial premises may limit the availability of wind power for production of green hydrogen.

This SWOT analysis can be summarised as shown in Figure 76.

Strengths	**Weaknesses**
• UK hydrogen, energy security and decarbonisation strategies • Government commitment to commercial development projects • Credible plans for development of commercial scale production • Access to suitable permanent CO_2 stores • Significant availability of offshore wind energy • Significant cavern capacity for hydrogen storage • Industrial commitment to develop capacity • Broad range of suppliers of equipment, materials and services • Internationally recognised UK capability in electrolysis technologies • UK-based technology providers for blue hydrogen production • Commitment to develop fuel cell technologies for automotive applications	• Lack of clarity on supply chain development priorities • Lack of widespread awareness of the opportunities arising • Shortage of qualified producers of line pipe steel • Shortage of UK manufacturers of specialist high-integrity valves and packaged equipment • Shortage of suppliers able to support large-capacity, medium-pressure compression required for hydrogen transmission • Limited UK suppliers that can provide CO2 compressor packages for transport of CO2 away from blue hydrogen plants for permanent storage
• Widespread conversion of equipment and infrastructure to run on hydrogen • Expand commercial-scale electrolyser capacity • Exploit globally-recognised institutions for qualification of materials for hydrogen-service • Develop UK compressor capability • Develop capabilities in the conceptual design and engineering of salt caverns	• European competition for green hydrogen manufaturing • Lack of confidence for supply chain investment • Competition from alternative net zero solutions • International supply chains dominate UK supply opportunities • Lack of high quality water availability • Competiton for renewable energy capacity
Opportunities	**Threats**

Figure 76: SWOT Analysis of the UK Hydrogen Supply Chain

7.2 Supply Chain Challenges – Linking Strengths and Threats

As with many SWOT analyses, the current perceived strengths can be undermined by future threats, whilst areas of weakness can be turned around into opportunities for expansion. The links between some of the strengths and threats are discussed below, whilst Section 7.3 considers future opportunities.

The UK Government has shown international leadership by being one of the first to set a binding commitment to achieve Net Zero greenhouse gas emissions by 2050 and generating the Ten-Point Plan to achieve this target. The early phases of development of industrial clusters and offshore CO_2 stores have proceeded well, with clear support from the Government providing the confidence needed by investors that the projects will move forward into deployment. However, whilst confidence takes years to develop, it is often fragile and can be undermined very quickly, so consistent policy and Government support is critically important. It is essential, therefore, that the Government continues its consistent messages about the market for hydrogen and supporting technologies.

The potential for low-carbon hydrogen production is significant but may be undermined if there is not a supportive framework for hydrogen demand.

UK supply chain strengths, in, for example electrolysis manufacture, should be supported to ensure they remain internationally competitive.

The recent applications to the BEIS Cluster Sequencing Programme for Track-1, Phase-2 project status [42] have demonstrated the enthusiasm from investors to be involved at the forefront of the hydrogen economy. The list includes oil & gas majors that are keen to transition their companies into low-carbon energy suppliers. Typical contracting practice amongst many energy suppliers is to engage an international EPC contractor to deliver hydrogen projects and place the cost and schedule risks on this contractor, so that the developer gains price certainty. However, this approach removes the control of where materials are manufactured one step further away from the UK Government. Once the EPC contracts are let, the contractors will maximise their existing supply chains to ensure security of supply and protect their schedule, rather than seek opportunities to find new UK suppliers. A mechanism to engage with UK supply chains, support supplier development and develop procurement processes that recognise UK company development ambitions (e.g. innovate procurement approaches) should be implemented.

The enhanced targets for green hydrogen set in the recent UK Government Energy Security Strategy [43] provide a strong commitment to installing at least 5 GW of green hydrogen production capacity by 2030, which gives confidence that increased manufacturing capacity for electrolyser packages will be required. However, the European Union is now developing its own decarbonisation targets, including the 'Fit for 55' legislative package. Several member nations have set out similarly ambitious targets for green hydrogen development over the remainder of this decade and so the apparent market for electrolyser packages in Europe appears much larger than in the UK. The right investment support mechanisms should be offered to encourage investors to develop new manufacturing capacity in the UK, rather than in mainland Europe.

The UK benefits from some key geographical and geological advantages with respect to the development of a hydrogen economy. It has good access to natural gas fields, which can supply blue hydrogen plants, and extensive saline aquifers, depleted gas fields and other geological features in the North Sea for permanent storage of the CO_2 that is generated. For production of green hydrogen, the UK has the significant advantage of huge offshore wind resources, which can be developed over the coming decades and could lead to hydrogen export opportunities. However, there is already great demand for renewable electricity to supply households and to facilitate charging of the increasing number of electric vehicles. Green hydrogen will compete with these other applications for low carbon electricity. There is also another resource need for green hydrogen plants that is often overlooked – water. As the UK climate warms, we should be aware of the increased risk of water shortages in some regions of the country.

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42 https://www.gov.uk/government/publications/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc/cluster-sequencing-phase-2-eligible-projects-power-ccus-hydrogen-and-icc

43 https://www.gov.uk/government/publications/british-energy-security-strategy

Water availability will likely contribute to the site location of green hydrogen production assets and as discussed earlier in section 4.3.1.2 water supply quality will vary from project to project. For this reason, this report assumes that future green hydrogen plants will be required to generate their own water supply through desalination of seawater. Depending on the uptake of green hydrogen within the hydrogen economy, and competition for water resources, significant deployment of green hydrogen could lead to offshore hydrogen production where UK offshore engineering capabilities should ensure that this can be successfully delivered. It should be noted however that an offshore design basis has not been considered in this analysis when illustrating the respective supply chains for hydrogen production assets.

7.3 Supply Chain Development – Linking Weaknesses and Opportunities

Whilst the UK has a broad range of companies that have developed to support the Oil & Gas and oil refining industries, it is not clear whether many of these companies are aware of or are actively preparing to support the expansion of hydrogen as an energy vector. As this was a desk-based study, UK supply chain companies were not surveyed. Whilst equipment suppliers were identified in certain fields, their existing capacity, range of services or appetite to expand in support of the hydrogen economy was not ascertained. A follow-up assessment, where suppliers are specifically surveyed to determine their capabilities and readiness to support this growing market would be valuable.

The UK is the first country to commit to developing hydrogen pipeline networks as part of Hynet and the East Coast Cluster (Teesside and Humberside), but UK line pipe manufacturers have faced a highly competitive market in recent years and have not been eager to invest in qualification of the full range of higher steel grades necessary for hydrogen-service. At present, this creates a risk that they may not pre-qualify to bid for the supply of some pipelines. Providing support for the cost of qualification should be considered.

The UK does not have many manufacturers of packaged hydrogen or CO_2 compressors, but it does have the manufacturing skills to expand in this area of perceived growth. Early deployment within industrial clusters provides an opportunity to encourage international companies to establish UK bases for either manufacture of the compressors themselves, or for packaging the compressors, ready for delivery. Global suppliers of high-capacity centrifugal hydrogen compressors have not been identified, which will be needed for bulk transmission throughout the UK under most scenarios. This creates an opportunity for UK-based suppliers to take a lead in design and supply of these machines.

Future storage of hydrogen for diurnal or seasonal fluctuations will become increasingly important as hydrogen provides a greater proportion of the UK's energy supply. For the long-term, this may be through the use of offshore aquifers and exhausted gas reservoirs but, in the shorter term, it is possible that salt cavern storage will provide buffer capacity. There is a small number of salt caverns already in use in the UK but there are many more in use in continental Europe. The expertise for designing salt caverns is, therefore limited within the UK. Broader use of salt caverns for storage of hydrogen may provide an opportunity for UK-based consultancies to expand their knowledge base and target this market.

8 UK Supply Chain Development Opportunities

8.1 UK Market Opportunities

8.1.1 High Value UK Opportunities

The economic impact analysis presented in Section 5 showed that the scale of the supply chain to meet 2030 and 2050 UK targets range from between £7.9 and £9.3 billion in 2030 to between £33.5 and £124 billion in 2050. It also highlighted the most attractive opportunities *within each supply chain segment*. These are listed in Figure 77 which includes rankings of the ten most economically attractive opportunities based on average annual employment and average annual GVA data.

Supply Chain Segment	Category	2030							2050						
		Average Annual Scale of Activity (£M)	Range of Average Annual Emplyment Across the Scenarios	Average Annual Employment	Emp. Based Rank	Range of Average Annual GVA Across the Scenarios	Average Annual GVA (£M)	GVA Based Rank	Average Annual Scale of Activity (£M)	Range of Average Annual Emplyment Across the Scenarios	Average Annual Employment	Emp. Based Rank	Range of Average Annual GVA Across the Scenarios	Average Annual GVA (£M)	GVA Based Rank
Blue Hydrogen Manufacturing Capacity	Civil and structural materials (including buildings)	351	57 - 256	152	8	8 - 36	21	6	74	32 - 566	223	10	4 - 79	31	8
	Construction and installation labour	280	45 - 204	121		6 - 28	17	9	59	25 - 451	178		4 - 63	25	10
	Reformer package manufacture	37	72 - 325	193	5	7 - 31	18	7	54	40 - 719	283	7	4 - 67	27	9
	Engineering services	157	61 - 273	162	7	4 - 18	11		33	34 - 603	238	9	2 - 40	16	
Green Hydrogen Manufacturing Capacity	Electrolysis package manufacture	245	965-1580	1,287	1	91 - 148	121	1	273	779-2634	1,434	2	73 - 247	135	2
	Electrical equipment and materials manufacture	105	327 - 536	437	3	22 - 36	30	4	117	264 - 893	486	5	18 - 60	33	7
	Civil and structural materials (including buildings)	55	125 - 204	166	6	17 - 28	23	5	61	100 - 340	185		14 - 47	26	
	Cooling water package manufacture	29	114-187	152	8	11 - 18	14		32	92 - 312	170		9 - 29	16	
Hydrogen Manufacture	Green Hydrogen Manufacture	118	386 - 626	512	2	50 - 81	66	2	278	952 - 1708	1,207	3	123 - 220	155	3
Hydrogen Transport - Gas Grid Repurposing	Replacing Domestic Gas Meters excluding installation	10	50	50		4.5	4		53	27 - 617	270		3 - 55	23	
	Labour and Fittings for Installation of Domestic Gas Meters	10	93	93		4.3	4		52	43 - 1156	503	6	3 - 53	22	
	Replacing Gas Detectors excluding installation	9	45	45		4.0	4		48	27 - 557	244		3 - 50	21	
	Replacing Low Pressure Steel Pipelines	9	27	27		3.7	4		47	42 - 334	155		3 - 46	20	
Hydrogen Storage (Cavern)	High Pressure H2 Compressor Package	62	245 - 490	327	4	23 - 46	31	3	405	948 - 4323	2,129	1	89 - 406	200	1
	Civil/ Structural Materials (Including Buildings)	125	94 - 188	126	10	13 - 26	17	8	271	364 - 1662	818	4	51 - 231	114	4
	Construction and Installation (Labour only)	39	87 - 175	117		12 - 24	16	10	760	338 - 1544	760	5	47 - 215	106	5
Fuel Cell Manufacture	Membrane Electrode Assembly (MEAs) Manufacture	21	66 - 150	100		5 - 11	7		91	219 - 504	333	8	21 - 56	35	6

Figure 77: Ranking of Attractive Supply Chain Opportunities

This shows that the five most attractive opportunities, based on average annual employment and average annual GVA data for 2030 and 2050 are:

1. Green hydrogen manufacturing capacity – electrolysis package manufacture
2. High pressure hydrogen compressor package manufacture for cavern storage

3. Green hydrogen manufacture
4. Green hydrogen manufacturing capacity – electrical equipment and materials manufacture
5. Civil/structural materials (including buildings) for cavern storage

The uncertainty regarding storage data has already been highlight and should again be noted here with reference to 2) and 5), above.

This analysis also highlights that civil/structural materials (including buildings) is an attractive area across a number of parts of the hydrogen supply chain.

8.1.2 Potential UK Market Share

8.1.2.1 2030 Market Share

There is limited evidence on which to assess a 2030 market share for the UK supply chain, but initial estimates have been made based on a combination of:

- Evidence of UK supply chain capability detailed in Section 6. Key points from this are:
    - Wide ranging capability across a number of products and services
    - Identified supply chain gaps in:
        - Reformers
        - Line pipe
        - Electrolyser packages, where there is only one recognised UK-based supplier of industrial-scale electrolyser packages for hydrogen services.
        - Hydrogen compressors
        - CO2 compressors
        - High integrity valves
        - Packaged dehydration units
- Published data which presents estimated future UK market shares[44] in 2050. For 2030 we have assumed that:
    - Equipment market shares are 50% of 2050 values, for areas where there are existing UK capabilities, as in most cases it has been noted that the capacity is not sufficient to meet expected demand
    - Equipment market shares are 25% of 2050 values, for areas where UK supply chain gaps have been identified
    - Civil engineering, installation and operations and maintenance services are at 2050 levels of 95%, due to the low tradability of these services
    - Engineering, procurement and construction management are at 2050 levels of 77%, in line with existing market share in the oil and gas market
    - Fuel cell manufacturing is 50% of the 2050 UK market share (73%)

This provides estimates of the potential of the UK supply chain in 2030 to address the UK market opportunity under each scenario as shown in Figure 78.

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[44] Energy Innovation Needs Assessment, Sub-theme report: Hydrogen and fuel cells, Vivid Economics, October 2019

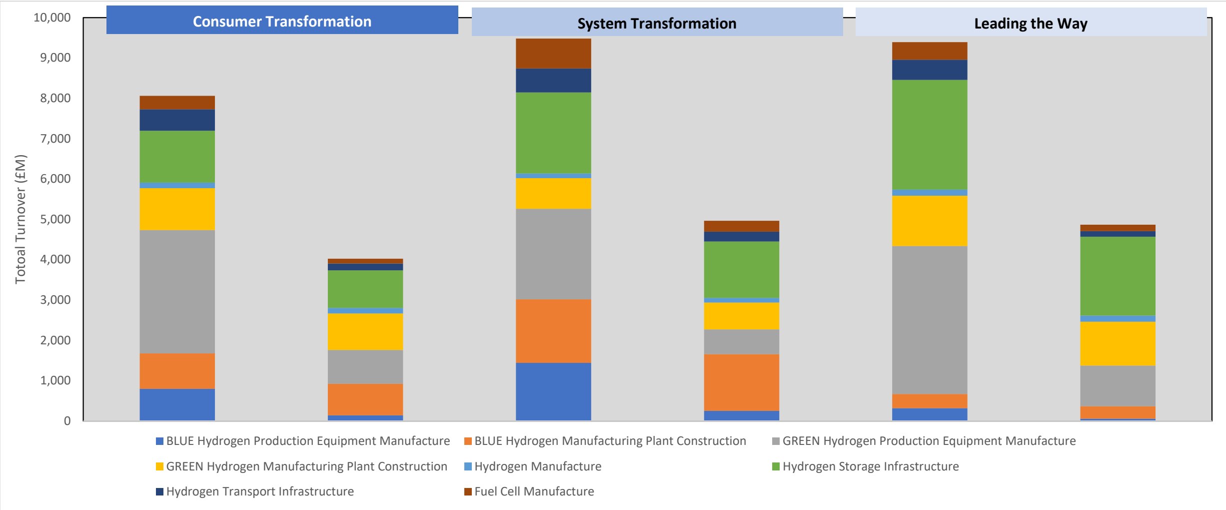

Figure 78: Initial Estimate of the Potential UK Supply Chain Market Opportunity in 2030

This shows the potential, based on these illustrative shares, for the UK based supply chain to win around 50% of the turnover required to deliver the 2030 hydrogen capacity under each scenario. However, there is significant uncertainty around these predictions as there are a number of factors, as highlighted in the SWOT analysis, which could influence the potential of the UK supply chain.

8.1.2.2 2050 Market Share

The potential market share that could be won by UK industry to establish the hydrogen supply chains under each of the three scenarios in 2050 has been estimated at a high level using published data[44], which is based on current and projected data for similar existing sectors, namely:

- Equipment market shares are:
    - 47% for blue hydrogen manufacturing equipment
    - 78% for green hydrogen manufacturing equipment
    - 79% for underground storage equipment manufacture
    - 15% for hydrogen transport equipment manufacture
- Civil engineering, installation and operations and maintenance services at 95%
- Engineering, procurement and construction management at 77%
- Fuel cell manufacturing at 73%

This is compared to the full scale of demand for each of the scenarios in Figure 79. This shows that UK industry will win significantly more than 50% of the available market using these market share estimates.

It is, however, recognised that this is a high level estimate and that further work is required to accurately assess the potential future UK market share.

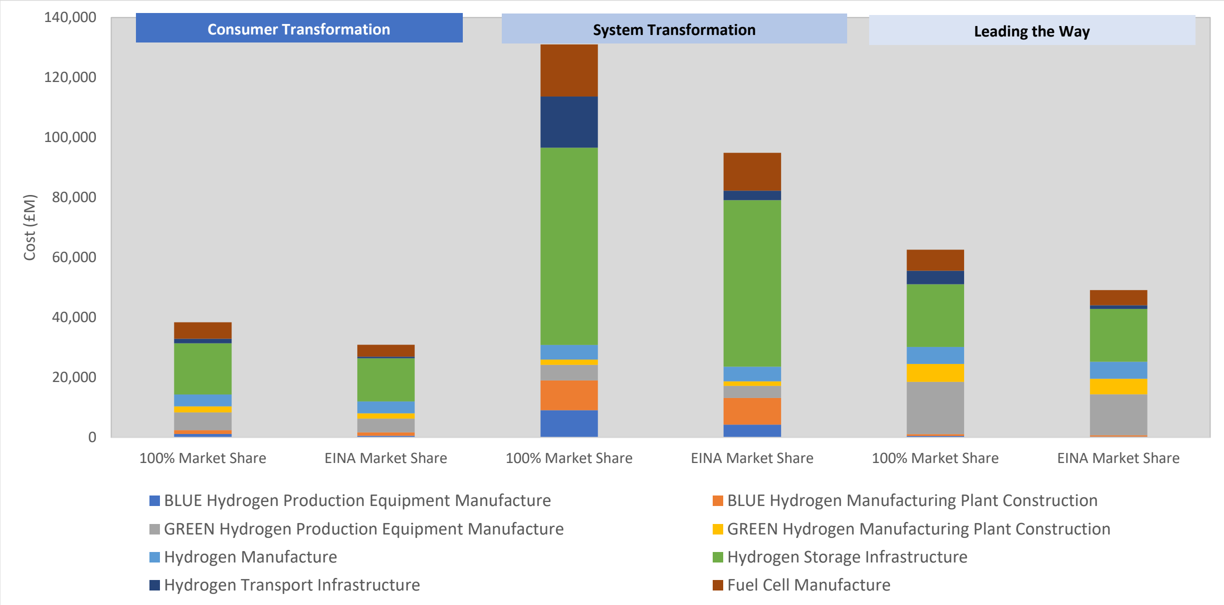

Figure 79: Initial Estimate of the Potential UK Supply Chain Market Opportunity in 2050

8.2 Export Opportunities

The potential scale of export markets has been assessed using low and high scenarios for European and global markets, as detailed in Section 2. Published evidence[44]Error! Bookmark not defined. estimates current and 2 050 market shares in the European and global market for some parts of the hydrogen supply chain. These have been used to make initial estimates of potential export market shares in 2030 and 2050 as shown in Figure 80.

	2030 Market Share		2050 Market Share	
	EU	Global	EU	Global
Blue hydrogen production equipment	11%	5%	15%	7%
Blue hydrogen production plant design and engineering	5.5%	5.5%	11%	11%
Green hydrogen production equipment	8.5%	2%	10%	3%
Green hydrogen production plant design and engineering	5.5%	5.5%	11%	11%
Fuel cells	2.5%	1.5%	5%	3%

Figure 80: UK Market Shares in European and Global Markets

Here the market shares for 2030 are mid-way between current and 2050 market shares and it is assumed 2030 activity is developed evenly over a seven year period from 2023 to 2030 and 2050 capacity over the intervening 20 year period. Further, this analysis assumes the market for these categories is fully tradable, i.e. all activity is able to be completed by companies from abroad. If some of the activity was not tradable, so had to be carried out by domestic companies, then the UK market share and the export opportunities would be lower than modelled.

Data is not available for other aspects of the hydrogen supply chain. It would be expected that there would be some export opportunities in transport and storage aspects of the supply chain but as construction and installation activities have low tradability exports are unlikely.

More work is required, however, to assess the export potential of each of these products and services in more detail.

For the purposes of this study, these listed products and services have been used to prepare an early estimation of export potential, based on market data presented in Appendix A and estimated market shares in Europe and globally, shown in Figure 80. This is presented in Figure 81 for 2030 and Figure 82 for 2050.

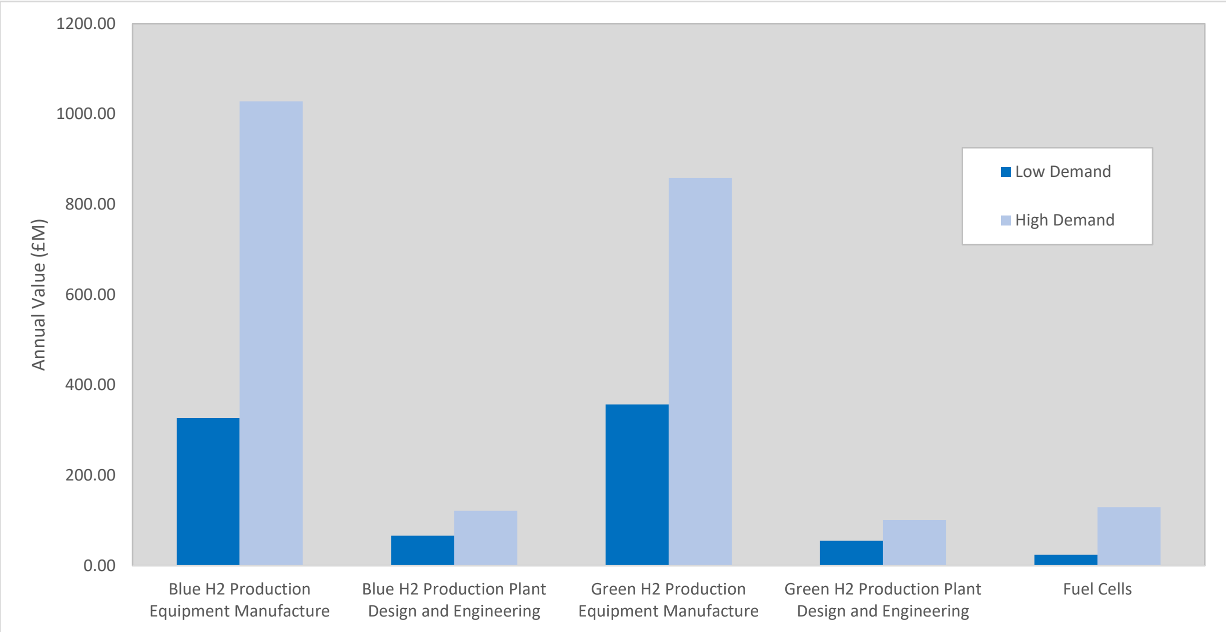

Figure 81: Initial Estimate of Annual Export Market Potential (2030)

Total exports in 2030 across all categories shown in Figure 81 is £830 million (low demand) and £2,200 million (high demand). This compares with average annual figures to deliver the UK hydrogen supply chain in 2030 of between £1,260 million and £1,430 million.

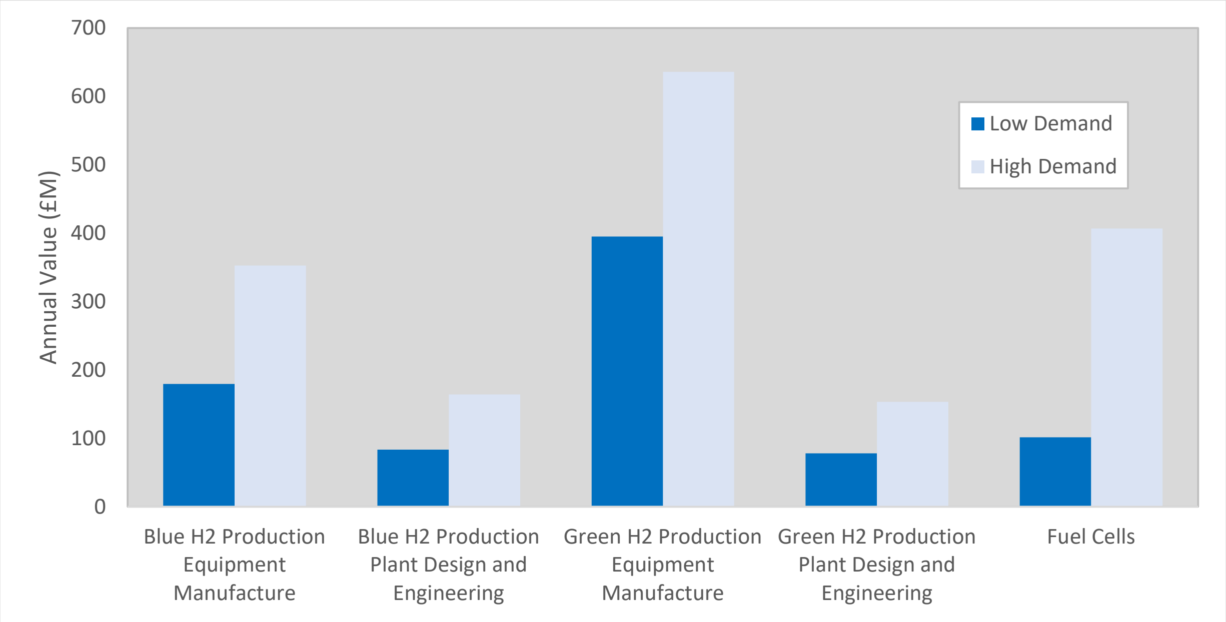

Figure 82: Initial Estimate of Annual Export Market Potential (2050)

Total exports in 2050 across all categories in Figure 82 are £840 million (low demand) and £1,700 million (high demand). This compares with average annual figures to deliver the UK hydrogen supply chain in 2050 of between £1,900 million and £5,750 million.

The figures for blue and green hydrogen production reflect the European and global growth predictions (in Figures 2 and 3) which show higher growth in the period to 2030 than over the subsequent period to 2050. Further, they show a higher focus on green hydrogen in 2050 compared to 2030.

The fuel cell data demonstrates the significant market growth expected over the period to 2050.

8.3 Priority Development Opportunities

Priority development opportunities are considered in two parts, firstly, actions required to establish a market environment that encourages and supports UK supply chain development and, secondly, support for specific parts of the supply chain.

8.3.1 Developing a Supportive Market Environment

This is considered a critical activity to provide an attractive market environment for UK industry to exploit.

The UK Government should continue to provide a consistent message regarding the future use of hydrogen as key elements of the Ten-Point Plan[5] and the British Energy Security Strategy[7]. The ambitious targets for installation of blue and green hydrogen production facilities through to the end of this decade need, however, to be aligned with market demand.

Further, the constraints to supply chain development linked to the complexity and immaturity of the hydrogen supply chain should be addressed. The Sector Development Plan to be published by BEIS is a positive move to address this issue. Its impact should be closely monitored and further work carried out if required.

Industrial cluster deployment plans are proceeding at pace through front-end engineering and design (FEED) and a large expansion of projects is expected when BEIS announces which projects have been prioritised for Track-1 Phase-2. Strategies that will maximise UK share of these opportunities should be developed.

BEIS should also prioritise investment funds / tax credits to support existing UK-based manufacturers seeking to expand into the hydrogen market and international companies seeking to establish UK manufacturing facilities. Target areas may include packaged equipment such as electrolysers, hydrogen and CO_2 compressors and CO_2 dehydration packages. Advice and financial support should also be provided to UK steel line pipe manufacturers to ensure pre-investment to qualify their products for hydrogen-service.

Finally, work should be carried out to promote greater awareness of the opportunities that the hydrogen economy will deliver and to prepare a clearer assessment of suppliers' existing capacity, ambitions and growth potential. A wide ranging survey, in partnership with relevant trade associations would address this point.

8.3.2 Supply Chain Development

Support to specific parts of the supply chain, either to exploit attractive opportunities or address identified supply chain gaps should be pursued. These are shown in Figure 83, where the most attractive opportunities in each segment (see Figure 77) and identified supply chain gaps (see Section 6.1.6.2) are included.

Supply Chain Segment	Category	Atractive Market Opportunity	UK Supply Chain Gap
Blue Hydrogen Manufacturing Capacity	Civil and structural materials (including buildings)	●	
	Construction and installation labour	●	
	Reformer package manufacture	●	●
	CO_2 compressors		●
	Engineering services	●	
Green Hydrogen Manufacturing Capacity	Electrolysis package manufacture	●	●
	Electrical equipment and materials manufacture	●	
	Civil and structural materials (including buildings)	●	
	Cooling water package manufacture	●	
Hydrogen Manufacture	Green Hydrogen Manufacture	●	
Hydrogen Transport - Gas Grid Repurposing	H2 Compressor Package		●
Hydrogen Storage (Cavern)	High Pressure H2 Compressor Package	●	●
	Civil/ Structural Materials (Including Buildings)	●	
	Construction and Installation (Labour only)	●	
Fuel Cell Manufacture	Membrane Electrode Assembly (MEAs) Manufacture	●	
Several Segments	High integrity valves		●

Figure 83: Specific Supply Chain Development Opportunities

9 Conclusions and Recommendations

9.1 Conclusions

The supply chain opportunities arising from the development of the future hydrogen economy have been assessed for hydrogen production, transport and storage and fuel cell manufacture. Based on the analysis carried out we conclude that:

- The estimated supply chain investments to establish UK hydrogen economies in 2030 and 2050, based on the scenarios used in this study, are between £7.9 billion and £9.3 billion in 2030 and between £34 billion and £124 billion in 2050
- It is expected that the UK supply chain will win a share of this impact, but more work is required to provide a robust assessment of the actual share
- Delivering a supportive environment is critical to overcoming the complexity and immaturity of the supply chain and optimising supply chain development and growth. Providing clarity in end user market development priorities, to underpin market driven supply chain growth would support supply chain development.
- Most equipment and services for use in production and transmission of hydrogen are common to the oil & gas or oil refining industries and there are a significant number of UK-based manufacturers that are well placed to expand into the hydrogen market, although it should be noted that there will be hydrogen specific specifications that will need to be met.
- The five most attractive UK supply chain opportunities, based on average annual employment and average annual GVA data for 2030 and 2050 are:
    - Electrolysis package manufacture
    - High pressure hydrogen compressor package manufacture for cavern storage
    - Green hydrogen manufacture
    - Electrical equipment and materials manufacture for green hydrogen manufacture
    - Civil/structural materials (including buildings) for cavern storage

  However, the uncertainty with cavern storage data, as already highlighted should, again, be noted.
- Civil/structural materials (including buildings), their construction and installation of equipment are attractive areas across a number of parts of the UK hydrogen supply chain
- A number of gaps have been identified in the capacity of the UK supply chain to address future demand. These include:
    - Reformers, where no suppliers of industrial scale reformers were identified.
    - Line pipe, where UK manufacturers are not qualified for production of the full range of higher grades of pipe for hydrogen service.
    - Electrolyser packages, where there is only one recognised UK-based supplier of industrial-scale electrolyser packages for hydrogen services
    - Hydrogen compressors, as there is a shortage of suppliers able to support large-capacity, medium-pressure centrifugal compressors required for hydrogen transmission systems.

- CO_2 compressors, as there are limited UK suppliers that can provide CO_2 compressor packages for transport of CO_2 away from blue hydrogen plants for permanent storage.
- High integrity valves, as the number of UK manufacturers is small
- Packaged dehydration units, where no UK manufacturers were identified.

- Export opportunities exist for UK manufacturers of tradeable goods and services. These have been identified as blue and green production equipment, blue and green manufacturing plant design services and fuel cells, while aspects such as construction of plant and infrastructure are not considered to be tradeable. Initial estimates of exports in 2030 across all categories are between £830 million and £2,200 million, increasing to between £5,800 million and £9,800 million in 2050, but additional work is required to prepare more robust estimates.

9.2 Recommendations

Based on the analysis carried out in this study it is recommended that:

- The UK Government continues to provide consistency in messaging the importance of hydrogen as a key element of the UK's ten-point plan to steadily increase market confidence.
- Further detail is provided on priority areas for hydrogen supply chain development
- Appropriate mechanisms are established to:
  - Support UK companies to expand capacity or capability
  - Encourage international companies to build manufacturing capacity in the UK
- Collaboration with Trade Associations is established to seek broader engagement of UK-based suppliers of equipment, materials and services to improve awareness of the forthcoming market opportunities and support mechanisms to develop the skills and manufacturing capacity to address these opportunities.
- The attractive areas of opportunity and supply chain gaps, as listed above, are prioritised to prepare and implement appropriate supply chain development programmes
- The following areas, where further research may be valuable, are considered:
  - Analyse supply chains in relevant hydrogen end user markets to identify potential opportunities and supply chain gaps as the basis for supply chain development programmes
  - Evaluate UK supply chain capability at a more granular level (potentially using the collaboration with Trade Associations highlighted above) to identify at a product level the share of UK supply chain opportunities that can be obtained by the UK company base
  - Characterise international markets and internationally competitive UK products and services to more accurately identify the export market opportunities that are available to the UK supply base

Appendices

Appendix A – Market Demand

The potential growth of the hydrogen economy, and the opportunities this will offer to the supply chain have been assessed at a UK, European and global level. This provides input to the future scenarios used in this analysis and offers an evidence base to estimate the scale of the opportunity for the UK supply chain in both domestic and export markets.

A1 Current Demand

Currently, most of the hydrogen used worldwide is in industrial sectors, with refining, the chemical industries and steel making cumulatively using around 90 million tonnes (Mt) per year, with very little hydrogen consumption in other sectors[45]. Refining utilises 40 Mt of hydrogen per year as a feedstock, reagent or as a source of energy. The chemicals industry consumes around 45 Mt of hydrogen per year with around 75% of this going to ammonia production and 25% to methanol production. A further 5 Mt of hydrogen is consumed for steel making, using the direct reduced iron process. This distribution of hydrogen use has been broadly consistent since the year 2000. As a comparison, the current annual global demand for hydrogen in transport is 20 kilo tonnes (kt) (i.e. 0.02 Mt per year)[45].

Most of the global hydrogen production is carbon intensive, with only 0.7% currently produced from low carbon sources (fossil fuel with carbon capture and storage)[45]. Most hydrogen is made from processing natural gas (59% of production), or coal (19%) or is a by-product of another process (21%, primarily from refinery processes), with significant CO_2 emissions. Clearly then, hydrogen is an important chemical for industrial processes but there is currently no significant use of it as an energy vector and no industrial scale low-carbon production in any sector of the economy.

A2 Potential Demand

There are many potential applications for low carbon hydrogen in a zero-carbon economy, namely:

- Existing uses – these applications offer both short term and long-term opportunities for low carbon hydrogen
- Likely uses – where future demand is likely to be large, but development may take some time
- Transitional uses – offering short time but translational opportunities for hydrogen
- New uses – which could include potentially large future applications but where the relative advantages of hydrogen over other options is very uncertain

An example list of potential application across these four groups is presented in the figure below.

Hydrogen Applications			
Existing	**Likely**	**Transitional**	**New**
Refining	Industrial heat - Steel	Co-firing - coal and gas plants	HDV
Chemicals - Ammonia	Shipping - Ammonia	Grid blending	Rail
Chemicals - Methanol	Aviation - Synfuels		Heating
	Power - Balancing		
Uncertainty →			

Figure 84: Potential Low Carbon Hydrogen Applications

45 Global Hydrogen Review 2021, International Energy Association, October 2021

The degree to which hydrogen penetrates various end use applications is dependent on many different factors. Government policies and incentives are expected to be important drivers but so are factors such as the cost of hydrogen compared to other low carbon alternatives and the investment required in new equipment to switch to hydrogen. There is therefore considerable uncertainty over the potential future demand for hydrogen.

In sections that follow we present analysis of hydrogen demand based on several different sources of information.

A2.1 UK Market

Context

The UK Government has made a range of commitments and set out numerous policies and initiatives to support its aim for net zero by 2050. This included a commitment to establish 10GW of low carbon hydrogen production capacity by 2030. In addition to supporting the development of hydrogen production capacity, various sector level policies have been proposed that are likely to stimulate demand for low carbon hydrogen, for example:

- The UK Industrial Decarbonisation Strategy[46] sets out a range of policies and initiatives to support the decarbonisation of industry, including investment in infrastructure to support fuel switching to low carbon alternatives such as hydrogen.
- As set out in the Energy White Paper[47], UK government is aiming to fully decarbonise the power system by 2050. This will require rapid growth of renewable and other forms of low carbon generation. Hydrogen could play a role in flexible power generation to help meet short and longer-term peaks in demand.
- In its Heat and Buildings Strategy[48], the UK government aims to set out plans to decarbonise heat in buildings in the UK, which comprises 74% of buildings emissions in the UK and about 23% of all UK emissions. Options for using hydrogen could include blending with natural gas and the use of 100% hydrogen-fuelled boilers for space heating. The UK Government plans to take strategic decisions in 2026 on the role of 100% hydrogen for heating.
- The UK government, as set out in the Hydrogen Strategy[1], believes hydrogen is likely to be fundamental to achieving net zero in transport. Like other analysis of this domain, the low hanging fruit is likely to be areas of heavy-duty vehicles and buses. Of course, hydrogen could be used in trains, in aviation and in shipping.

2030 UK Market Size

Hydrogen

The UK hydrogen market in 2030 can be summarised by application as follows:

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46 Industrial Decarbonisation Strategy, UK Government, 17/03/2021 https://www.gov.uk/government/publications/industrial-decarbonisation-strategy

47 Energy White Paper, UK Government 14/12/2020, https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future

48 Heat and Buildings Strategy, UK Government, 19/10/2021, https://www.gov.uk/government/publications/heat-and-buildings-strategy

	Low Estimate (TWh)	High Estimate (TWh)
Industrial	10	21
Heat	0	<1
Transport	0	6
Power Generation	0	10
Total	**10**	**37**

Figure 85: Estimated UK Hydrogen Demand in 2030[1, 49]

2050 UK Market Size

Projections for the scale of demand for hydrogen over the period from 2030 to 2050 are based on the data from the National Grid Future Energy Scenarios[50] for the consumer transformation (CT) system transformation (ST) and Leading the Way (LtW) scenarios and can be presented as follows:

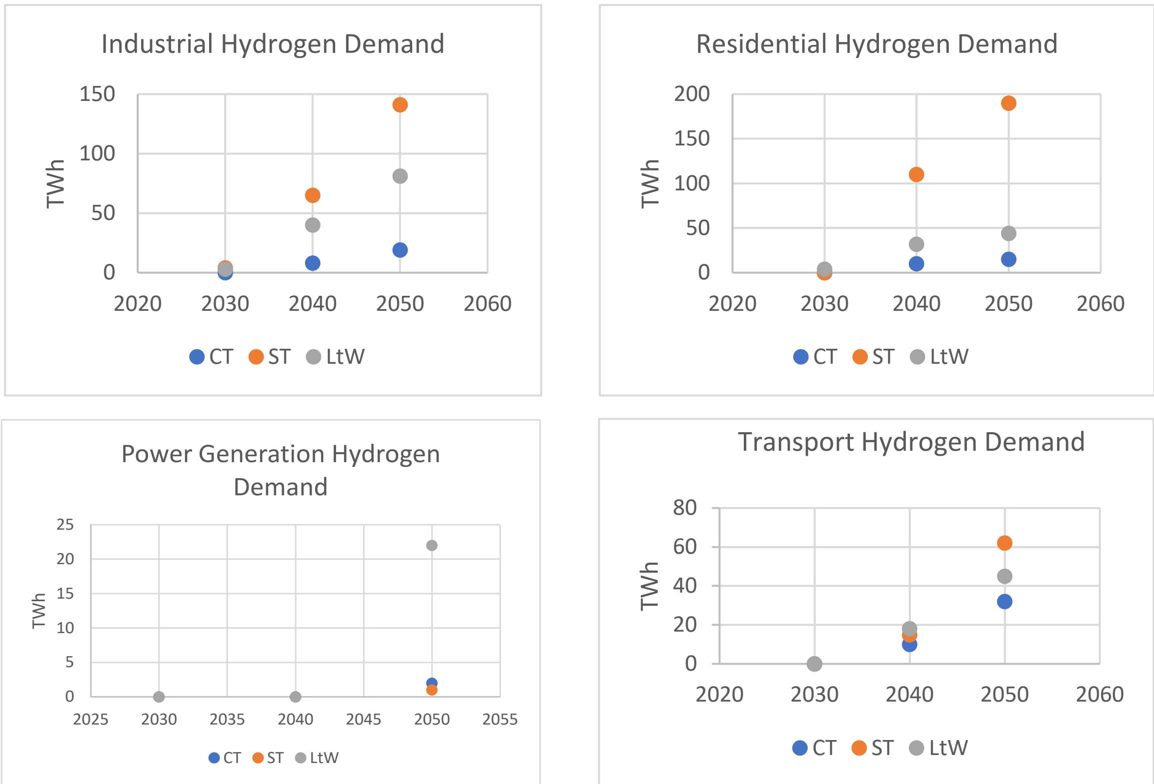

Figure 86: Indicative Projection for Hydrogen Demand in Key Markets to 2050

In addition, an aviation and shipping demand of 80 TWh is projected for 2050 in all scenarios, but no earlier projections are included.

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49 UK hydrogen demand predicted to grow to 10 TWh in 2030 says Cornwall Insight, Renewable Energy Magazine, 5th November 2021

50 Future Energy Scenarios, National Grid ESO, 2021, https://www.nationalgrideso.com/document/202851/download

The growth in demand for hydrogen using these projections can be presented as follows:

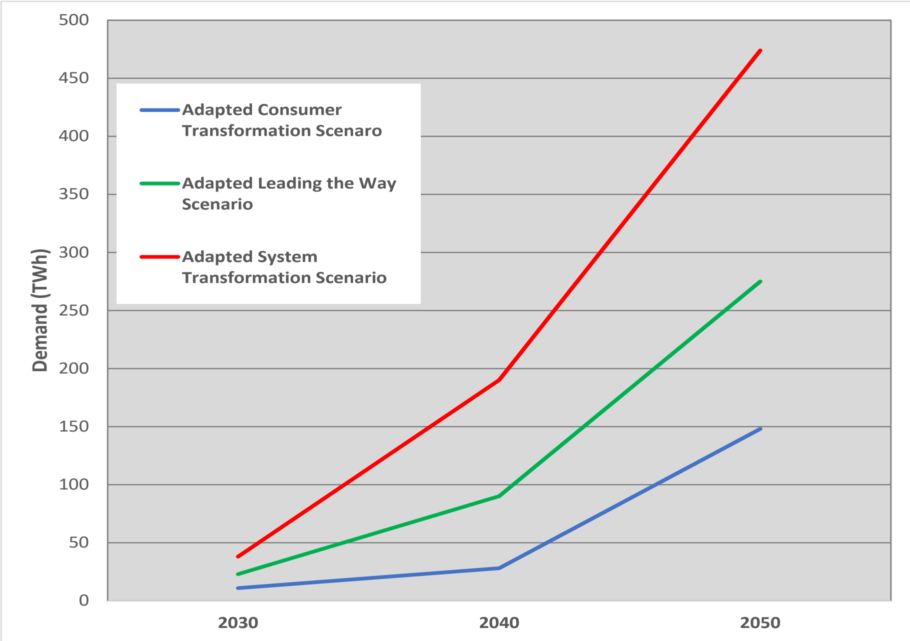

Figure 87: Total UK Hydrogen Demand Growth (2030 to 2050)

In comparison, the UK Hydrogen Strategy estimates a demand of between 250 and 460 TWh of hydrogen in 2050 (making up 20-35 per cent of UK final energy consumption).

A broader summary[51] of recently published scenarios, which includes sources such as Committee on Climate Change, the National Grid[50], the Energy Networks Association[51] and Aurora Energy Research[52], shows that the National Grid ESO Future Energy Scenarios are consistent with other sources.

Fuel Cells

UK fuel cell demand[8] in 2030 and 2050 can be presented as shown in Figure 88[53].

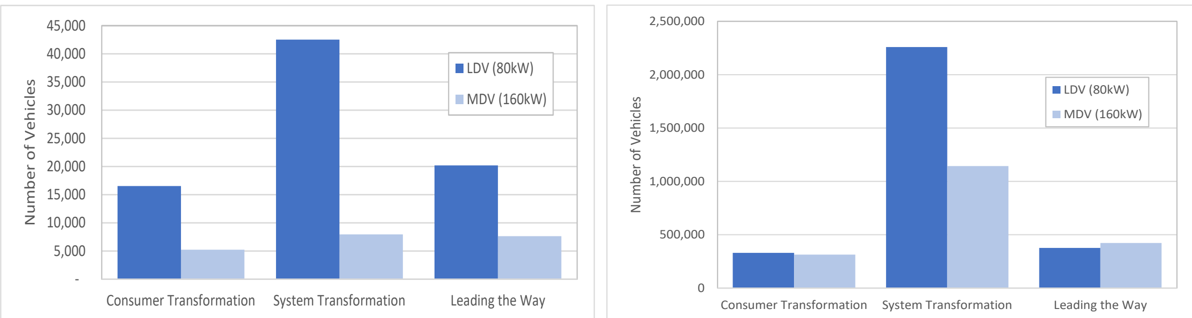

Figure 88: Project UK Fuel Cell Demand in 2030 (left) and 2050 (right)

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51 Britain's Hydrogen Network Plan, Energy Networks Association

52 Hydrogen for a Net Zero GB: An integrated energy market perspective, Aurora Energy Research, 2020, https://auroraer.com/insight/hydrogen-for-a-net-zero-gb/

53 LDV (light duty vehicles) includes cars and motorbikes while MDV (medium duty vehicles) includes vans, buses and HGVs

A2.2 European Demand

Context

The European Union hydrogen strategy[54] asserts an explicit focus on the deployment of renewable hydrogen (i.e. production of hydrogen through electrolysis with electricity from renewable sources, often termed "green hydrogen" in other reports) with an objective to install at least 6GW of renewable hydrogen electrolysers between 2020 and 2024. There is limited focus on production of hydrogen from fossil sources with carbon capture and only a policy that *"some of the existing hydrogen production plants should be decarbonised by retrofitting them with carbon capture and storage technologies"*. Large electrolysers are also a focus of the strategy with manufacturing of units larger than 100 MW a focus of activity until 2024. Between 2025 and 2030, the EU ambition is to embed hydrogen as an integral part of the energy system with a strategic objective to install at least 40 GW of renewable hydrogen electrolysers by 2030 and produce up to 10 million tonnes of renewable hydrogen. In this stage of hydrogen adoption, it is forecast that local hydrogen clusters will develop with hydrogen being used for industry, transport, energy balancing and heat in buildings. Between 2025 and 2030, it is predicted that a need for an EU-wide logistical infrastructure will develop. It is proposed that this could be addressed by a combination of repurposing the existing gas network, new hydrogen transport infrastructure and large-scale hydrogen storage facilities.

In contrast strategies developed by several European countries[55] indicate that a balance of both blue and green hydrogen is being pursued. However, it should be noted that green hydrogen is central to all strategies.

More recently, the European Union REPower EU Plan[56] proposes a hydrogen accelerator to catalyse production of an additional 15 million tonnes of renewable hydrogen by 2030 a significant addition to the 5.6 million tonnes foreseen under its hydrogen strategy.

Market Size

There are a number of analyses of the potential scale of the European hydrogen market over the period to 2050. For example, research conducted as part of the collaborative European project Hydrogen4EU[57] shows that total European demand could reach

- 1,062 TWh in 2030
- 2,805 TWh in 2040
- Over 3300 TWh in 2050

This demand is also segmented by end use sector showing significant growth in both industrial and transport demand over the period from 2030 to 2050.

Other analysis by the Gas for Climate Initiative [58] on the potential European future demand shows similar market growth although the total demand figures are lower as follows:

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54 A hydrogen strategy for a climate-neutral Europe, European Commission, July 2020
55 International Hydrogen Strategies, World Energy Council, September 2020
56 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A108%3AFIN
57 Hydrogen4EU – Creating Pathways to Enable Net Zero, Deloitte, 2021
58 European Hydrogen Backbone, Gas for Climate Initiative, June 2021

- 338 TWh in 2030
- 1,353 TWh in 2040
- 2,266 TWh in 2050

In this analysis demand from the transport sector is much more modest than in the Hydrogen4EU European project.

Based on two illustrate datasets, European demand growth can be presented as follows:

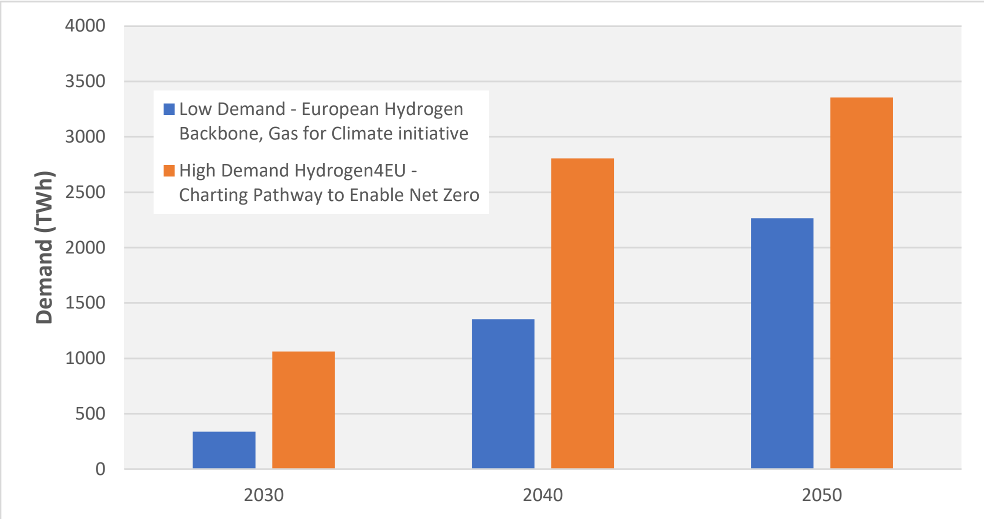

Figure 89: Potential European Hydrogen Demand

These sources do show higher growth in the 2030 to 2040 period compared to the later ten year period.

Fuel Cells

European deployment of fuel cell vehicles in 2024 is estimated[59] at 480,000 passenger cars and 9,900 medium duty vehicles, growing to 2,600,000 and 44,000 respectively in 2030.

A2.3 Global Market

It is recognised that there is a huge amount of uncertainty in global demand. We have chosen scenarios in the IEA Global Hydrogen Review[60] to illustrate potential scale of global demand but there is massive uncertainty here. In this review the global demand for hydrogen is estimated with reference to (a) projects that are in construction or planned, (b) pledges that have been announced and (c) a scenario the leads to net zero by 2050. Estimated growth in demand in the latter two of these options can be presented as follows:

59 Value Added of the Hydrogen and Fuel Cell Sector in Europe, Supporting European growth and competitiveness, Ecorys et al, September 2019

60 Global Hydrogen Review 2021, International Energy Agency, October 2021

	Demand (TWh)		
	2030	2040	2050
Announced Pledges	3,800	6,100	8,400
Net Zero Emissions by 2050	6,900	12,900	17,500

Figure 90: Hydrogen Demand by Sector in the Announced Pledges and Net zero Emissions scenarios, 2030-2050

This shows a development option that meets net zero targets (high market demand) and one which is significantly below this target (low demand).

The scenario that leads to net zero by 2050s shows a demand of 17,500 TWh of Hydrogen in 2050, with the balance between blue and green hydrogen over the period as follows:

	2030	2040	2050
Blue Hydrogen	27%	30%	35%
Green Hydrogen	36%	55%	60%

Figure 91: Projected Percentages of Blue and Green Hydrogen in Global Demand

The remainder of production is predicted to be grey hydrogen.

Fuel Cells

Global demand[59] of fuel cell vehicles in 2030 is estimated at 10,000,000 light duty vehicles and 500,000 medium duty vehicles with growth to 30,000,000 vehicles of all types, including heavy good vehicles, predicted by 2050[61].

[61] Electric Vehicle Outlook 2021, BloombergNEF and https://www.fuelfreedom.org/cars-in-050/#:~:text=By%202050%2C%20 here%20will%20be,%2C%20using%20petroleum%2Dbased%20fuels .

Appendix B – Detailed Supply Chain Model

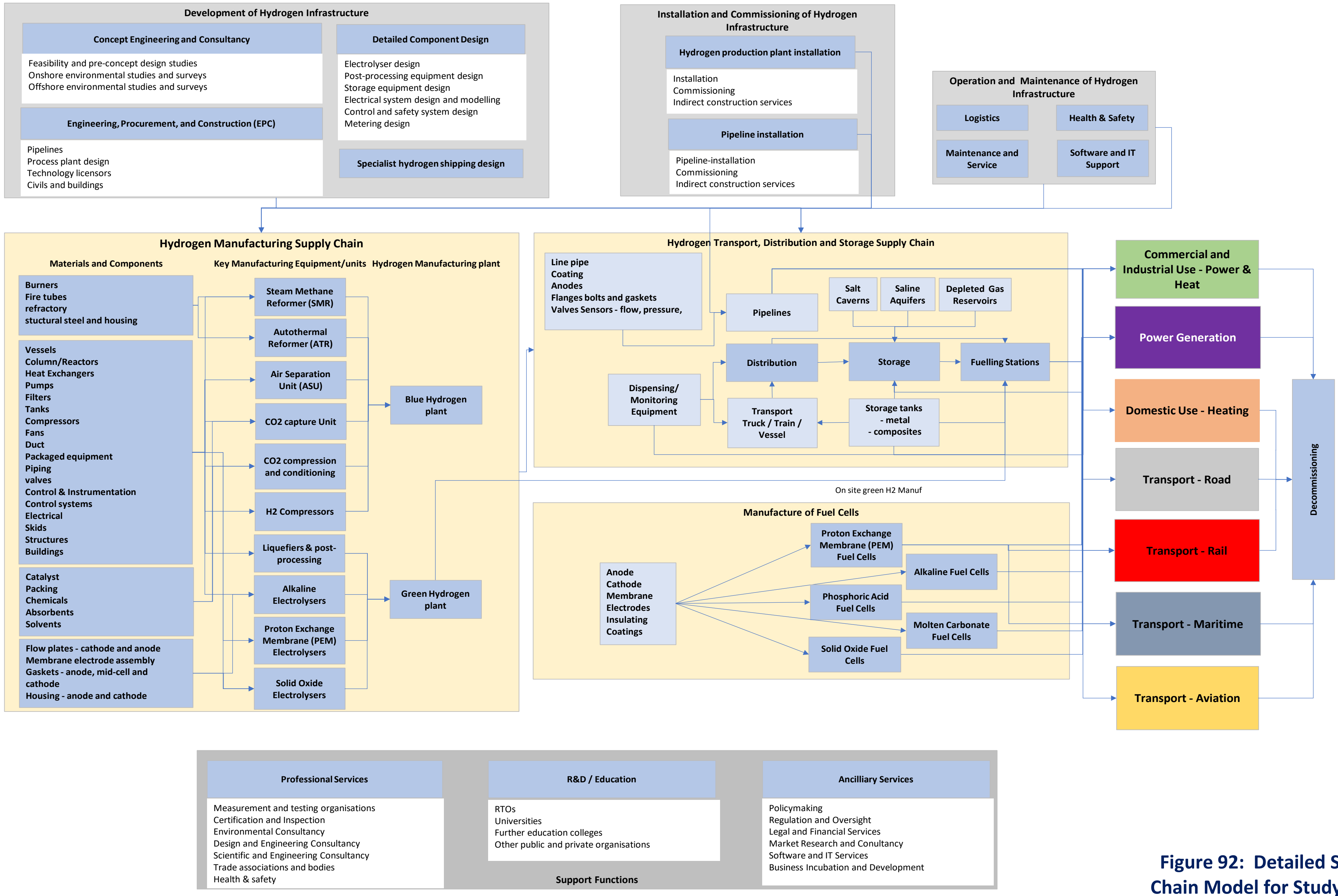

Figure 92: Detailed Supply Chain Model for Study Scope

Appendix C – Defining Future UK Hydrogen Economy Supply Chain Models

Approach

The activities carried out to develop these supply chain models were:

- Development of scenarios for the future UK hydrogen economy
- Use of the supply chain framework (Figure 6), which shows what the supply chain could look like, as the basis to develop scenario specific supply chain models
- Identification of common factors / cross cutting technologies
- Development of validated hydrogen economy supply chain models for each scenario

These activities were interlinked as follows:

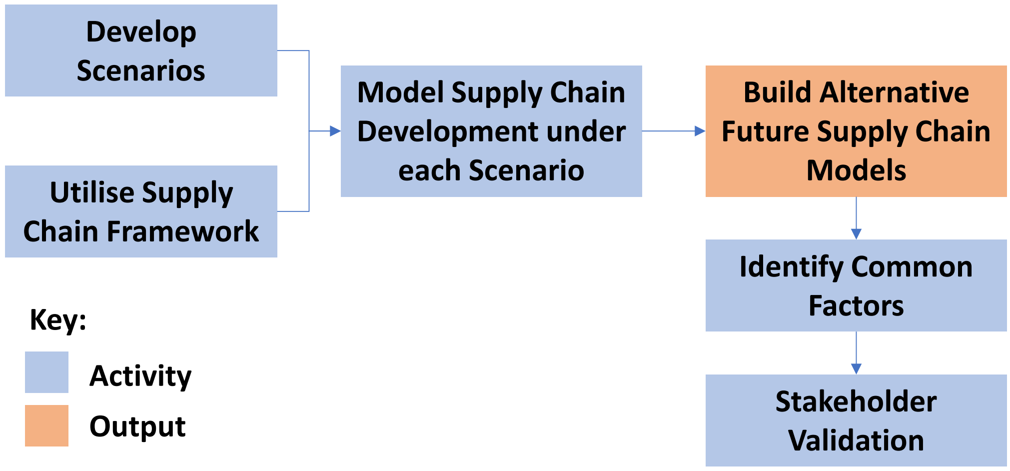

Figure 93: Approach – Assessment of Future UK Hydrogen Economy Supply Chains

Results obtained for each of these activities are presented below.

Development of Scenarios for the Future UK Hydrogen Economy

A number of scenario development exercises have already been carried out to assess how the future hydrogen economy in the UK may develop over the period to 2050, such as those referenced in Britain's Hydrogen Network Plan (Energy Networks Association)[10]. These offer a number of "alternative futures" for the hydrogen economy, with some similarities between the different scenarios considered by different organisations. Therefore, rather than developing an additional set of scenarios it was considered more prudent to use some of the existing scenarios.

As a result, we have selected three of the four National Grid Future Energy Scenarios[8], published in July 2021, as a robust basis to assess how the hydrogen supply chain is likely to develop. These scenarios were selected as they build on the Climate Change Committee's sixth carbon budget, provide detailed evidence of hydrogen demand and estimate potential growth in a range of market applications over the period to 2050 and place hydrogen demand within wider energy needs.

The scenarios selected and their descriptions[8] are:

1. ***Consumer Transformation***

The 2050 net zero target is met with measures that have a greater impact on consumers and is driven by higher levels of consumer engagement. A typical homeowner will use an electric heat pump with a low temperature heating system and an electric vehicle. They will have made extensive changes to improve their home's energy efficiency and most of their electricity demand will be smartly controlled to provide flexibility to the system. The system will have higher peak electricity demands managed with flexible technologies including energy storage, demand side response and smart energy management.

Focusing on hydrogen, relevant aspects of this scenario are:

- *Expected demand for hydrogen grows to 147 TWh in 2050 as detailed by end use application in Figures 8*
- *Hydrogen supply in 2050 is mainly (~75%) green hydrogen*
- *14 TWh of hydrogen storage installed by 2050*
- *A minority of industrial consumers who cannot switch to electricity look to hydrogen, and begin to relocate nearer to a reliable source in the 2030s*
- *Phasing out of sales of new petrol and diesel cars and vans in 2030 and the sale of plug-in-Hybrid cars and vans banned in 2035*
- *By the mid-2030s, uptake of hydrogen lorries begins to increase.*
- *Hydrogen use in this scenario is mainly for HGVs, which rely on regional refuelling infrastructure, since there is no national hydrogen network in this scenario*
- *Around 280,000 hydrogen HGVs on the road*

2. ***System Transformation***

The typical domestic consumer will experience less disruption than in Consumer Transformation as more of the significant changes in the energy system happen on the supply side, away from the consumer. A typical consumer will use a hydrogen boiler with a mostly unchanged heating system and an electric vehicle or a fuel cell vehicle. They will have had fewer energy efficiency improvements to their home and will be less likely to provide flexibility to the system. Total hydrogen demand is high, mostly produced from natural gas with carbon capture and storage.

Focusing on hydrogen, relevant aspects of this scenario are:

- *Assumes that 5 GW of blue hydrogen will be built, initially operating at a reduced load factor*
- *Expected demand for hydrogen grows to 474 TWh in 2050 as detailed by end use application in Figures 9*
- *Hydrogen supply in 2050 is ~70% blue hydrogen*
- *2 industrial clusters connected to hydrogen in 2026 and 5 by 2032*
- *First Hydrogen town by 2030*
- *Hydrogen-ready boilers and appliances like hobs and kettles are installed from 2025 in readiness for switching the natural gas network to hydrogen from 2030.*
- *New build homes include hydrogen-ready boilers and appliances from 2025.*
- *A national hydrogen network means 69% of homes use hydrogen boilers for heating*
- *By 2045 the nationwide gas grid is almost all converted to transport hydrogen*
- *In 2050 21 million homes are heated by hydrogen*
- *52 TWh of hydrogen storage installed by 2050*

- *The phasing out of new petrol and diesel car sales is delayed until 2032 and the sale of plug-in-Hybrid cars and vans banned in 2035*
- *From the mid-2030s, consumer uptake of hydrogen fuel cell vehicles (HFCVs) increases in line with the development of local and national hydrogen infrastructure.*
- *Almost 400,000 hydrogen HGVs on the road*

3. Leading the Way

It is assumed that the UK decarbonises rapidly with high levels of investment in world-leading decarbonisation technologies. The assumptions used in different areas of decarbonisation are pushed to the earliest credible dates. Consumers are highly engaged in reducing and managing their own energy consumption. This scenario includes more energy efficiency improvements to drive down energy demand, with homes retrofitted with insulation such as triple glazing and external wall insulation, and a steep increase in smart energy services. Hydrogen is used to decarbonise some of the most challenging areas such as some industrial processes, produced solely from electrolysis powered by renewable electricity.

Focusing on hydrogen, relevant aspects of this scenario are:

- *Assumes that 5 GW of electrolysers will be built with government support but initially operating at a reduced load factor*
- *Expected demand for hydrogen grows to 275 TWh in 2050 as detailed by end use application in Figures 10*
- *Hydrogen supply in 2050 is almost all green hydrogen*
- *15 TWh of hydrogen storage installed by 2050*
- *First Hydrogen town by 2030*
- *The development of local hydrogen networks leads to an increase in hydrogen boiler and hybrid hydrogen heat pump installations from 2028*
- *Uptake of electric, hybrid and hydrogen low carbon heating technologies starts to increase from the mid-2020s*
- *Fuel switching occurs from 2025, with a slightly higher proportion of industrial consumers switching to electricity, rather than hydrogen.*
- *In 2050 6 million homes are heated by hydrogen*
- *The petrol and diesel ban is effective for cars and vans in 2030 and the sale of plug-in-Hybrid cars and vans banned in 2035*
- *Almost 400,000 hydrogen HGVs on the road*

The fourth scenario developed by the National Grid, "*Steady Progression*", is not considered because it does not deliver net zero by 2050.

We have developed these scenarios further to include other highly relevant factors that are expected to affect supply chain development, namely:

- "Strategic outcomes" in the UK Hydrogen strategy[1], published in August 2021, namely a 5GW target for low carbon hydrogen manufacturing capacity by 2030, with rapid growth thereafter and 2030 hydrogen demand of between 10 and 37 TWh. Different levels of hydrogen demand are included in each scenario reflecting the minimum, median and maximum figures of the range defined.

- The recently published British Energy Security Strategy[2], which increases the UK hydrogen manufacturing capacity to 10GW, with at least %GW of green hydrogen production
- Adaptation of the percentages of blue and green hydrogen production in each scenario (25%:75%, 45%:55% and 10%:90% respectively) to reflect a range of different future options
- The European Commission’s target for >40 GW of renewable (green) hydrogen manufacturing capacity by 2030
- European and global export market opportunities, as defined in section 2, above

Appendix D – Product Level Categorisation and Taxonomies

Products

Within the taxonomy there are five products:

- Blue Hydrogen
- Green Hydrogen
- Fuel Cells
- Hydrogen Storage
- Hydrogen Transport and Distribution

Products have been divided into the following key supply chain segments:

- **Materials:** Physical items to support production
- **Services:** Services required to support production

Segments and sub segments

Materials can then be divided further into sub-segments or areas/units. These will differ slightly between products, as follows:

Blue Hydrogen:

- CO2 Capture
- CO2 Compression and conditioning for transport
- Feed Pre-treatment (Natural Gas)
- Gas Reforming
- Hydrogen Compression and conditioning for transport
- Hydrogen Liquefaction and conditioning for transport
- Supporting Utilities and Offsites.

Green Hydrogen:

- Feed pre-treatment (water)
- Electrolysis
- Hydrogen treatment & Compression
- Hydrogen Liquefaction and Conditioning
- Supporting Utilities and Offsites.

Fuel Cells:

- PEM Fuel Cells
- Alkaline Fuel Cells
- Phosphoric Acid Fuel Cells
- Solid Oxide fuel cells
- Molten Carbonate fuel cells

Hydrogen Storage:

- Physical Storage
  - Liquid storage

  - High pressure storage
- Geological Storage
  - Salt caverns

Hydrogen transport and distribution:

- Road and rail tankers
  - Liquid
  - High pressure Gas
- Pipeline

Categories

Within the sub-segments or areas/units

- Materials and services have been categorised or summarised by type as follows:
  - Catalysts and Chemicals
  - Civil/ Structural Materials
  - Electrical Equipment/Materials
  - Fired Equipment
  - Instrumentation and Control Equipment/Materials
  - Piping Materials
  - Rotating Equipment
  - Static Equipment
  - Thermal Equipment
  - Packaged Equipment
- Services have been categorised as follows:
  - Engineering
  - Construction/Installation
  - Operations and Maintenance
  - Other

Components / materials are then presented as the lowest level of the taxonomy.

Taxonomies

Components	Equipment/Material Category	Area/Unit	Segment	Product
air coolers	Catalysts and Chemicals	Carbon Dioxide (CO2) Capture	Materials	Blue Hydrogen
Basins/Sumps	Civil/ Structural Materials	CO2 compression and Conditioning		
Blower	Electrical Equipment/Materials	Feed Pre-treatment (Natural Gas)		
Buildings	Fired Equipment	Gas Reforming		
Burners	Instrumentation and Control Equipment/Materials	Hydrogen Compression and Conditioning		
Cables	Piping Materials	Hydrogen Liquefaction and Conditioning		
Catalysts	Rotating Equipment	Temporary Hydrogen Storage		
Continuous Emissions Monitoring System	Static Equipment	Utilities and Offsites		
Columns	Thermal Equipment			
Control systems	Packaged Equipment			
Control valves				
Dampers				
desuperheaters				
Drains/Undergrounds				
Ducts				
Electrical Switchgear				
Emergency shutoff device (ESD) valves				
Expansion Turbines				
Filters				
Fire and gas detection systems				
Foundations				
Insulation				
Mol sieves/Absorbents				
Plate &Frame Heat exchangers				
Packages				
Packing				
Paving				
Pipe				
Pipe supports				
Pressure relief valves				
Process Analysers				
Process Instruments				
Pumps				
Reactor vessel				
Reactor/heat exchanger				
Roads				
Shell and tube Heat exchanger				
Security Fencing				
Separator vessel				
Solvents				
Support Structures				
Switchgear				
Tanks				
Transformers				
Trays				
Valves				
Vessel				
Business Incubation and Development	Construction/Installation		Services	
Certification and Inspection	Engineering			
Civil Installation	Manufacturing			
Commissioning	Operations and Maintenance			
Concept Engineering	Other			
Construction				
Design and Engineering Consultancy				
Education				
Electrical Installation				
Engineering Studies				
Environmental Consultancy				
Environmental Consultancy				
Engineering Procurement Construction (EPC) Services				
Front End Engineering and Design (FEED) Services				
Health & safety				
Legal and Financial Services				
Maintenance				
Maintenance				
Management consultancy				
Market Research and Consultancy				
Measurement and testing				
Mechanical Installation				
Planning consultancy				
Policymaking				
Pre Commissioning				
PreFEED Engineering				
procurement				
project management				
Regulation and Oversight				
Scientific and Engineering Consultancy				
Software and IT Services				
Surveying				
Trade associations and bodies				
Vendor Engineering				

Figure 94: Blue Hydrogen Taxonomy

Components	Equipment/Material Category	Area/Unit	Segment	Product
air coolers	Catalysts and Chemicals	Feed pre-treatment (water)	Materials	Green Hydrogen
Basins/Sumps	Civil/ Structural Materials	Electrolysis		
Buildings/shelters	Electrical Equipment/Materials	Hydrogen treatment & Compression		
Bus Systems	Fired Equipment	Hydrogen Liquefaction and Conditioning		
Cable Trays	Instrumentation and Control Equipment/Materials	Temporary Hydrogen Storage		
Cables	Piping Materials	Utilities and offsites		
catalyst	Rotating Equipment			
Cell Stack	Static Equipment			
Continuous Emissions Monitoring Systen	Thermal Equipment			
Chemicals	Packaged Equipment			
compressors				
control system				
Control valves				
Drainage Systems				
Ducts				
electric heaters				
Emergency shutoff device (ESD) valves				
Expansion Turbines				
filter				
Fire and gas detection systems				
Foundations				
Insulation				
Mol sieves/Absorbents				
packages				
Packing				
Paving				
Pipe				
Pipe supports				
Pressure relief valves				
Process Analyser				
Process instruments				
pumps				
Rectifiers				
Roads				
Shell and tube Heat exchanger				
Security Fencing				
Solvents				
Support Structures				
switch gear				
Tanks				
Transformers				
Valves				
Vessels				
Business Incubation and Development	Construction/Installation		Services	
Certification and Inspection	Engineering			
Civil Installation	Manufacturing			
Commissioning	Operations and Maintenance			
Concept Engineering	Other			
Construction				
Design and Engineering Consultancy				
Education				
Electrical Installation				
Engineering Studies				
Environmental Consultancy				
Environmental Consultancy				
Engineering Procurement Construction (EPC) Services				
Front End Engineering and Design (FEED) Services				
Health & safety				
Legal and Financial Services				
Maintenance				
Maintenance				
Management consultancy				
Market Research and Consultancy				
Measurement and testing				
Mechanical Installation				
Planning consultancy				
Policymaking				
Pre Commissioning				
PreFEED Engineering				
procurement				
project management				
Regulation and Oversight				
Scientific and Engineering Consultancy				
Software and IT Services				
Surveying				
Trade associations and bodies				
Vendor Engineering				

Figure 95: Green Hydrogen Taxonomy

Components	Category	Segment	Product
MEA (membrane Electrode Assemblies)	PEM Fuel Cells	Materials	Fuel cell manufacture
7 Layer	Alkaline Fuel Cells		
5 layer	Phosphoric Acid Fuel Cells		
3 Layer (CCM) Catalyst Coated Membranes	Solid Oxide fuel cells		
Electrolyte (solid Oxide)	Molten Carbonate fuel cells		
Electrolyte (Alkali)			
Electrolyte (Phosphoric Acid)			
Electrolyte (carbonate + BASE)			
Membranes			
Electrodes			
Catalysts			
GDLs (Gas Diffusion Layers)			
Bi-Polar flow Plates			
Gaskets			
Current collectors			
Insulation			
Casing			
Instrumentation			
Pumps			
tanks/vessels			
Coolant pump			
Coolant tank			
heat exchangers			
compressors			
piping/tubing			
cables			
Inverters			
control system			
fans			
Containers/shelters			
Business Incubation and Development	Manufacture	Services	
Certification and Inspection	Engineering		
Commissioning	Technology Development		
Concept Engineering	Operations		
Manufacture	Other		
Design and Engineering Consultancy			
Business Administration			
Education			
Health & safety			
Legal and Financial Services			
Management consultancy			
Market Research and Consultancy			
Measurement and testing			
Policymaking			
procurement			
project management			
Regulation and Oversight			
Software and IT Services			
Trade associations and bodies			

Figure 96: Fuel Cell Taxonomy

Components	Equipment/Material Category	Area/Unit	Segment	Product
air coolers	Catalysts and Chemicals	High Pressure Gas	Road/ Rail tankers	Hydrogen Transport
Basins/Sumps	Civil/ Structural Materials	liquid		
Buildings/shelters	Electrical Equipment/Materials			
Cable Trays	Instrumentation and Control Equipment/Materials			
Cables	Piping Materials			
catalyst	Rotating Equipment			
Chemicals	Static Equipment			
compressors	Thermal Equipment			
control system	Packaged Equipment			
Control valves				
Drainage Systems				
electric heaters				
Emergency shutoff device (ESD) valves				
filter				
Fire and gas detection systems				
Foundations				
Insulation			Pipeline Network	
packages				
Pipe				
pipe fittings				
Pipe supports				
Pressure relief valves				
Process Analyser				
Process instruments				
Valves				
Vessels				
Business Incubation and Development	Construction/Installation		Services	
Certification and Inspection	Engineering			
Civil Installation	Manufacturing			
Commissioning	Operations and Maintenance			
Concept Engineering	Other			
Construction				
Design and Engineering Consultancy				
Education				
Electrical Installation				
Engineering Studies				
Environmental Consultancy				
Environmental Consultancy				
Engineering Procurement Construction (EPC) Services				
Front End Engineering and Design (FEED) Services				
Health & safety				
Legal and Financial Services				
Maintenance				
Maintenance				
Management consultancy				
Market Research and Consultancy				
Measurement and testing				
Mechanical Installation				
Planning consultancy				
Policymaking				
Pre Commissioning				
PreFEED Engineering				
procurement				
project management				
Regulation and Oversight				
Scientific and Engineering Consultancy				
Software and IT Services				
Surveying				
Trade associations and bodies				
Vendor Engineering				

Figure 97: Transport Taxonomy

Components	Equipment/Material Category	Area/Unit	Segment	Product
air coolers	Catalysts and Chemicals	Gas Storage	Physical storage	Hydrogen Storage
Basins/Sumps	Civil/ Structural Materials			
Buildings/shelters	Electrical Equipment/Materials			
Bus Systems	Instrumentation and Control Equipment/Materials			
Cable Trays	Piping Materials			
Cables	Rotating Equipment			
catalyst	Static Equipment			
Continuous Emissions Monitoring System	Thermal Equipment			
Chemicals	Packaged Equipment			
compressors				
control system		liquid Storage		
Control valves				
Drainage Systems				
electric heaters				
Emergency shutoff device (ESD) valves				
Expansion Turbines				
filter				
Fire and gas detection systems		Salt caverns	Geological Storage	
Foundations				
Insulation				
Mol sieves/Absorbents				
packages				
Packing				
Paving				
Pipe				
Pipe supports				
Pressure relief valves				
Process Analyser				
Process instruments				
pumps				
Roads				
Shell and tube Heat exchanger				
Security Fencing				
Solvents				
Support Structures				
Tanks				
Transformers				
Valves				
Vessels				
Business Incubation and Development	Construction/Installation		Services	
Certification and Inspection	Engineering			
Civil Installation	Manufacturing			
Commissioning	Operations and Maintenance			
Concept Engineering	Other			
Construction				
Design and Engineering Consultancy				
Education				
Electrical Installation				
Engineering Studies				
Environmental Consultancy				
Environmental Consultancy				
Engineering Procurement Construction (EPC) Services				
Front End Engineering and Design (FEED) Services				
Health & safety				
Legal and Financial Services				
Maintenance				
Maintenance				
Management consultancy				
Market Research and Consultancy				
Measurement and testing				
Mechanical Installation				
Planning consultancy				
Policymaking				
Pre Commissioning				
PreFEED Engineering				
procurement				
project management				
Regulation and Oversight				
Scientific and Engineering Consultancy				
Software and IT Services				
Surveying				
Trade associations and bodies				
Vendor Engineering				

Figure 98: Storage Taxonomy

Appendix E – Supply Chain Models

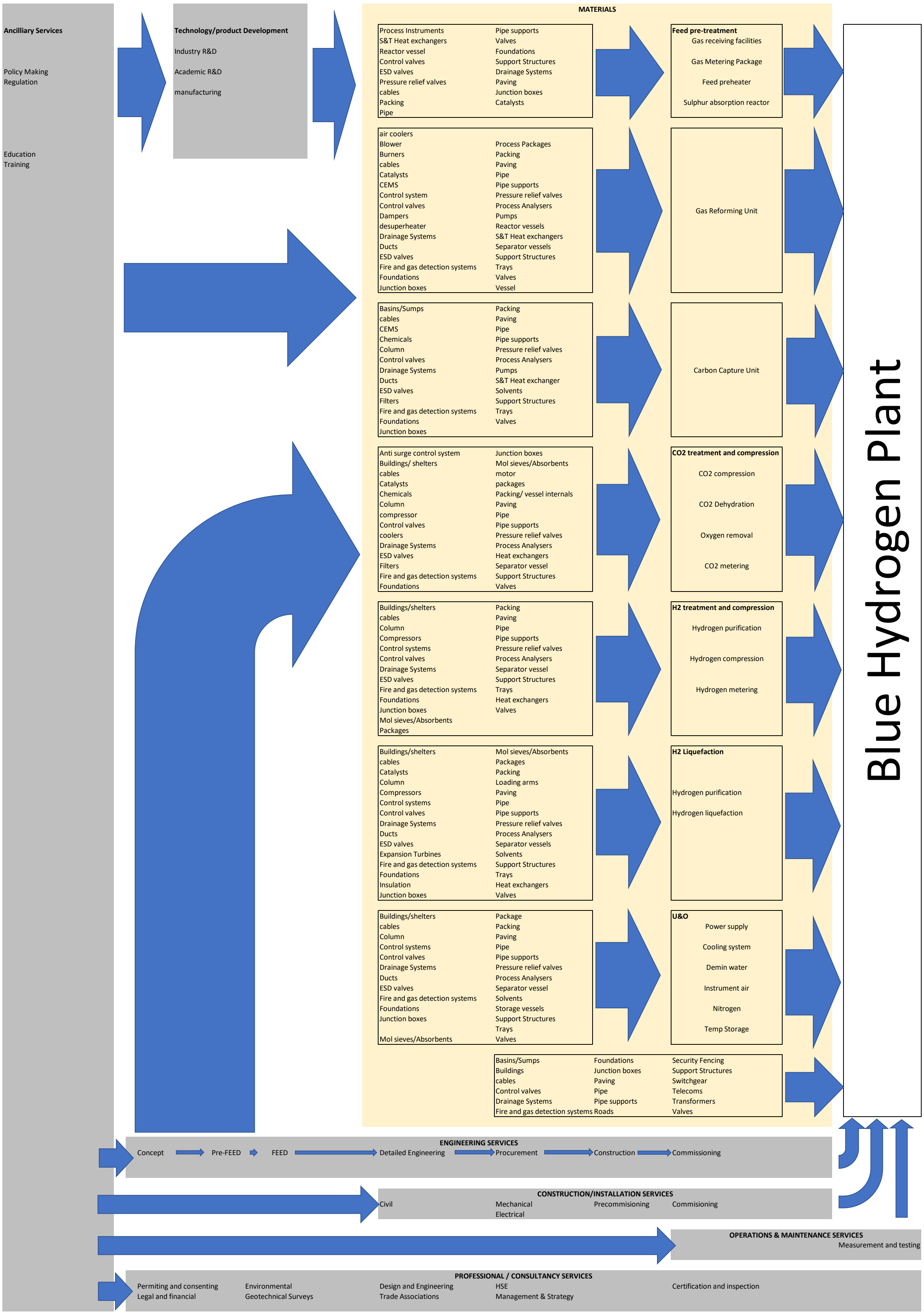

Figure 99: Blue Hydrogen Supply Chain Model

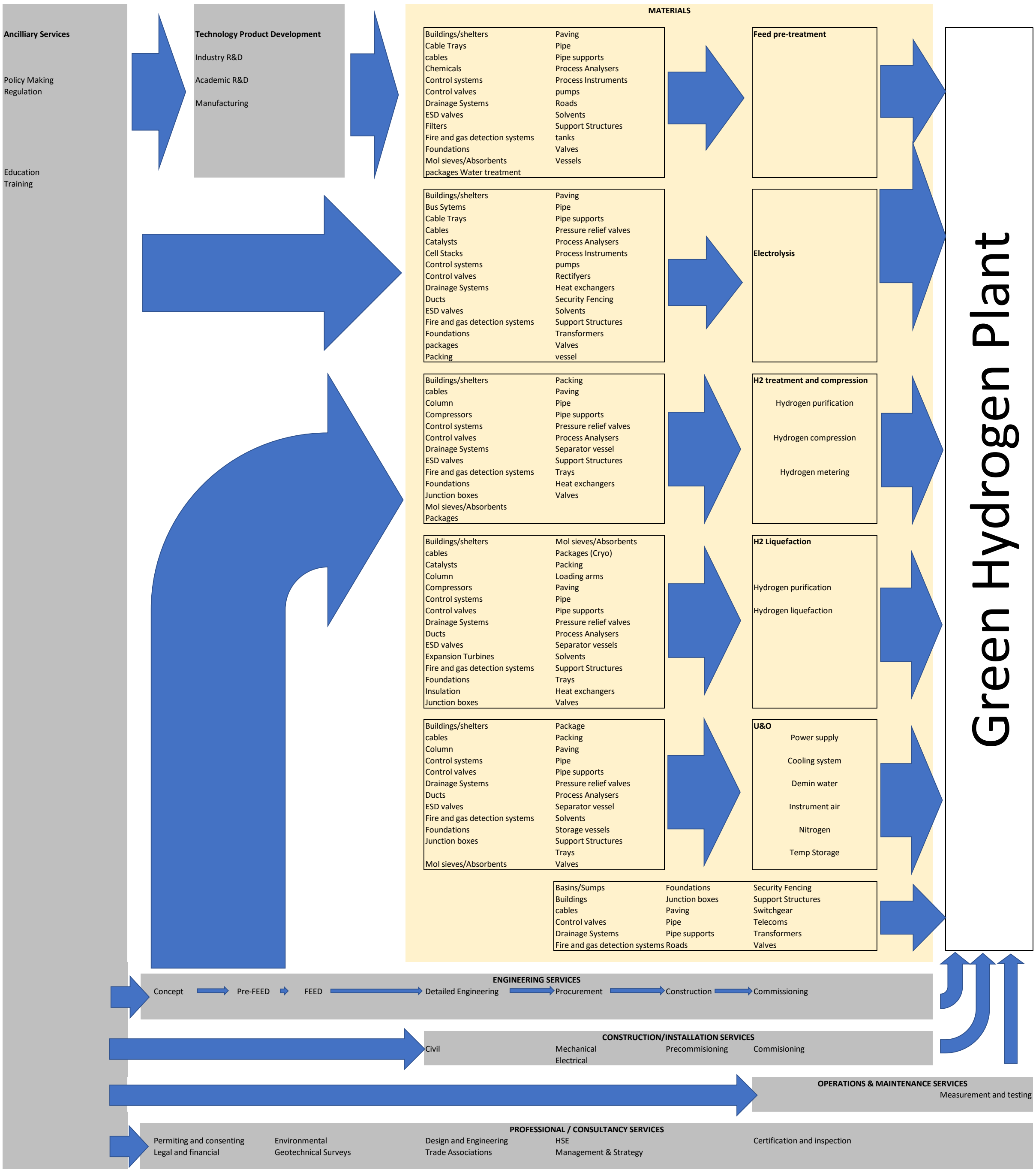

Figure 100: Green Hydrogen Supply Chain Model

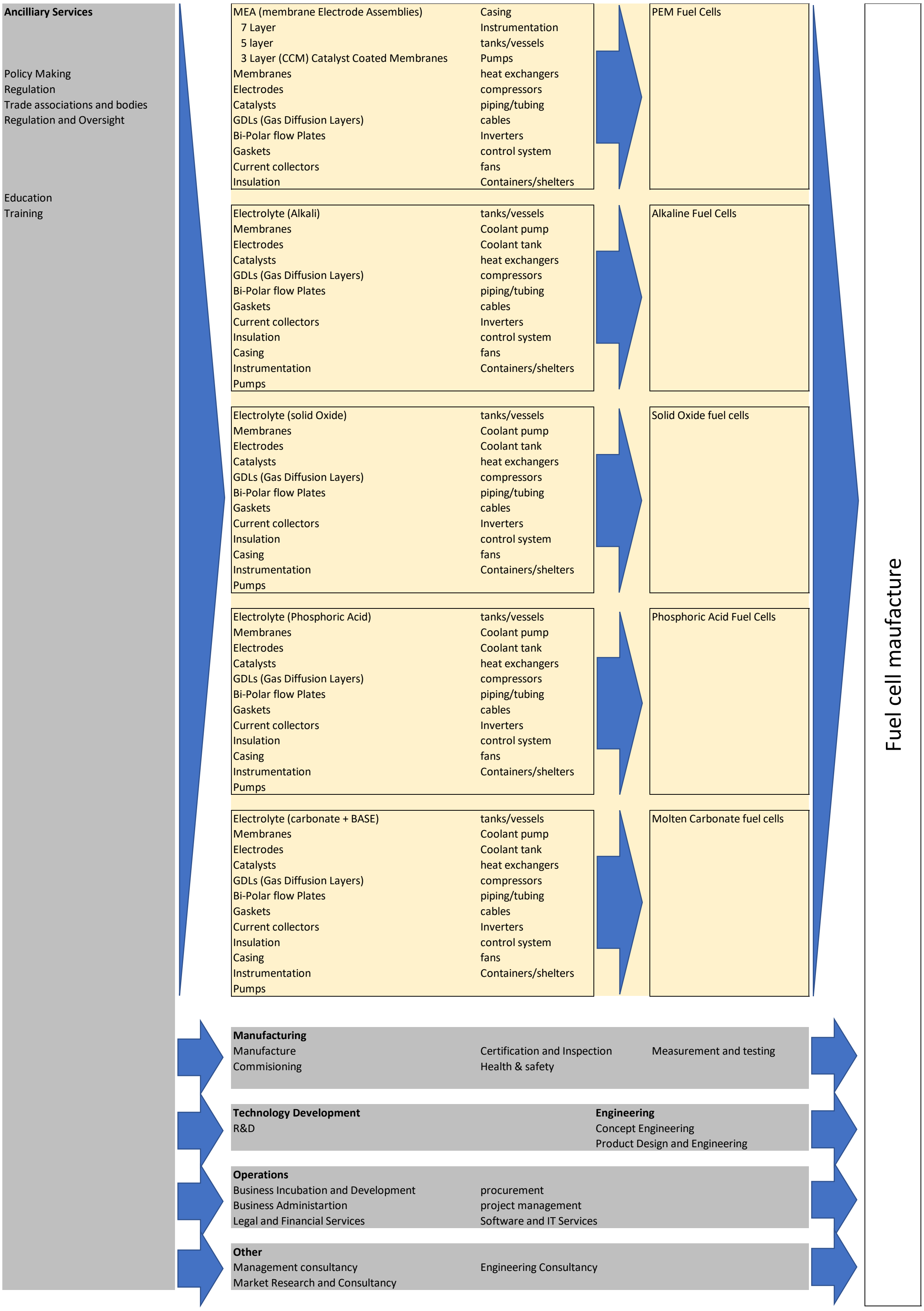

Figure 101: Fuel Cells Supply Chain Model

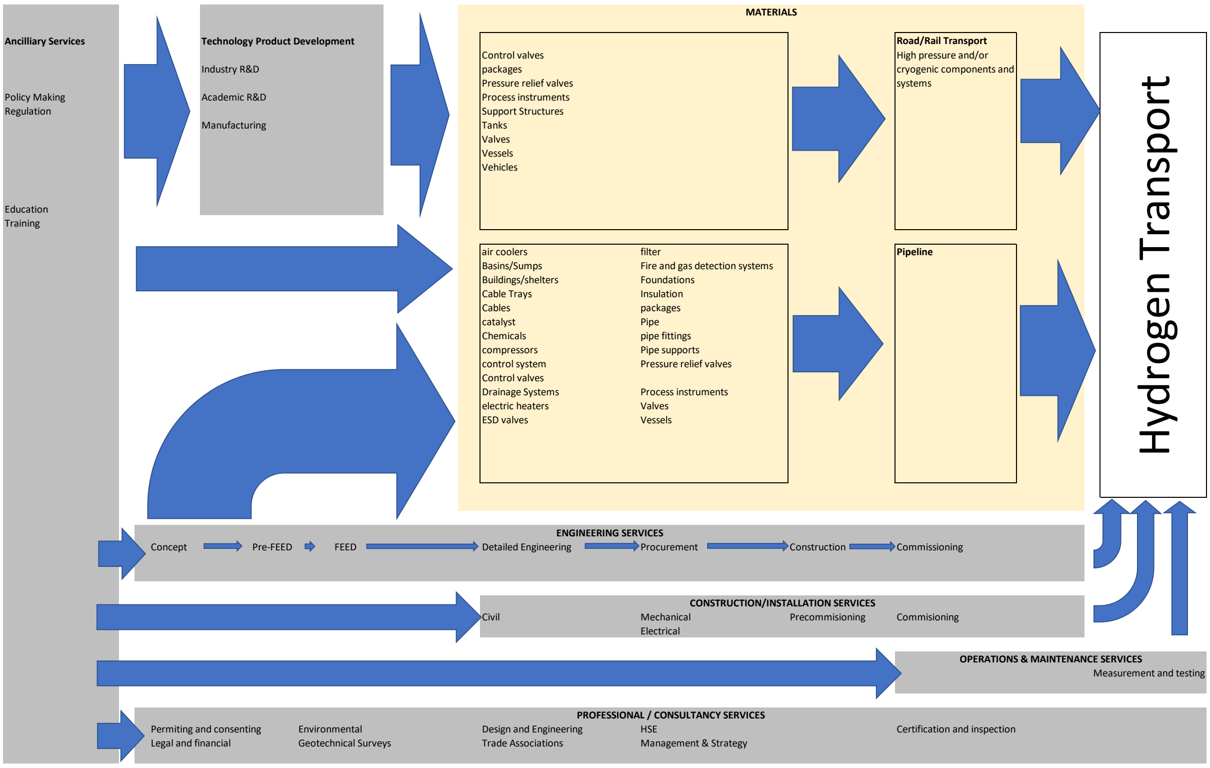

Figure 102: Transport Supply Chain Model

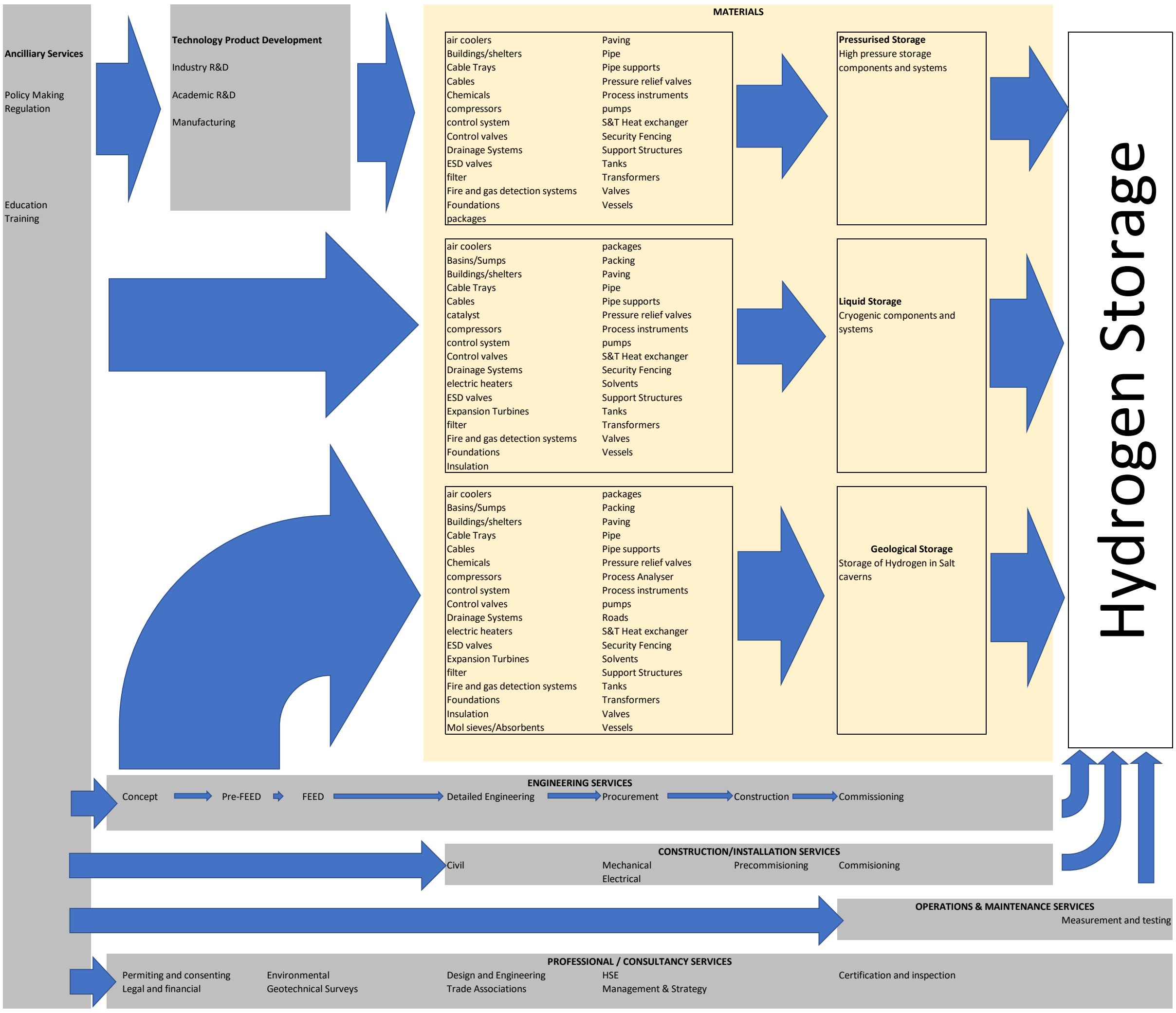

Figure 103: Storage Supply Chain Model

Appendix F – Supply Chain Capability Analysis

Common Equipment & Services Across Categories											
			UK Manufacturers			UK Suppliers / Stockist - Distributer / Agent			Foreign Supplier / Manufacturer		
			Number of Major Manufacturers	Capability	Experience	Number of Major Suppliers	Capability	Experience	Number of Major Manufacturers	Capability	Experience
Materials: Manufacture & Construction											
Components	**Detail**	**Materials**									
Air coolers	Standard conventional equipment within capacity range of current designs	Standard materials	1	1	1	1	1	1	1	1	1
Basins/Sumps	Standard concrete basins and sumps	concrete	1	1	1	1	1	1	1	1	1
Buildings	Nothing novel	Standard materials	1	1	1	1	1	1	1	1	1
Bus Systems	Standard electrical offering although a significant quantity will be required		1	1	1	1	1	1	1	1	1
Cables	standard bulks		1	1	1	1	1	1	1	1	1
Cable Trays			1	1	1	1	1	1	1	1	1
CEMS (Continuous Emission Monitoring System)	standard		1	1	1	1	1	1	1	1	1
Control systems	standard- varying in complexity dependant on size of facility		1	1	1	1	1	1	1	1	1
Control valves	Standard bulks		1	1	1	1	1	1	1	1	1
Drains/Undergrounds			1	1	1	1	1	1	1	1	1
Electric heaters	process heaters		1	1	1	1	1	1	1	1	1
Electrical Switchgear	Standard supply		1	1	1	1	1	1	1	1	1
ESD valves			3	1	1	1	1	1	1	1	1
Filters	Standard cartridge filters		1	1	1	1	1	1	1	1	1
Fire and gas detection systems			1	1	1	1	1	1	1	1	1
Foundations		concrete and steel	1	1	1	N/A	N/A	N/A	1	1	1
Heat exchangers - Plate & Frame	standard plate and frame	Standard materials	1	1	1	1	1	1	1	1	1
Heat exchangers - Shell & Tube	assume within known ranges of scale		1	1	1	1	1	1	1	1	1
Insulation	pipe insulation covering both hot and cold service as well as protective cover		1	1	1	1	1	1	1	1	1
Molecular sieves/Absorbents	standard offering		3	1	1	1	1	1	1	1	1
Packages - Main equipment supplier	Key packages across the industry include:	various									
	H2 Compressor	reciprocating	1	1	1	1	1	1	1	1	1
	CO2 compressor	various	2	2	2	1	1	1	1	1	1
	Dehydration	various	3	1	1	2	1	1	1	1	1

Common Equipment & Services Across Categories											
			UK Manufacturers			UK Suppliers / Stockist - Distributer / Agent			Foreign Supplier / Manufacturer		
			Number of Major Manufacturers	Capability	Experience	Number of Major Suppliers	Capability	Experience	Number of Major Manufacturers	Capability	Experience
Packing	fixed packing for columns of varying diameter	assume SS	1	1	1	1	1	1	1	1	1
Paving		concrete	1	1	1	1	1	1	1	1	1
Pipe - Metallic	bulks	Metallic	3	1	1	1	1	1	1	1	1
Pipe supports	bulks		1	1	1	1	1	1	1	1	1
Pressure relief valves			2	1	1	1	1	1	1	1	1
Process Analysers	CO2 and H2		1	1	1	1	1	1	1	1	1
Process Instruments	standard pressure, temp and flow instrumentation		1	1	1	1	1	1	1	1	1
Pumps	centrifugal pumps mainly -assume API. Size and capacity will vary depending on application		1	1	1	1	1	1	1	1	1
Roads			1	1	1	N/A	N/A	N/A	1	1	1
Security Fencing			1	1	1	1	1	1	1	1	1
Support Structures			1	1	1	1	1	1	1	1	1
Switchgear	standard scope for project size		1	1	1	1	1	1	1	1	1
Tanks	atmospheric storage tanks		1	1	1	1	1	1	1	1	1
Transformers	standard scope for project size		1	1	1	1	1	1	1	1	1
Valves	standard piping materials		1	1	1	1	1	1	1	1	1
Vessels	Pressure vessels -up to 30barg		1	1	1	1	1	1	1	1	1

Common Equipment & Services Across Categories

Services	UK / UK Based Companies: Number of Major Companies	UK / UK Based Companies: Capability	UK / UK Based Companies: Experience	Foreign Companies: Number of Major Companies	Foreign Companies: Capability	Foreign Companies: Experience
Business Incubation and Development	1	1	1	1	1	1
Certification and Inspection	1	1	1	1	1	1
Civil Installation	1	1	1	1	1	1
Commissioning	1	1	1	1	1	1
Concept Engineering	1	1	1	1	1	1
Construction	1	1	1	1	1	1
Design and Engineering Consultancy	1	1	1	1	1	1
Education	1	1	1	1	1	1
Electrical Installation	1	1	1	1	1	1
Engineering Studies	1	1	1	1	1	1
Environmental Consultancy	1	1	1	1	1	1
EPC Services	1	1	1	1	1	1
FEED Services	1	1	1	1	1	1
Health & Safety	1	1	1	1	1	1
Legal and Financial Services	1	1	1	1	1	1
Maintenance	1	1	1	1	1	1
Management consultancy	1	1	1	1	1	1
Market Research and Consultancy	1	1	1	1	1	1
Materials Testing	3	1	1	1	1	1
Measurement and testing	1	1	1	1	1	1
Mechanical Installation	1	1	1	1	1	1
Planning consultancy	1	1	1	1	1	1
Policymaking	1	1	1	1	1	1
Pre-Commissioning	1	1	1	1	1	1
Pre-FEED Engineering	1	1	1	1	1	1
Procurement	1	1	1	1	1	1
Project management	1	1	1	1	1	1
Regulation and Oversight	1	1	1	1	1	1
Scientific and Engineering Consultancy	1	1	1	1	1	1
Software and IT Services	1	1	1	1	1	1
Surveying	1	1	1	1	1	1
Trade associations and bodies	1	1	1	1	1	1
Vendor Engineering	1	1	1	1	1	1

Blue H2 Production												
				UK Manufacturers			UK Suppliers / Stockist - Distributer / Agent			Foreign Supplier / Manufacturer		
				Number of Major Manufacturers	Capability	Experience	Number of Major Suppliers	Capability	Experience	Number of Major Manufacturers	Capability	Experience
Materials: Manufacture & Construction												
Components		**Detail**	**Materials**									
	Blower	Induced draft fans and blowers -usually supplied as part of the reformer package. Scale dependent on size of reformer but scale up of blue hydrogen plants is expected to utilise a train approach based on the largest available reformers.	Standard materials	1	1	1	1	1	1	1	1	1
	Burners	Part of reformer package -standard offering	Standard materials	1	1	1	1	1	1	1	1	1
	Catalysts	standard established catalysts used in gas reforming	Standard materials	2	1	1	1	1	1	1	1	1
	Columns	Packed columns used for Absorbers and strippers with the Carbon capture process. Scale is dependant on size of plant but is not expected to be abnormally large or require specialist metallurgy		1	1	1	1	1	1	1	1	1
	Dampers	Part of reformer package -standard offering		1	1	1	1	1	1	1	1	1
	Desuperheaters	Standard bulks		2	1	1	1	1	1	1	1	1
	Ducts	Part of reformer package -standard offering		1	1	1	1	1	1	1	1	1
	Packages - Main equipment supplier	Key packages specific to blue hydrogen production:	various									
		Reformer	various	3	1	1	2	1	1	2	1	1
	Reactor vessel	standard pressure vessels up to 30barg with design temp of around 500oC -size will be dependent on design and capacity. Not expected to be anything abnormally large	Will be a range but will include exotic material linings such as Hastelloy in certain applications	1	1	1	1	1	1	1	1	1
	Reactor/heat exchanger	Pressure vessels up to 30barg with design temps of around 500oC also internals - nothing especially large but will vary depending on design of plant	Will be a range but will include exotic material linings such as Hastelloy in certain applications	1	1	1	1	1	1	1	1	1
	Solvents	Amine or similar based on chosen technology provider		1	1	1	1	1	1	1	1	1
	Trays	vessel internals		1	1	1	1	1	1	1	1	1
Services				UK / UK Based Companies						Foreign Companies		
				Number of Major Companies	Capability	Experience				Number of Major Companies	Capability	Experience
	Process Licensor			2	2	2				2	2	2

Green Hydrogen												
				UK Manufacturers			UK Suppliers / Stockist - Distributer / Agent			Foreign Supplier / Manufacturer		
				Number of Major Manufacturers	Capability	Experience	Number of Major Suppliers	Capability	Experience	Number of Major Manufacturers	Capability	Experience
Materials: Manufacture & Construction												
Equipment		Detail	Materials									
	Catalyst	Part of Cell stack and Electrolyser packages	Precious metal based for PEM	2	1	1	1	1	1	1	1	1
	Cell Stack	Part of electrolyser package		2	1	1	1	1	1	1	1	1
	Chemicals	various -used in water treatment and part of Water treatment packages		1	1	1	1	1	1	1	1	1
	Packages - Main equipment supplier	Key packages specific to green hydrogen production:	various									
		Electrolyser		1	2	2	1	1	1	1	1	1
		Desalination - water treatment		1	1	1	1	1	1	1	1	1
	Rectifiers	normally supplied as part of electrolyser package min scope of supply		1	1	1	1	1	1	1	1	1
	Solvents	used in water treatment		1	1	1	1	1	1	1	1	1

Hydrogen Storage

Salt cavern storage and operation and gas storage in vessels			UK Manufacturers			UK Suppliers / Stockist - Distributer / Agent			Foreign Supplier / Manufacturer		
			Number of Major Manufacturers	Capability	Experience	Number of Major Suppliers	Capability	Experience	Number of Major Manufacturers	Capability	Experience
Materials: Manufacture & Construction											
Equipment	**Detail**	**Materials**									
Catalyst	For Hydrogen clean up after transmission -de oxidising and dehydration etc		2	1	1	1	1	1	1	1	1
Chemicals	various -used in water treatment as part of cavern construction		1	1	1	1	1	1	1	1	1
Services			**UK / UK Based Companies**						**Foreign Companies**		
			Number of Major	Capability	Experience				Number of Major	Capability	Experience
Salt Cavern Design and Engineering Consultancy			3	3	3				2	1	1
Topsides Design and Engineering Consultancy			1	1	1				1	1	1

Hydrogen Transport

Transmission pipelines and distribution networks			UK Manufacturers			UK Suppliers / Stockist - Distributer / Agent			Foreign Supplier / Manufacturer		
			Number of Major Manufacturers	Capability	Experience	Number of Major Suppliers	Capability	Experience	Number of Major Manufacturers	Capability	Experience
Materials: Manufacture & Construction											
Equipment	**Detail**	**Materials**									
Catalyst	For Hydrogen clean up after transmission -de oxidising and dehydration etc		2	1	1	1	1	1	1	1	1
Packages	Key packages for hydrogen transport:	various									
	H2 compressor (high capacity)	Centrifugal	3	3	3	3	3	3	3	3	3
	Metering		1	1	1	1	1	1	1	1	1
Vessels	pressure vessels -including very high pressure composite storage vessels for road transportation		1	1	1	1	1	1	1	1	1

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Hydrogen Fuel Cells - Auto									
				UK Manufacturers			Foreign Supplier / Manufacturer		
				Number of Major Manufacturers	Capability	Experience	Number of Major Manufacturers	Capability	Experience
Materials: Manufacture & Construction									
Equipment		**Detail**	**Materials**						
	MEA (membrane Electrode Assemblies)								
	- 7 Layer								
	- 5 layer								
	- 3 Layer (CCM) Catalyst Coated Membranes								
	Electrolyte (solid Oxide)								
	Electrolyte (Alkali)								
	Electrolyte (Phosphoric Acid)								
	Electrolyte (carbonate + BASE)								
	Membranes	**Assessing as Fuel Cell Electric Vehicle packaged item.**							
	Electrodes			3	2	3	1	1	1
	Catalysts								
	GDLs (Gas Diffusion Layers)								
	Bi-Polar flow Plates								
	Gaskets								
	Current collectors								
	Insulation								
	Casing								
	Instrumentation								
	Pumps								
	Tanks/vessels	Small High pressure composite storage tanks 600/700 barg		2	3	3	1	1	1
	Coolant pump	Assume small scale for automotive applications i.e. fuel cell electric vehicles		1	2	3	1	1	1
	Coolant tank			1	2	3	1	1	1
	Heat exchangers			1	2	3	1	1	1
	compressors			1	2	3	1	1	1
	piping/tubing			1	2	3	1	1	1
	Cables			1	2	3	1	1	1
	Inverters			1	2	3	1	1	1
	Control system			1	2	3	1	1	1
	Fans			1	2	3	1	1	1
	Containers/shelters			1	2	3	1	1	1

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