Energy Innovation Needs Assessment

Sub-theme report: Hydrogen & fuel cells

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Contents

Acronyms and abbreviations 3
Glossary 5
Introduction 6
Key Findings 9
Hydrogen and the whole energy system 16
Innovation opportunities within hydrogen and fuel cells 23
Business opportunities within hydrogen and fuel cells 45
Market barriers to innovation within hydrogen and fuel cells 72
Appendix 1: Organisations at expert workshop 75
Appendix 2: Business opportunities methodology 77
Appendix 3: Overall hydrogen and fuel cell business opportunities 84
Appendix 4: Assessment of business opportunities uncertainty 86

The views expressed in this report are the authors' and do not necessarily reflect those of the Department for Business, Energy and Industrial Strategy.

Acronyms and abbreviations

Table 1. **Key acronyms and abbreviations**

Acronym/abbreviation	Definition
AEC	Alkaline Electrolyser Cell
ASU	Air Separation Unit
ATR	Autothermal Reforming
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	Department for Business, Energy and Industrial Strategy
BoP	Balance-of-Plant
CCC	Committee on Climate Change
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CHP	Combined Heat and Power
CO	Carbon monoxide
CO_2	Carbon dioxide
EINA	Energy Innovation Needs Assessment
EPCm	Engineering, Procurement, and Construction Management
ESC	Energy System Catapult
ESME	Energy System Modelling Environment
ETI	Energy Technologies Institute
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gases
GHR	Gas Heated Reforming

GVA	Gross Value Added
H_2	Hydrogen
HDV	Heavy-Duty Vehicle
HHV	Higher Heating Value
HMG	Her/His Majesty's Government
HRS	Hydrogen Refuelling Station
IEA	International Energy Agency
IP	Intellectual Property
ITM	Ion Transport Membrane
JIVE	Joint Initiative for Hydrogen Vehicles across Europe
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier
MSW	Municipal Solid Waste
N_2	Nitrogen
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PEMEC	Polymer Electrolyte Membrane Electrolyser Cell
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PSA	Pressure Swing Adsorption
R&D	Research and Development
SME	Small and Medium Sized Enterprise
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell
SOFC	Solid Oxide Fuel Cell

TRL	Technology Readiness Level
WGS	Water-Gas Shift

Glossary

Table 2. **Key terms used throughout this report**

Term	Definition
Learning by doing	Improvements such as reduced cost and/or improved performance. These are driven by knowledge gained from actual manufacturing, scale of production, and use. Other factors such as the impact of standards which tend to increase in direct proportion to capacity increases.
Learning by research, development and demonstration	Improvements such as proof of concept or viability, reduced costs, or improved performance driven by research, development, and demonstration (RD&D); increases with spend in RD&D and tends to precede growth in capacity.
Sub-theme	Groups of technology families that perform similar services which allow users to, at least partially, substitute between the technologies. For example, a variety of technology families (heat pumps, district heating, hydrogen heating) have overlapping abilities to provide low-carbon thermal regulation services and can provide flexibility to the power system.
System value and Innovation value	Estimates of change in total system cost (measured in £ GBP, and reported in this document as cumulative to 2050, discounted at 3.5%) as a result of cost reduction and performance improvements in selected technologies. This is the key output of the EINAs and the parameter by which improvements in different technologies are compared. System benefits result from increasing deployment of a technology which helps the energy system deliver energy services more efficiently while meeting greenhouse gas targets. Energy system modelling is a vital tool in order to balance the variety of interactions determining the total system costs. Innovation value is the component of system value that results from research and development (rather than from 'learning by doing')
Technology family	The level at which technologies have sufficiently similar innovation characteristics. For example, heat pumps are a technology family, as air-source, ground-source and water-source heat pumps all involve similar technological components (compressors and refrigerants). Electric vehicles are also a technology family, given that the battery is a common component across plug-in hybrids and battery electric vehicles.
Gross Value Add	Gross Value Add (GVA) measures the generated value of an activity in an industry. It is equal to the difference between the value of the outputs and the cost of intermediate inputs.

Introduction

Box 1. **Background to the Energy Innovation Needs Assessment**

The Energy Innovation Needs Assessment (EINA) aims to identify the key innovation needs across the UK's energy system, to inform the prioritisation of public sector investment in low-carbon innovation. Using an analytical methodology developed by the Department for Business, Energy & Industrial Strategy (BEIS), the EINA takes a system-level approach, and values innovations in a technology in terms of the system-level benefits a technology innovation provides.[1] This whole system modelling in line with BEIS's EINA methodology was delivered by the Energy Systems Catapult (ESC) using the Energy System Modelling Environment (ESME^{TM}) as the primary modelling tool.

To support the overall prioritisation of innovation activity, the EINA process analyses key technologies in more detail. These technologies are grouped together into sub-themes, according to the primary role they fulfil in the energy system. For key technologies within a sub-theme, innovations and business opportunities are identified. The main findings, at the technology level, are summarised in sub-theme reports. An overview report will combine the findings from each sub-theme to provide a broad system-level perspective and prioritisation.

This EINA analysis is based on a combination of desk research by a consortium of economic and engineering consultants, and stakeholder engagement. The prioritisation of innovation and business opportunities presented is informed by a workshop organised for each sub-theme, assembling key stakeholders from the academic community, industry and government.

This report was commissioned prior to advice being received from the CCC on meeting a net zero target and reflects priorities to meet the previous 80% target in 2050. The newly legislated net zero target is not expected to change the set of innovation priorities, rather it will make them all more valuable overall. Further work is required to assess detailed implications.

[1] The system-level value of a technology innovation is defined in the EINA methodology as the reduction in energy system transition cost that arises from the inclusion of an innovation compared to the energy system transition cost without that innovation.

The hydrogen and fuel cells sub-theme report

The hydrogen energy sector is significantly wider than most other EINA sub-themes. It encompasses a broad range of technologies covering hydrogen production, delivery, and end use. For this reason, this sub-theme required further characterisation and subdivision into smaller groups that were analysed individually. The three groups into which the sub-theme was divided are: hydrogen production, hydrogen infrastructure, and hydrogen final use.

Hydrogen production includes the following technology families:

- **Natural Gas Reforming** includes processes such as Steam Methane Reforming (SMR) and Autothermal Reforming (ATR). In a low-carbon economy, natural gas reforming needs to be coupled to Carbon Capture and Storage (CCS). However, innovation opportunities specifically related to CCS are treated separately in the Carbon Capture, Utilisation and Storage (CCUS) sub-theme.
- **Gasification** is focussed on large-scale coal gasification. It does not include biomass gasification, which is treated in the Bioenergy sub-theme. Similar to gas reforming, coal gasification would need to be coupled with CCS to provide a clean source of hydrogen with low greenhouse gases (GHG) emissions, and this would rely on highly efficient CO_2 capture.
- **Electrolysis** includes polymer electrolyte membrane electrolysers (PEMEC), alkaline electrolysers (AEC), and solid oxide electrolysers (SOEC).

Hydrogen infrastructure was further divided into three technology families:

- **The delivery** of hydrogen group refers to all the technologies that allow the transportation of hydrogen from the point of production to the point of consumption. The main delivery technologies considered in this report are: gaseous hydrogen in tube trailers, pipelines, cryogenic tanks, ammonia, and Liquid Organic Hydrogen Carriers (LOHC). Some of these technologies could also be employed as storage solutions (e.g. cryogenic tanks, ammonia).
- **Storage** is focussed on bulk seasonal storage of hydrogen. The two technologies considered for bulk hydrogen storage are salt caverns and pipeline line-packing.
- **Refuelling Stations** refer to road vehicle refuelling stations.

The only end use of hydrogen considered within this sub-theme report was fuel cells, with an exclusive focus on stationary combined heat and power (CHP) applications. Other hydrogen end-uses are included in other EINA sub-theme reports. The reasons for excluding other final uses from this sub-theme are summarised below.

- Hydrogen domestic boilers are covered in the Heating and Cooling sub-theme report, despite being related to the scope of this sub-theme.
- Hydrogen internal combustion engines and turbines were not highlighted as having strong innovation potential in the UK, in the pre-screening of the technology families.

- Hydrogen use in industry is covered in the Industry sub-theme report, despite being related to the scope of this sub-theme.
- Hydrogen use in transport is covered in the Road Transport sub-theme report.

The report has four sections:

- **Hydrogen and the energy system:** The role of hydrogen in the energy system.
- **Innovation opportunities:** Provides lists of the key innovations available within hydrogen and fuel cells, and their approximate impact on costs.
- **Business opportunities:** Summarises the export opportunities of hydrogen and fuel cells, the GVA and jobs supported by these opportunities, and how innovation helps the UK capture the opportunities.
- **Market barriers to innovation:** Highlights areas of innovation where market barriers are high.

Key Findings

Priority innovations areas in hydrogen and fuel cells

The high-priority innovations for the hydrogen and fuel cell sector are identified below. The innovations are listed following the supply-chain sequence, not in order of priority. This list is a guide for policymakers on key areas to be considered in any future innovation programme design, rather than a detailed cost-reduction study.

The innovation priorities below select individual or groups of the top scoring innovations. Table 3 maps the top scoring innovations to individual technology components, and Tables 14 to 20 set out the full list of innovations and their scores.

- **Integration of hydrogen production from fossil sources with CCS**. ATR is identified as the most suitable reforming technology to be integrated with carbon sequestration at reasonable cost. Coal gasification coupled with CCS remains to be proven at scale as a feasible clean hydrogen production route.

- **Advanced techniques and automation of electrolyser and fuel cell manufacturing**. High-volume production methods would enable significant capital cost reduction.

- **Electrolyser and fuel cell materials**. Advancements in cell component materials can improve performance and reduce the cost of electrolysers and fuel cells. The UK has a global leading role in material science and could exploit this competitive advantage.

- **Proving the ability of the existing natural gas network to be repurposed to hydrogen** is essential to enable widespread hydrogen to use in heat. Proving safety and operability of a hydrogen gas network could also reduce deployment barriers to hydrogen use in industry and transport.

- **Optimising pressure levels across the hydrogen delivery chain at the network design stage is key for future cost savings, especially in the transport sector**. Simplification and cost reduction of hydrogen infrastructure can be achieved at the inception of infrastructure development.

Business opportunities to the UK

Business opportunities from export are uncertain, primarily because of the large uncertainty around the level of hydrogen use in the global energy system. Predicted global hydrogen use differs by an order of magnitude. This implies the associated export market for equipment producing and using hydrogen varies by an order of magnitude as well. In the business opportunities section below, GVA and jobs results are set out by component (Table 19).

- **Business opportunities associated with export of hydrogen generation equipment and stationary fuel cells may add £0.5 billion to GVA and 3,600 jobs per annum** in a high-hydrogen scenario by 2050. However, if global hydrogen demand is closer to International Energy Agency (IEA) expectations, jobs supported may be limited to several hundred (<£0.1 billion GVA) by 2050.
- **The UK is well positioned to be competitive in 2050.** Building on research strength and an early lead in demonstration projects, the UK could capture a significant market share in various hydrogen technologies. However, given the immaturity of the sector this is less certain than, for example, established UK competitiveness in the UK's auto industry.
- **The export opportunity is small relative to potential domestic opportunities, which may reach £1.5 billion in GVA and 15,000 jobs per annum at 2050.** This is primarily because of the expected scale of sizeable expected UK deployment, and the significant domestic service opportunities.
- **Hydrogen is a cross-cutting business opportunity** and strength in one area is likely to create positive spillovers. This sub-theme report focusses on hydrogen export opportunities directly associated with hydrogen production and (stationary) fuel cells. Several broader opportunities are captured in the Heating and Cooling (hydrogen boilers), Road Transport (fuel cells for vehicles) and Industry sub-themes. Appendix 3 summarises all opportunities analysed across the EINAs.

Market barriers to innovation in the UK

Opportunities for HMG support exist when market barriers are significant and they cannot be overcome by the private sector or international partners. In the market barriers section below, the barriers are set out by component, where possible (Table 21). The main market barriers identified by industry relate to:

- A consistent and credible policy position is needed to support deployment of hydrogen and fuel cells. Without certainty, incentives for firms to invest in developing new technology with returns far into the future are low. A coordinated set of signals, regulatory requirements and commercial incentives would reduce uncertainty about the size of the future hydrogen market. As an example, for successful policy support, industry referenced California's policy to provide financial incentives for purchasing alternative fuel vehicles to stimulate deployment.[2]

[2] Alternative Fuels Data Center (n.d.) Hydrogen Laws and Incentives in California https://afdc.energy.gov/fuels/laws/HY?state=CA

- Uncertainty about deployment of CCS is a barrier to hydrogen production. Without policy intervention on CCS, investment in low-carbon hydrogen production from gas reforming and coal gasification is unlikely.

Key findings by component

Government support is justified when system benefits and business opportunities are high, but market barriers prevent innovation.

Table 3. **Cost and performance in hydrogen and fuel cells (see key to colouring below)**

Overall statistics for hydrogen and fuel cells: System value by 2050 for upstream innovation = £2.6 billion (range: £1.1-5.3 billion), 2050 export opportunity (GVA) for upstream and fuel cells = £0.5 bn, 2050 potential direct jobs supported by exports= 3,600				
Component	**Example innovation**	**Business opportunity**	**Market barriers**	**Strategic assessment**
Natural Gas Reforming	Proving autothermal reforming with CCS at scale	Low	Severe	The relatively small size of the export market likely limits business opportunities. CCS is indispensable, therefore without government intervention, innovation will not occur in the UK.
Coal Gasification	Proving integration with CCS at scale	Low	Severe	The relatively small size of the export market likely limits business opportunities. This production route is disfavoured because of its high GHG emissions. CCS is indispensable, thus without government intervention, innovation will not occur in the UK.
Electrolysis	Advanced manufacturing techniques	Low	Moderate	Manufacturing and material improvements can provide significant cost reductions. However, the relatively small size of the export market likely limits business opportunities. Without government intervention, innovation will occur but at a lower scale.
Hydrogen Delivery	Proving feasibility of repurposing the natural gas grid to hydrogen	Primarily domestic opportunity	Moderate	Proving the feasibility of repurposing the natural gas grid to hydrogen is the main priority. Due to the need for strong policy coordination, without government intervention innovation will occur at a lower scale.
Hydrogen Storage	Chemical hydrogen storage (ammonia, LOHC)	Primarily domestic opportunity	Moderate	Innovation in alternative forms of bulk hydrogen storage is the key priority. Without government intervention, innovation will occur but at a lower scale.
Hydrogen Refuelling Station	Efficient and reliable purification equipment	Primarily domestic opportunity	Moderate	Innovation in purification is the top priority. HRS uptake requires strong coordination with FCEVs deployment. Without government intervention to support hydrogen refuelling stations, innovation will occur at lower scale.

Component	Example innovation	Business opportunity	Market barriers	Strategic assessment
Fuel Cells	Advanced manufacturing techniques	Medium-low	Moderate	Fuel cells are the largest market and business opportunity, nonetheless it is relatively small compared to other sub-themes. Note, there is significant cross-over with fuel cells for vehicles which are potentially a significantly larger export opportunity (considered in the Road Transport sub-theme). Without government intervention in fuel cells, innovation will occur at a lower scale.

Source: *Vivid Economics, E4tech*

Note: *The main innovations per component are the innovations that score highest in the innovation inventory. This table only includes component-specific market barriers. Cross-cutting barriers are included in the market barriers section below. We only include export markets in this assessment because it is more directly linked to additional benefits to the UK economy. However a assessment of the domestic market is included in the report below.*

Table 4. **Key to colouring in the key barriers by component**

Business opportunities	**Market barriers**
High: more than £1 billion annual GVA from exports by 2050	**Critical:** Without government intervention, innovation, investment and deployment will not occur in the UK.
Medium-High: £600-£1,000 million annual GVA from exports by 2050	**Severe:** Without government intervention, innovation, investment and deployment are significantly constrained and will only occur in certain market segments / have to be adjusted for the UK market.
Medium-Low: £200-£600 million annual GVA from exports by 2050	**Moderate**: Without government intervention, innovation, investment and deployment will occur due to well-functioning industry and international partners, but at a lower scale and speed.
Low: £0-200 million annual GVA from exports by 2050	**Low:** Without government intervention, innovation, investment and deployment will continue at the same levels, driven by a well-functioning industry and international partners.

Source: Vivid Economics, E4tech

Box 2. **Industry workshop**

A full-day workshop was held on 13th February 2019 with delegates from the hydrogen industry, academic community, and research agencies. Key aspects of the EINA analysis were subjected to scrutiny, including innovation opportunity assessment, and business and policy opportunities assessment. New views and evidence were suggested; these have been incorporated into these assessments.

The views of the attendees were included in the innovation assessment. In addition, several contextual issues were raised during the workshop:

- Some technology pieces within the hydrogen industry are already mature and do not have innovation priority (e.g. salt cavern storage). In these cases, the expansion of the sector primarily requires measures that support deployment rather than R&D.
- Several attendees envisioned a hydrogen delivery infrastructure for the heat sector mainly based on pipelines. The infrastructure would be composed of a new high-pressure transmission network linked to medium-pressure distribution networks. The existing distribution network could be repurposed from natural gas to hydrogen.
- A case needs to be built around the safety of the hydrogen infrastructure. This could be done by improving/adjusting safety standards and demonstrating the feasibility of safe and reliable distribution of hydrogen.
- To unlock lower-cost electrolysers and fuel cells, more funding should target early-commercial stage small and medium sized enterprises (SMEs). Support is needed to allow transition from Technology Readiness Level (TRL) 5 to TRL 7/8, alongside early-stage technology. It was suggested that an equivalent institution to the Advanced Propulsion Centre for vehicles could be established for hydrogen and fuel cells, with the aim to bridge the gap to the fully commercial stage.
- Some attendees expressed concerns that the technology cost and performance assumptions, used in the ESME modelling for this study to derive system-level innovation value, were too pessimistic. The project team explained that this modelling was used to select sub-themes for EINA analysis, with a wide range of sensitivities considered. The data was not used to form the basis for assessment of innovation opportunities or business opportunities.

Hydrogen and the whole energy system

Current situation

The UK produces around 700,000 tonnes of hydrogen each year (roughly 27 TWh of energy equivalent), which represents 1.4% of global production. Globally, the majority of this is produced from either steam methane reforming (49%) or partial oil oxidation (29%). The remainder is produced from coal gasification (18%) or electrolysis (4%).[3]

The predominant demand for hydrogen today is as an industrial feedstock. Worldwide, just under half of current hydrogen consumption is in the petroleum refining industry. The second largest use of hydrogen is in producing ammonia for fertilisers. The rest is employed across the food, methanol, metals, and electronics industries. If all the hydrogen currently produced in the UK was used for energy, this would be equivalent to less than 2% of the country's primary energy demand.[4]

There is growing interest in the use of low-carbon hydrogen in various sectors of the UK economy. Apart from industry, the second largest sector using hydrogen is transport. In the UK there are currently 13 operational hydrogen refuelling stations (HRSs) and two Fuel Cell Electric Vehicle (FCEV) models available on the market.[5] Furthermore, a total of 88 hydrogen buses are expected to be deployed by 2020 in the UK as part of the Joint Initiative for Hydrogen Vehicles across Europe (JIVE) projects.[6] Additional deployments are supported through the UK's Low Emission Bus Scheme, which is expected to deliver 22 fuel cell buses in Birmingham and 20 in London.[7] Another prospective use of hydrogen, which is currently under discussion, is heating in buildings. This could be achieved by repurposing the current low-pressure gas grid to hydrogen and installing hydrogen boilers and/or hybrid heat pumps. Finally, in the power sector, hydrogen is considered as an option for energy storage.

[3] CCC (2018) Hydrogen in a low-carbon economy.
[4] IEA (2019) online public statistics for UK 2016 https://www.iea.org/statistics/?country=UK&year=2016&category=Energy%20consumption&indicator=TFCbySource&mode=chart&dataTable=BALANCES
[5] CCC (2018) Hydrogen in a low-carbon economy.
[6] FCHJU (2018) Joint Initiative for hydrogen Vehicles across Europe, https://www.fch.europa.eu/sites/default/files/documents/ga2011/4_Session%201_JIVE_Michael%20Dolman%20%28ID%204811591%29.pdf
[7] DfT (2019) Low Emission Bus Scheme, https://www.gov.uk/government/publications/low-emission-bus-scheme-performance-monitoring/low-emission-bus-scheme-performance-monitoring

Future deployment scenarios

The Committee on Climate Change (CCC) has presented three potential deployment scenarios for hydrogen, based on the Energy System Catapult's ESME model.[8] These scenarios represent different options for decarbonising the UK energy system.

- **Full Hydrogen:** In this scenario, gas networks are repurposed to hydrogen. The heating demand in buildings is primarily satisfied through hydrogen boilers. Widespread availability of a hydrogen grid means low-carbon hydrogen supplies being available for multiple applications. The annual hydrogen consumption reaches 704 TWh by 2050, with 67% of the hydrogen demand from heating in buildings and 12% from industry.
- **Hybrid Hydrogen:** In this scenario, gas networks are also repurposed to hydrogen. However, the heating demand in buildings is mainly covered by hybrid heat pumps. Hydrogen demand would be significantly lower in this scenario, roughly 346 TWh in 2050. The main applications would be buildings heating, light-duty vehicles, and industry, respectively responsible for 31%, 29%, and 24% of the hydrogen consumption.
- **Niche Hydrogen:** This is a scenario in which gas grids are not switched to hydrogen, with heat decarbonisation for on-gas buildings relying primarily on electrification through full and hybrid heat pump systems. The annual hydrogen consumption would be around 81 TWh by 2050. In the Niche scenario hydrogen would be primarily used in heavy-duty vehicles (HDVs) (40%) and power generation (35%).

Producing the volume of hydrogen needed under the Full Hydrogen scenario would be both technically and economically challenging.[9] It would require high capacity build rates resulting in large financial investments. In all three scenarios, hydrogen is assumed to be produced mainly from natural gas reforming with CCS.

Such high levels of low-carbon hydrogen penetration into the energy system could achieve 190 MtCO_2 avoided emissions per annum by 2050. Putting this number into perspective, the avoided emissions correspond to 40% of the total UK GHG emissions in 2017.[10] In a more electricity-based scenario like the "Niche" one, the total avoided emissions would correspond to one third of the "Full" scenario.

[8] CCC (2018) Hydrogen in a low-carbon economy.
[9] Ibid.
[10] BEIS (2019) National statistics UK Greenhouse Gas Emissions, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/776083/2017_Final_emissions_statistics_one_page_summary.pdf

Sub-theme system integration: Benefits, challenges and enablers

From a system perspective, hydrogen presents several benefits and challenges. The principal benefits are summarised below.

Being an energy vector like electricity, hydrogen could be used in all sectors of the UK economy, including transport, industry, building heating, and power generation. Hydrogen represents a decarbonisation option in multiple applications, when produced from low-carbon sources. Synergies across different hydrogen applications could be established thus accelerating the UK economy decarbonisation.

Hydrogen does not produce greenhouse gases when it is burned or electrochemically oxidised. When combined with carbon capture and storage, hydrogen production can provide a route to low or even negative greenhouse gas emissions (when using biomass). It has potential to give an important contribution to meeting long-term carbon targets. Furthermore, in some applications hydrogen can bring air quality benefits in addition to decarbonisation.

Hydrogen can be stored in large quantities for long periods. Therefore, it is considered as one option to provide flexibility to the energy system. As highlighted in the EINA smart system sub-theme, hydrogen storage is one of the few ways to enable inter-seasonal storage. Additionally, converting electricity to hydrogen (often referred as Power-to-Gas) and hydrogen storage could support the power grid under future higher penetration of intermittent energy sources. Hydrogen could enable more widespread penetration of renewable electricity, to store large amounts of intermittent electricity supply and enable its use in other sectors, such as heating and transport. It could be an alternative to reinforcing the electricity grid to access remote renewables.

There are some challenges associated with the transition to a low-carbon hydrogen economy. The main ones are summarised below.

There are low market values for some benefits of hydrogen technologies, such as greenhouse gas reduction and air quality benefits.[11] Most hydrogen applications cannot compete with incumbent technologies based on their costs alone. Some benefits only arise from considering the system, and therefore are difficult to value in policy support. For example, the possibility of storing hydrogen adds flexibility to the energy system, allowing peaks of demand to be shaved.

[11] E4tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth.

A system approach is essential to capture system benefits and determine the most appropriate actions to be taken.[12] Hydrogen supply chains can interact with many other areas of the energy system, including production options, infrastructure (electricity grid, gas network, CO_2 transport, and storage infrastructure), and end-use sectors. This means that strategic planning at a regional and/or national level is required to encourage investment in, and reduce the costs of, many hydrogen options. Maximising the benefits to the UK system can only be achieved if there is coordination across all the relevant sectors.

There is a need to consider interactions between different hydrogen applications, particularly around hydrogen supply.[13] For example, hydrogen supply for heating via the gas grid could change the options available for hydrogen supply to the transport sector. Supply chain growth for one fuel cell application could reduce costs and increase supply chain strength for another.

[12] E4tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth
[13] Ibid.

Box 3. **System modelling: Hydrogen in the UK energy system**

Following the BEIS EINA methodology, whole energy system modelling was conducted using the ESME^{TM} Version 4.4 to estimate where innovation investments could provide most value to support UK energy system development.

ESME is a peer-reviewed whole energy system model (covering the electricity, heat and transport sectors, and energy infrastructure) that derives cost-optimal energy system pathways to 2050 meeting user-defined constraints, e.g. 80% greenhouse gas (GHG) emissions reduction.[14] The model can choose from a database of over 400 technologies which are each characterised in cost, performance and other terms (e.g. maximum build rates) out to 2050. The ESME assumption set has been developed over a period of over 10 years and is published.[15] ESME is intended for use as a strategic planning tool and has enough spatial and temporal resolution for system engineering design.

Like any whole system model, ESME is not a complete characterisation of the real world, but it is able to provide guidance on the overall value of different technologies, and the relative value of innovation in those technologies.

The EINA Methodology prescribes the approach to be taken to assess the system-level value of technology innovation. This involves creating a baseline energy system transition without innovation (from which a baseline energy system transition cost is derived), and on a technology-by-technology basis assessing the energy system transition cost impact of "innovating" that technology. Innovation in a technology is modelled as an agreed improvement in cost and performance out to 2050.

For the EINA analysis, the technology cost and performance assumptions were derived from the standard ESME dataset as follows:

- In the baseline energy system transition, the cost and performance of all technologies is assumed to be frozen at their 2020 levels from 2020 out to 2050.
- The "innovated" technology cost and performance for all technologies are assumed to follow the standard ESME dataset improvement trajectories out to 2050 (these are considered techno-optimistic).

Whole system analysis using the BEIS EINA Methodology described above shows that there is significant value to the UK in continued (and accelerated) innovation in hydrogen. The value to the energy system of innovation in upstream hydrogen technologies is £2.6 billion cumulatively to 2050 (discounted at 3.5%).[16]

There is further value in transportation fuel cells, accounted for in the transport EINA instead.

The system analysis has highlighted that innovation investments in low-carbon technologies are required to meet decarbonisation targets. Innovation is needed across the whole hydrogen value chain:

- Lower cost, low-carbon hydrogen production methods delivering significant quantities of hydrogen into the energy system (>500 TWh per annum by 2050)
- Low-cost hydrogen delivery and storage infrastructure (gas network repurposing, new hydrogen transmission lines, storage caverns, etc.).
- Lower cost, better performing and safe conversion technologies (hydrogen to electricity, heat, and motive power).

Further work is required to estimate the value of particular innovations in hydrogen and fuel cells, or how these estimates may change in the case of different energy system scenarios.

[14] More details of the capabilities and structure of the ESME model can be found at eti.co.uk/programmes/strategy/esme. This includes a file containing the standard input data assumptions used within the model.
[15] The ESME assumption set has been developed is published with data sources at https://www.eti.co.uk/programmes/strategy/esme
[16] Hydrogen upstream technologies referred to in this report section include all forms of hydrogen production, power-to-gas plants, hydrogen storage in salt caverns, and hydrogen vehicle refueling. As set out in the introduction section, many downstream, end use technologies related to hydrogen are covered in separate EINA subthemes.

Box 4. **Learning by doing and learning by research**

The total system value follows from two types of technology learning:

- **Learning by doing:** Improvements such as reduced cost and/or improved performance. These are driven by knowledge gained from actual manufacturing, scale of production, and use. Other factors, such as the impact of standards which tend to increase in direct proportion to capacity increases.
- **Learning by research:** Improvements such as proof of concept or viability, reduced costs, or improved performance driven by research, development, and demonstration (RD&D). It increases with spend in RD&D and tends to precede growth in capacity.

The EINAs are primarily interested in learning by RD&D, as this is the value that the government can unlock as a result of innovation policy. Emerging technologies will require a greater degree of learning by RD&D than mature ones. Academic work suggests[17] that for emerging technologies around two-thirds of the learning is due to RD&D, and for mature technologies it contributes around one-third.

To reach a quantitative estimate of the system value attributable to RD&D, these ratios are applied to the system value. This implies that, as an emerging technology, around £1.7 billion of the £2.6 billion system value for upstream hydrogen technologies follows from RD&D efforts. Note, this is an illustrative estimate, with the following caveats:

- The learning-type splits are intended to apply to cost reductions. However, in this study, they are applied to the system value. As system value is not linearly related to cost reduction, this method is imperfect.
- In practice, learning by research and learning by doing are not completely separable. It is important to deploy in order to crowd-in investment to more RD&D, and RD&D is important to unlock deployment.

These estimates are used in the EINA Overview Report to develop a total system value that results from innovation programmes across the energy system.

[17] Jamasb, Tooraj (2007). "Technical Change Theory and Learning Curves", The Energy Journal 28(3).

Innovation opportunities within hydrogen and fuel cells

Introduction

Box 5. **Objective of the innovation opportunity analysis**

The primary objective is to identify the most promising innovation opportunities within hydrogen and fuel cells and highlight how these innovations may be realised and contribute to achieving the system benefit potential described above. This section provides:

- A breakdown of the costs across key components and activities of the hydrogen and fuel cell supply-chain.
- A list of identified innovation opportunities, and an assessment of their importance to reducing costs and deployment barriers.
- Deep dives into the most promising innovation opportunities.

The hydrogen and fuel cell sectors are developing at a rapid pace around the world.[18] Public and private enterprises are already supporting initiatives to roll-out hydrogen and fuel cell-based technologies at scale. Technological innovation across the whole hydrogen supply chain plays a large role in enabling this uptake. The UK has the strengths and capabilities to capture part of this global innovation potential and position itself as a leading hydrogen technology developer.[19]

The focus of this work is on understanding how innovation could bring down the cost of, and reduce the barriers to, deploying technologies within the hydrogen and fuel cells sub-theme. However, it is important to point out that innovation is not the only means of reducing technology cost and overcoming deployment barriers. For more mature technologies, deployment is a more effective cost-reduction driver than R&D. Across the hydrogen and fuel cell industry the technology advancement status is not uniform. The technologies are spread across the entire TRL spectrum from proof-of-concept to fully commercial. R&D and innovation typically have bigger impact on low- and medium-TRL technologies, such as material-based hydrogen storage or Polymer Electrolyte Membrane (PEM)

[18] E4tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth
[19] E4tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth

electrolysers. However, the economics of high-TRL technologies like steam methane reforming or salt cavern storage will mainly benefit from progressive deployment.

The following sections of the report will highlight the key innovations needed in hydrogen and fuel cell technology. The technologies are presented separately in order to reflect their different cost structures and innovation needs.

Cost breakdown

For each technology family an archetype was selected to illustrate the cost breakdown. Although within each technology family cost varies depending on the specific technology and size, the chosen archetypes were considered the most representative for the whole family.

The levelised cost definition varies across the technology families. For reforming, gasification, and electrolysis it is defined as the cost of hydrogen production. For delivery, storage, and refuelling stations it represents the cost of the service. For fuel cells it is the cost of the electricity generated. A set of tables summarising the levelised cost of the different technology families is presented below.

Table 5. **Cost Model of Steam Methane Reformer + CCS**

Cost Element	Levelised cost of production	Other factors affecting deployment
CAPEX	12%	Size: 1,000 MW (H_2 HHV)
O&M	10%	
CCS cost + carbon emission price	28%	Carbon Capture Rate: 90% Carbon price: £15/tCO_2
Fuel Cost	50%	Efficiency (kWh_e in / kWh H_2 out, HHV): 65% Gas price (bulk): £23/MWh
Total (£/MWh H_2 HHV)	**44 (100%)**	

Note: The carbon cost includes the additional cost of installation and operation of the CCS unit and the carbon emission price.

Source: CCC (2018) Hydrogen in a low-carbon economy. PDF pages: 68 to 71

Building a new steam methane reformer equipped with CCS in the UK today would cost £44/MWh on a levelised cost basis. Most of the costs for a gas reforming plant are made up of fuel and carbon capture and emission costs, which comprise around 80% of overall costs. This share could become even bigger if the carbon price increased in the future. Note that the expert participants in the workshop considered that the most likely natural gas reforming technology to be built today would be autothermal reforming with CCS, rather than the steam methane reforming with CCS option chosen as the archetype here.

Table 6. **Cost Model of Coal Gasification + CCS**

Cost Element	Levelised cost of production	Other factors affecting deployment
CAPEX	23%	Size: 2,700 MW (H_2 HHV)
O&M	27%	
CCS cost + carbon emission price	21%	Carbon Capture Rate: 90% Carbon price: £15/tCO_2
Fuel Cost	29%	Efficiency (kWh$_e$ in / kWhH2 out, HHV): 52% Gas price (bulk): £63/tonne
Total (£/MWh H_2 HHV)	**68 (100%)**	

Note: The carbon cost includes the additional cost of installation and operation of the CCS unit and the carbon emission price.

Source: CCC (2018) Hydrogen in a low-carbon economy. PDF pages: 77 to 79

Building a new coal gasification plant in the UK today would cost around £68/MWh, including the costs of CCS. Capital and operation and maintenance costs represent half of the overall levelised cost. As coal gasification is a mature technology, there is limited room for further technical improvements to reduce costs aside from through improved integration with CCS at scale. However, savings from building larger-scale coal gasification plants are significant, with estimates suggesting that capital costs roughly halve for every doubling of plant size. This contrasts with other hydrogen production technologies, which can be effectively deployed at much smaller plant sizes.

Although hydrogen production from biomass gasification is treated in the Biomass and Bioenergy sub-theme, it is interesting to highlight here the cost comparison with coal gasification. Before accounting for potential negative emissions, a biomass gasification plant equipped with CCS would cost roughly 1.5 times the coal equivalent.[20] Fuel costs represent a larger part (60%) of the total cost of a bio-gasifier. This is a consequence of two factors. Firstly, biomass gasification has lower conversion efficiencies (46%-60%) than coal gasification (over 60%).[21] Secondly, the feedstock cost per unit of energy (£/GJ) is higher for biomass compared to coal. The total costs of biomass gasification with CCS would depend on the potential scope for negative emissions, which could lower costs by 10-20%.[22]

Table 7. **Cost Model of Electrolyser**

Cost Element	Levelised cost of production	Other factors affecting deployment
CAPEX	6%	Size: 10 MWe Type: PEM
O&M	8%	Load factor: 90%
Fuel Cost	86%	Efficiency (kWh_e in / kWhH2 out, HHV): 65% Electricity price (bulk): £46 /MWh
Total (£/MWh H_2 HHV)	**89 (100%)**	

Source: CCC (2018) Hydrogen in a low-carbon economy. PDF pages: 72 to 75

Current estimates of levelised costs for hydrogen production from a PEM electrolyser in the UK are around £90/MWh. In a case where the operation of the electrolyser is maximised (90% load factor), the bulk of the hydrogen production cost is made of input electricity (86%), and capital costs are a small proportion of an electrolyser's costs. If utilisation is lower, capital costs become more important. Electrolysers are a modular technology, so could benefit from cost reductions through repeated deployment. For electrolysis, this 'learning rate' has been estimated at around 7% per doubling of globally installed capacity.[23]

[20] CCC (2018) Hydrogen in a low-carbon economy.
[21] Ibid.
[22] CCC (2018) Biomass in a low carbon economy. Biomass gasification with CCS has a carbon intensity of roughly 300kgCO_2/MWh.
[23] Element Energy for BEIS (2018) Hydrogen supply chain evidence base.

Table 8. **Cost Model of Tube Trailers**

Cost Element	Levelised cost of service	Other factors affecting deployment
CAPEX – Tractor	9%	- Conventional diesel tractor - 5-year lifetime (6 trucks required over levelisation period)
CAPEX – Trailer	7%	- Payload: 720 kg H_2 - Operating pressure: 250 bar - 30-year lifetime
Fix O&M – Tractor	16%	Insurance + property taxes + licensing and permits + maintenance + overhead and general & administrative
Fix O&M – Trailer	1%	Operation and maintenance of tube trailer
Labour	51%	$21.68/man-hour (truck operator with offloading capabilities)
Fuel Cost	16%	- 0.14 litre/km diesel consumption - 280 km round-trip
Total	**100% £35 / MWh H_2 HHV (£1.4 / kg H_2)**	**- 30-year levelisation period - 0.7406 £/$ 2016 average exchange rate**

Notes: *Costs annuitised by E4tech (no discounting applied), considering 30-year tube trailer lifetime.*

Source: Capital cost of tube trailer from DOE - Technical targets for hydrogen delivery (2015 status), https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery; *all other costs from DOE - HDSAMv3.1, https://www.hydrogen.energy.gov/h2a_delivery.html*

The main cost component of tube trailer delivery is the labour cost (51%). Tractor operation and maintenance cost and fuel cost are the second most important pieces, both accounting for 16% of the total levelised cost.

Table 9. **Cost Model of Salt Cavern Storage**

Cost Element	Levelised cost of service	Other factors affecting deployment
CAPEX	37%	-Location: East Yorkshire -Storage Size: 300,000 m^3 -Operating pressure: 270 bar -Well depth: 1,800 m -60% of CAPEX is above-ground facility
O&M	63%	-Storage size, operating pressure, well depth as for CAPEX
Total (£/MWh storable H_2 HHV)	**127 (100%)**	**30-year lifetime**

Notes: *CAPEX annuitised by E4tech (no discounting applied), considering 30-years lifetime.*

Source: *Element Energy & Jacobs for BEIS (2018) Hydrogen supply chain evidence base. PDF page: 105; ETI (2015) The role of hydrogen storage in a clean responsive power system. PDF page: 10.*

The cost structure of underground hydrogen storage is location-specific. A report from the Energy Technologies Institute (ETI) compares the capital cost breakdown of a selection of three potential salt cavern hydrogen storage sites in the UK.[24] The results suggest that the costs of shallow stores (Teesside) are dominated by cavern construction costs, having lesser above-ground equipment. By contrast, the deep stores (East Yorkshire) have very high topside costs to compress hydrogen from 20-60 bar up to storage pressures of 270 bar.

However, over the lifetime of the storage facility the main component of the levelised cost is operation and maintenance. The cost of compression is the biggest part of the operational cost, especially in the case of deep storage.

Table 10. **Cost Model of Hydrogen Refuelling Station**

Cost Element	Levelised cost of service	Other factors affecting deployment
CAPEX – Station Equipment	43%	Size: 200 kg H_2 / day
CAPEX – Station Installation	15%	Location: US
CAPEX – Site Preparation	13%	Location: US
Electricity	5%	Electricity price (commercial retail): \$104/MWh_e
Labour	9%	Labour cost: 20 \$/hr
Maintenance	16%	
Total	**100% £220 / MWh H_2 HHV (£8.7 / kg H_2)**	**- Levelised cost over 7-year payback period - 40% average utilisation factor over the first 10 years of operation - 0.6542 £/\$ 2015 average exchange rate**

Source: *NREL (2017) Comparison of conventional vs. modular hydrogen refuelling stations, and on-site production vs. delivery. PDF pages: 19 to 25*

The main cost component of a hydrogen refuelling station is its capital cost. Equipment, installation, and site preparation costs grouped together represent 71% of the levelised cost of the station. The chosen archetype refers to a 200 kg/day station. Scaling up the capacity to 300 kg/day decreases the total cost by

[24] ETI (2015) The role of hydrogen storage in a clean responsive power system.

27%. This highlights that significant cost savings can be achieved through economy of scale.

The utilisation factor is another key parameter affecting the levelised cost of Hydrogen Refuelling Stations. Cost modelling studies have shown that a 10% utilisation rate (a common value for the initial period of operation) is associated with 4.7 times higher levelised cost compared to a 90% utilisation rate.[25] This suggests that high utilisation rates have a great impact on the total lifetime cost of refuelling stations.

At low utilisation rates, cheaper, smaller, 350 bar HRSs may prove more cost-effective than 700 bar stations.[26] However, 350 bar refuelling could ultimately limit the number of vehicles that can refuel at these stations, and reduced capacity would lead to worse economic performance than large stations when used at high capacity.

Additionally, the cost table is based on a current standard configuration in which hydrogen is centrally produced through SMR (without CCS) and delivered by tube trailers. Another possible configuration is to produce hydrogen on-site through an electrolyser. In this case, for the same station capacity (200 kg/day), the overall cost would be 45% higher (including the cost of hydrogen delivery in the reference case).

Table 11. **Cost Model of Stationary Fuel Cell**

Cost Element	Levelised cost of electricity	Other factors affecting deployment
CAPEX	21%	Size: 50 kW_e Type: Solid Oxide Fuel Cell Stack Operational Lifetime: 20,000 hours
O&M	24%	Same as CAPEX
Fuel Cost	55%	-Net electrical efficiency (nominal, LHV): 59% -CHP efficiency (nominal): 84% -Natural gas price: 72 £/MWh
Total (£/MWh_e)	**210**	

Notes: *The archetype is referred to a medium-scale residential application (hotel) in New York, US. The electrical utilisation rate of the fuel cell is 75% (i.e. the fuel cell supplies 75% of the electric energy demand). The thermal utilisation rate is 82%.*

Source: *DOE (2015) A Total Cost of Ownership Model for Solid Oxide Fuel Cells in Combined Heat and Power and Power-Only Applications. PDF page: 187.*

[25] E4tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth.
[26] Ibid.

Owning and operating a 50 kW_e fuel cell for CHP residential application costs around £200 per MWh_e of electricity produced over the fuel cell lifetime. The fuel cost represents more than half of the total cost and it is dependent on the natural gas price and the electrical efficiency of the system. Experts who participated in the workshop noted that in the last couple of years significant performance improvements have been achieved in fuel cell technology. Some Solid Oxide Fuel Cell (SOFC) manufacturers now commercialise stacks with longer lifetimes (around 40,000 operational hours) and electrical efficiency higher than 65%. Because of these better characteristics these systems may be cheaper than the archetype presented here.

Inventory of innovation opportunities

The following areas of innovation constitute the largest opportunities for reduction in cost and deployment stimulation across the UK hydrogen supply chain.

Proving autothermal reforming with CCS at scale is the priority to secure a reliable source of clean hydrogen. ATR is the most suitable technology for integration with CCS to produce hydrogen from natural gas at scale. It is predicted to be able to achieve carbon capture rates of up to 98% when combined with Gas Heated Reforming (GHR). Although ATR is an existing process, there is innovation in deploying it at scale in combination with CCS, and proving high CO_2 capture rates. This deployment at scale could also include GHR. Cost reduction would be achieved through thermal and mechanical integration, improving efficiency and optimising separation processes.

Unlocking advanced manufacturing of electrolysers and fuel cells can significantly reduce their capital cost. A significant capital cost reduction for all types of electrolysers and fuel cells can be delivered by shifting to high-volume and highly automated production methods. This would be enabled by scaling up production rates. Examples of advanced manufacturing methods include tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes.

Proving the ability of the existing natural gas network to be repurposed to hydrogen is essential to enable widespread hydrogen use in heat. Proving safety and operability of a hydrogen gas network could also reduce deployment barriers to hydrogen use in industry and transport**.** Safe and reliable operation, and successful integration with a range of end uses, needs to be demonstrated through a diverse range of pilot schemes.

Optimising pressure levels across the hydrogen delivery chain at the network design stage is key for future cost savings, especially in the transport sector. Simplification and cost reduction of hydrogen infrastructure can be achieved at the inception of infrastructure development. System analysis can identify the optimal compression levels throughout each stage of the delivery chain (from hydrogen generation to refuelling). The correct sizing of infrastructural components such as compressors, valves, pipes, and tanks is key to limiting the overall expenditure associated with hydrogen delivery.

The workshop participants discussed the contents of the cost and innovation tables and agreed on prioritisation of the innovations needed. After the workshop, the tables were revised by E4tech to reflect the relative importance of innovations that emerged from the workshop consultation. The updated tables were then circulated amongst workshop delegates, who were given the opportunity to provide further minor comments, which were included.

The magnitude of the contributions to cost reduction and reducing deployment barriers are described in qualitative terms relative to the innovation opportunities belonging to the same technology family.

- Significantly above average = 5
- Above average = 4
- Average = 3
- Below average = 2
- Significantly below average = 1

An indicative timeframe for each innovation is provided. The timeframe given relates to the year the technology is deployed commercially at scale (gaining 10-20% market share).

Table 12. **Innovation mapping for Natural Gas Reforming**

	Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
General	Integration with CCS	**Proving Autothermal Reforming with CCS at scale**	5	5	Reforming		2025
Component-specific	Reformer	**Alternative Reforming Technologies.** Metal oxide reforming, methane pyrolysis, calcium looping routes.	3	4	Reforming	CCS	2035
	Water-gas shift reactor	**New Water-Gas Shift Technologies**. Ceramic membranes, sorption-enhanced water-gas shift and metal oxide shift.	3	1	Reforming and all types of gasification	Reforming, Biomass Gasification, CCS	2030
	Reformer	**Small-scale Modular Reformers**. Small-scale modular reformers at around 50 MW, to produce hydrogen closer to the point of utilisation.	1	2	Reforming		2025

Source: Workshop input, Element Energy for BEIS (2018) Hydrogen supply chain evidence base, DOE (2017) Hydrogen production roadmap.

Table 13. **Innovation mapping for Coal Gasification**

	Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Technology affected	Impact on other energy technology families	Feasible timeframe
General	Integration with CCS	**Proving Coal Gasification with CCS at scale**	4	1	Gasification (non-bio)	CCS	2025
Component-specific	Gasifier + Gas Purification Unit	**Use of Low-Quality Feedstocks**. Low-rank coal and Municipal Solid Waste (MSW).	3	2	Gasification (non-bio)	Biomass Gasification	2025
	Gasifier	**Novel Refractory Materials**	1	3	Gasification (non-bio)	Biomass Gasification	2025
	Air Separation Unit (ASU)	**Advanced Air Separation**. E.g. Ion Transport Membranes (ITM)	1	1	Gasification (non-bio), CO_2 separation	Reforming + CCS, Biomass Gasification	2025

Source: Workshop input, Element Energy for BEIS (2018) Hydrogen supply chain evidence base, DOE (2017) Hydrogen production roadmap

Table 14. **Innovation mapping for Electrolysis**

	Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Which technology will this innovation affect	Impact on other energy technology families	Feasible timeframe
Component-specific	Manufacturing	**Advanced Manufacturing.** Shift to high-volume production methods such as tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes.	5	5	All types of electrolysers	Fuel Cells	2025
	Cell	**Novel Cell Architectures.** E.g. reduced inter-electrode gap.	3	3	All types of electrolysers	Fuel Cells	2030
	Cell	**Better Materials.** In PEMEC, low platinum catalyst loading and alternative catalyst material. In AEC, more stable electrodes and electrolytes. In SOEC, alternative cell materials.	3	3	All type of electrolysers	Fuel Cells	2030
	Purification Equipment	**Efficient feed-water purification.** Increased purification and desalination equipment efficiency.	2	3	All types of electrolysers	Reforming, Gasification	2030
	Purification Equipment	**Efficient H_2 Purification.** Higher efficiency purification equipment providing purer H_2.	3	3	All types of electrolysers	Reforming, Gasification	2030

	Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Which technology will this innovation affect	Impact on other energy technology families	Feasible timeframe
General	System Integration	**Optimised System Integration.** Better component integration into the electrolyser system and optimal operational set points.	5	4	All types of electrolysers		2025
	Other Routes	**Novel Hydrolysis Routes.** E.g. thermochemical water decomposition.	3	2			2040
	Other Applications	**Power-to-Chemicals.** Chemicals that can be produced through electrolysis are chlorine, ammonia, methanol, synfuels, oxygen, and syngas.	2	3	All types of electrolysers		2030
	Modelling	**Advanced Modelling & Diagnostics**	2	2	All type of electrolysers	Fuel Cells	2025

Source: *Workshop input, Schmidt et al. (2017), Future cost and performance of water electrolysis, IEA (2015) Technology Roadmap Hydrogen and Fuel Cells, Carbon Trust (2014) TINA Hydrogen for Transport*

Table 15. **Innovation mapping for Delivery**

	Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Which technology will this innovation affect	Impact on other energy technology families	Feasible timeframe
General	Pressure Levels	**Optimised Pressure Levels Across the Delivery Chain**	5	3	Tube Trailers, Pipelines	Refuelling Stations, Storage	2020-2025
	Safety	**Safety Standards**. All hydrogen handling equipment: valves, pipes, sealing, compressors.	1	5	All delivery technologies	Whole hydrogen supply chain	2025
Component-specific	Pipelines	**New Network Design**. New high-pressure (~70 bar) transmission pipelines. Repurposing and testing of existing (plastic pipe) distribution networks.	3	5	Pipelines		2025-2030
	Tube Trailers	**Higher Tube Pressure**	4	3	Tube Trailers	Refuelling Stations, Storage	2025
	Compression	**Improved Compression Efficiency**. Re-designed centrifugal compressors for hydrogen, ionic liquid, and electrochemical compressors.	3	3	Tube Trailers, Pipeline	Refuelling Stations, Storage	2025-2035
	Liquefaction Process	**Advanced Liquefaction Process**. Highly-efficient Mixed Refrigerant Pre-Cooling processes such as PRICO-type, Kleemenko-type, or cascade-type.	3	3	Liquid Hydrogen	Refuelling Stations, Storage	2025

	Alternative Carriers	**Efficient Liquid Hydrogen Tankers.** Improved insulation of the vessel and increased pressure levels.	2	1	Liquid Hydrogen, Tube Trailers	Refuelling Stations, Storage	2030-2035
	Odorants	**Odorant Management**. Systems for odorant addition and removal.	1	4	All delivery technologies	Whole hydrogen supply chain	2020
	Sensors	**Leakage Detection Sensors**. Low unit cost hydrogen sensor to be deployed at high volumes.	1	3	All delivery technologies	Whole hydrogen supply chain	2020

Source: Workshop input, E4tech (2015) Scenarios for deployment of hydrogen, DOE (2016) Advanced Hydrogen Fuelling Station Supply: Tube Trailers, IEA (2015) Technology Roadmap Hydrogen and Fuel Cells

Table 16. **Innovation mapping for Storage**

	Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Which technology will this innovation affect	Impact on other energy technology families	Feasible timeframe
Component-specific	Alternative Hydrogen Storage	**Chemical Hydrogen Storage**. LOHCs and ammonia.	3	4		Delivery, Refuelling Stations	2030
	Alternative Hydrogen Storage	**Material-based Hydrogen Storage**. Metal hydrides and porous sorbents.	3	2		Delivery, Refuelling Stations	2030
	Cavern Topside Facility	**High-pressure Turboexpanders**. Not on the market now.	3	2	Underground Storage, Line-packing	Refuelling Stations, Delivery	2025
	Underground Storage	**Use of depleted oil/gas fields and aquifers**	2	3	Underground Storage		2025-2035

Source: Workshop input, ETI (2015) The role of hydrogen storage in a clean responsive power system, DOE (2015) Multi-Year Research, Development and Demonstration Plan - Hydrogen Delivery, IEA (2015) Technology Roadmap Hydrogen and Fuel Cells

Table 17. **Innovation mapping for Refuelling Stations**

	Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Which technology will this innovation affect	Impact on other energy technology families	Feasible timeframe
Component-specific	Purification	**Reliable and Efficient Purification Equipment**	3	4	Refuelling Stations	Gasification, Reforming, Electrolysis	2030
	Unloading Equipment	**Faster Hydrogen Delivery.** More rapid delivery of H_2 from tube trailers to local storage.	3	2	Refuelling Stations		2025
	Verification	**Reliable Verification Equipment**. Better H_2 purity control.	2	3	Refuelling Stations	Gasification, Reforming, Electrolysis	2030
General	Design	**Optimisation of HRS Design.** Optimal station layout, size, pressure, and compression scheme.	3	3	Refuelling Stations		2020-2025
	Standardisation	**Standardisation of Components**	3	2	Refuelling Stations	Delivery, Storage	2025

Source: *Workshop input, Carbon Trust (2014) TINA Hydrogen for Transport, IEA (2015) Technology Roadmap Hydrogen and Fuel Cells*

Table 18. **Innovation mapping for Fuel Cells**

	Component	Innovation opportunity	Contribution to cost reduction	Contribution to reducing deployment barriers	Which technology will this innovation affect	Impact on other energy technology families	Feasible timeframe
Component-specific	Manufacturing	**Advanced Manufacturing Techniques**. Scale-up of production rates for various components. Shift from batch to continuous manufacturing.	5	3	All fuel cell types	Electrolysis	2025
	Manufacturing	**Quality control**. High-speed inline quality control.	3	4	All fuel cell types	Electrolysis	2025
	SOFC	**Innovative Materials and Structure**. Nanostructured thin film micro SOFCs, thick film SOFCs, strain-engineered materials.	4	2	SOFC	Electrolysis	2030
	SOFC	**Electrochemical CO_2 separation**	2	3	All types of fuel cells using internal reforming of methane	CCS	2030
	PEMFC	**Improve flexibility, durability, and operational capability**	3	3	PEMFC	Electrolysis	2030
	PEMFC	**Innovative Materials**. Alternative catalysts being developed include non-noble metal, transition metal oxides, and bio-inspired catalysts.	3	3	PEMFC	Electrolysis	2030
General	Design	**Fuel cell system simplification**	3	3	All fuel cell types		2025
	Grid Services	**Integration with Grid Services**. The power and heat generation from decentralised fuel cell units could be coordinated with grid requirements to provide balancing services.	2	4	All types of fuel cells + electrolysers		2025

Source: Workshop input, E4tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth, IEA (2015) Technology Roadmap Hydrogen and Fuel Cells

Innovation opportunity deep dives

In this section the main innovation opportunities identified during the expert consultation are presented in greater depth. These innovations illustrate opportunities for cost reduction and overcoming deployment barriers across hydrogen and fuel cell technology families.

Natural Gas Reforming & Coal Gasification

Autothermal Reforming with CCS for low-carbon hydrogen production needs to be proven at scale. ATR is the most likely technology to be used to produce hydrogen from natural gas at scale and could have carbon capture rates of up to 98%.[27] ATR involves the separation of 100% of the CO_2 from H_2, unlike SMR where around 40% of the CO_2 produced in the process is separated in low concentration from exhaust combustion gases.[28] This difference makes carbon capture in ATR a less expensive process, which could halve the cost of CO_2 capture. Although ATR is an existing process, there is innovation in deploying it at scale in combination with CCS. This combination entails changes to the process flow characteristics, which is where innovation could play a role. Cost reduction would be achieved through thermal and mechanical integration, improving efficiency and optimising separation processes. The deployment at scale of ATR could also include Gas Heated Reforming (GHR). This is a technique through which the energy input to the reforming reaction is supplied by a hot gas stream, typically the reformed gas leaving the reformer. The addition of GHR to ATR provides maximal energy recovery, thus reducing fuel costs.

Alternative reforming technologies to SMR and ATR might play a role in the longer term. Metal oxide steam reforming is a process that has been used for making hydrogen which produces pure CO_2, thus it represents a good link to CCS. This technology is currently at TRL 5-6, so R&D investments may well drive its cost down. Another option is methane pyrolysis (TRL 3-4). The route produces only hydrogen and solid carbon from methane, avoiding the problem of CO_2 capture and storage.

Novel Water-Gas Shift (WGS) technologies could increase the efficiency, and reduce the cost, of natural gas reforming. Sorption-enhanced WGS and ceramic membranes are technologies that can efficiently combine the CO conversion and CO_2 separation steps in one reactor to provide high-purity H_2 streams. These

[27] IEAGHG (2017) Reference data and Supporting Literature Reviews for SMR Based Hydrogen Production with CCS.
[28] Ibid.

innovations would be relevant not just to reforming, but also to all types of gasification and the use of industrial syngas.

Few high-impact innovation opportunities exist for coal gasification, but the integration with CCS at scale is one of them. Coal gasification is a mature and well-established technological process (TRL 9). Opinion from the expert workshop (see Appendix 1: Organisations at expert workshop for participating organisations) was that it is not worth exploring and developing new coal gasification processes, but innovation potential remains around the efficient combination of the gasifier, CO_2 separation unit, and injection well while achieving a high CO_2 capture percentage. By contrast, biomass gasification for hydrogen production is still an emerging technology, thus it has significant innovation potential, regardless of its integration with CCS.

Electrolysis & Fuel Cells

Unlocking advanced manufacturing of electrolysers and fuel cells can significantly reduce their capital cost. A significant capital cost reduction for electrolysers and fuel cells can be delivered by shifting to high-volume and highly automated production methods. This is partially enabled by the scale-up of production rates. Examples of these methods include tape casting, expanded metal cutting, hydroforming, and additive manufacturing processes. Considering that advanced manufacturing techniques are widely implemented in other industries this innovation could be reasonably achieved before 2025. Another important enabler of upgrading manufacturing techniques would be the existence of large guaranteed orders. This would enable electrolysers and fuel cell manufacturers to access capital and build production lines.

Optimising component integration can improve the design and the operation of electrolyser systems. More operational experience would enable the optimisation of the electrolyser system design. The deployment of pilot plants is essential in order to gain more experience. Building upon this experience, it is possible to streamline system design (lower capital cost) and optimise system set-points to maximise the overall efficiency (lower fuel cost).

Continuous innovation in material science will contribute to low-cost stacks for both electrolysers and fuel cells. In PEMEC and fuel cells (PEMFC), low-titanium bipolar plates, low-platinum catalyst loading and alternative catalyst materials (non-noble metal, transition metal oxides and bio-inspired catalysts) can directly reduce material cost. In AEC, more stable electrode and electrolytes can unlock operation at higher temperature. In SOEC, alternative cell materials can reduce degradation and increase the cell lifetime. Improvement of SOFC microstructure and material properties can help to reduce the operating temperature, thus make the cell more cost-effective. This will help to achieve greater thermodynamic efficiencies, longer lifetimes and quicker start-up times. Possible approaches include nanostructured thin film micro SOFCs, thick film SOFCs, and strain-engineered materials. Additionally, other electrolyser chemistries which have not been specifically addressed in this report (e.g. Anion Exchange Membrane) might benefit from the innovations presented here for PEMEC, AEC, and SOEC. The UK has a global leading role in materials science and could exploit this competitive advantage.

Power-to-Chemicals: hydrogen from electrolysis could be used to produce low-carbon chemicals. The scale-up of electrolyser manufacturing volumes can be supported by extending the market beyond energy generation, where chemical products have high value. Examples of chemicals that can be produced by integrating electrolysis are chlorine, ammonia, methanol, and synfuels. This is also covered in the CCUS report.

Hydrogen Infrastructure

Proving the ability of the existing gas network to be repurposed to hydrogen is essential to enabling widespread hydrogen to use in heat and could also reduce deployment barriers to use in industry and transport. Safe and reliable operation, and successful integration with a range of end uses, needs to be demonstrated through a diverse range of pilot schemes.

Optimising pressure levels across the hydrogen delivery chain at the network design stage is key for future savings for transport applications. Simplification and cost reduction of the hydrogen infrastructure can be achieved at the inception of infrastructure development. System analysis can identify the optimal compression levels throughout each stage of the delivery chain (from hydrogen generation to refuelling). The correct sizing of infrastructural components such as compressors, valves, pipes, and tanks is key to limiting the overall expenditure associated with hydrogen delivery.

Increasing the nominal tube pressure of tube trailers would reduce the overall cost of hydrogen delivery for transport applications. Increasing the tube pressure above 500 bar could increase the capacity of hydrogen deliveries to more than 1 tonne. This measure reduces the need for compression at point of delivery (e.g. vehicle refuelling stations). Consequently, the upstream refilling terminals need to be equipped with compression systems of suitable pressures. However, fewer refilling terminals would be needed, and these would benefit from economies of scale, so that overall system cost reduction would be achievable.

More efficient liquid hydrogen tankers could reduce the cost of long-distance bulk hydrogen delivery. Liquid hydrogen as an energy vector could become more favourable if the liquid boil-off was reduced through improved insulation of the vessel, as well as increasing pressure levels. This innovation would be especially relevant to hydrogen shipping.

Alternative hydrogen storage technologies could simplify and reduce the cost of bulk and vehicle on-board storage. LOHCs and ammonia can contribute meaningfully at a system level as energy storage options. The most relevant innovation in these is likely to be in infrastructure and in managing de-/hydrogenation cycles. In the longer term, novel material-based storage technologies, characterised by high volumetric energy density, could deliver low-cost hydrogen stationary storage, as well as alternative mobile storage options. These novel technologies include metal hydrides and porous sorbents.

The levelised cost of hydrogen refuelling stations can be reduced by optimising their design and improving the cost and performance of H_2 purification equipment. Defining the optimal hydrogen station layouts will enable reduction of HRS' capital and operating costs and reduce the station area footprint. This means optimising the design with respect to the hydrogen phase (gas vs liquid), size, pressure, and compression scheme. Additionally, more efficient and reliable purification units would reduce the energy consumption and enable a successful roll-out of HRS.

Business opportunities within hydrogen and fuel cells

Introduction

Box 6. **Objective of the business opportunities analysis**

The primary objective is to provide a sense of the relative business opportunities against other energy technologies. To do so, the analysis uses a consistent methodology across technologies to quantify the 'opportunity'; in other words, what *could* be achieved by the UK. The analysis assumes high levels of innovation but remains agnostic about whether this is private or public. This distinction is made in the final section of the report. The two key outputs provided are:

- A quantitative estimate of the gross value added, and jobs supported associated with hydrogen and fuel cell technology, based on a consistent methodology across technologies analysed in the EINA. Note, the GVA and jobs supported are *not* necessarily additional, and may displace economic activity in other sectors depending on wider macroeconomic conditions.
- A qualitative assessment of the importance of innovation in ensuring UK competitiveness and realising the identified business opportunities. Note, the quantitative estimates for GVA and jobs supported cannot be fully attributed to innovation.

The following discussion details business opportunities arising both from exports and the domestic market. An overview of the business opportunities, and a comparison of the relative size of export and domestic opportunities, across all EINA sub-themes is provided in the overview report.

More detail on the business opportunities methodology is provided in Appendix 2.

Currently, the UK hydrogen production and fuel cell industries are small. The UK's hydrogen economy is primarily in a demonstration phase, with a focus on readying key technologies for wider commercial deployment.[29] This is reflected in the limited deployment of hydrogen technologies domestically. Given low deployment,

[29] E4tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth. A Roadmap for the UK http://www.e4tech.com/wp-content/uploads/2016/11/UKHFC-Roadmap-Final-Main-Report-171116.pdf

the hydrogen supply chain is small and immature. However, it is developing. There are over 100 companies and 35 research groups active in fuel cell and hydrogen production technologies in the UK.[30]

This business opportunity analysis focusses on hydrogen production equipment, stationary fuel cells, and tradeable services. There is a wide array of potential business opportunities associated with a UK hydrogen economy and the innovations described previously. This analysis focusses on export opportunities directly associated with the innovations discussed in this report, and which help support jobs in the UK. This includes export opportunities in both goods and selected engineering, procurement, and construction management (EPCm) and design services. In particular, the report focusses on opportunities to export:

- **Hydrogen generation equipment**, including equipment for electrolysis, coal gasification, and gas reforming.
- **Services**, primarily EPCm, associated with the deployment of hydrogen generation equipment.
- **Stationary fuel cells** and associated design services.

Given the cross-cutting nature of hydrogen, several business opportunities are captured in other sub-themes. Appendix 3 provides an overview of all hydrogen related business opportunity estimates across EINA sub-theme report. Key estimates include:

- **Hydrogen export:** Large-scale domestic hydrogen production could enable export of hydrogen itself. This opportunity is not considered in this sub-theme but is quantified in the Smart Systems sub-theme as a business opportunity related to vector coupling.[31]
- **Fuel cells for vehicles** are a potentially significant business opportunity and are considered within the Transport sub-theme.
- **Export of equipment which combusts hydrogen** including hydrogen boilers, or, for example, equipment associated with hydrogen-based steel production. Where relevant and sizeable, these opportunities are considered in the Heating and Cooling, and Industry sub-themes.

There are wider opportunities associated with a UK hydrogen economy. These are not quantified in this analysis and may not directly support UK jobs. Nonetheless, they may be significant. Notable opportunities include:

- **Indirect business opportunities:** The ability to manufacture and export low-carbon steel, or broader service strengths the UK could export (such as the

[30] UK Hydrogen and Fuel Cell Industry website http://www.ukhfca.co.uk/the-industry/
[31] Energy Research partnership (2016) Potential Role of Hydrogen in the UK Energy System http://erpuk.org/wp-content/uploads/2016/10/ERP-Hydrogen-report-Oct-2016.pdf

supply of financing and insurance for large-scale hydrogen infrastructure projects) may be significant but are out of scope of the EINA analysis.

- **Indirect service opportunities:** The strategic consulting opportunities around repurposing of natural gas infrastructure, or financial services for hydrogen projects, may be available to the UK if it leads on the hydrogen transition. However, these are not directly impacted by technical UK innovation and are not considered in detail.
- **IP licensing:** The UK has a strong hydrogen research base, with over 35 academic and contract research groups active in hydrogen and fuel cells.[32] By this metric, the UK is the second most active country in hydrogen and fuel cell research in Europe after Germany.[33] Building on this research strength, expert evidence suggests a potential business model is to license IP for foreign production. While this may present a significant business opportunity, it is not considered in detail in this analysis, given the focus on the potential for UK-based GVA and jobs.

The business opportunities analysis is set out as follows

- An overview of the global market, with a focus on markets for exports
- A discussion of the UK's competitive position, with a focus on exports
- A discussion of the business opportunities from exports
- A discussion of the UK business opportunities in the UK's domestic market, including a comparison of the relative importance of export and domestic opportunities

[32] UK Hydrogen and Fuel Cell Industry (as above).
[33] E4tech (2019), confidential sources.

Box 7. **The UK's current hydrogen and fuel cell industry**

- UK strengths include EPCm services, catalysis, electrochemistry, materials design, electrochemical diagnostics, and systems optimisation.
- UK producers include: Johnson Matthey, an international engineering company with speciality in manufacturing membrane electrode components; Ceres Power, which is designing fuel cell technologies; ITM Power, a manufacturer of electrolysers suited for operation in distributed applications, such as refuelling stations; Ricardo, a global engineering consultancy that has provided design and integration support, especially to vehicle companies deploying hydrogen technology; Shell, who operate hydrogen refuelling stations; and Siemens, who have demonstrated electrolysis projects in the UK.[34]
- Key competitors include Germany, the US, and China.

Market overview

The global hydrogen industry is currently immature, with only niche demand for hydrogen as an energy carrier. Although hydrogen is used at significant scale for various industrial processes, such as fertiliser production, hydrogen use as an energy carrier remains in its infancy. To illustrate, in 2018 there were just over 300 active hydrogen refuelling stations worldwide, with Germany and Japan contributing over half.[35] This contrasts with over 30,000 natural gas refuelling stations globally and over 100,000 petrol stations in the US alone.[36] Like its use in transport, hydrogen is not yet used at a meaningful scale as an energy carrier in other sectors.

Although hydrogen use is expected to grow, its use as an energy carrier will likely remain small compared to, for example, electricity or bioenergy. Hydrogen provides a low-carbon alternative to fossil fuels and can either be directly combusted or used in fuel cells to produce electricity. The IEA Energy Technology Perspectives (ETP) expects final hydrogen demand to be a modest 418 PJ by 2050

[34] Siemens (2018) website https://www.siemens.co.uk/en/news_press/index/news_archive/2018/siemens-develops-worlds-first-energy-storage-demonstrator-to-deliver-carbon-free-power-of-the-future-.htm
[35] (US data) Energy.gov (2018) Fact of the month https://www.energy.gov/eere/fuelcells/fact-month-18-01-january-29-there-are-39-publicly-available-hydrogen-fueling-stations
(International data) Hydrogen Tools (2018) International hydrogen fuelling stations https://h2tools.org/hyarc/hydrogen-data/international-hydrogen-fueling-stations
[36] NGV Global (2018) Current Natural Gas Vehicle Statistics http://www.iangv.org/current-ngv-stats/

(2-degree scenario). As a point of comparison, this is roughly 1% of final energy supply from biomass and waste demand in 2050.[37]

However, there is significant variation in the projected use of hydrogen globally by 2050. The IEA ETP scenarios used across the EINA analysis project a variation of 66 PJ – 640 PJ depending on climate action, with virtually all hydrogen used in transport. There has, however, been increased interest in the potential role of large-scale hydrogen production, trade, and use in the energy system in recent years. Global scenarios beyond the IEA include significantly more bullish projections for hydrogen demand. For example, the Shell Sky scenario projects total hydrogen use of 8,740 PJ by 2050, an order of magnitude greater than the IEA projections. In this scenario, significant hydrogen volumes are used in power and industry, as well as transport. Box 8 below gives a brief discussion of the reasons behind this large discrepancy.

Box 8. **Reasons for significant uncertainty on the global hydrogen market**

- High hydrogen demand, as included in the Shell Sky scenario, is partly driven by a handful of developed countries choosing to deeply decarbonise on a hydrogen pathway, likely partly driven through a cohesive hydrogen policy across sectors.
- Various hydrogen technologies are complementary, and hence countries or regions are likely to either switch meaningfully to hydrogen across several sectors, or only use hydrogen in limited (mostly heavy-duty transport) applications.
- This relatively binary choice leads to the order of magnitude difference in demand projections. This contrasts with, for example, renewable electricity technologies, which are expected to be deployed to a significant degree by most countries, relatively independently of the degree of policy action.

Driven by hydrogen demand and use, the global market for stationary fuel cell technologies, hydrogen production technologies, and associated services, could grow to over £35 billion by 2050. However, the market may be limited to only £1 billion. This large discrepancy is driven by the uncertainty around hydrogen use in the global energy mix, illustrated by the difference in the IEA ETP and Shell Sky scenarios. The market value of stationary fuel cells is expected to dominate the

[37] This is based on the IEA Energy Technology Perspectives 2017 (2 degrees scenario). This is consistently used across all EINA subthemes.

other markets, primarily because of the high capex (£/MWh of hydrogen) associated with fuel cells compared to hydrogen generation equipment. Services associated with the design and construction of plants are expected to represent 10-15% of the market value, and hence could represent a multi-billion-pound market.[38] Note, the presented market size excludes fuel cells for transport, a significant market, which is considered in the Transport sub-theme.

Much of the fuel cell market is likely to be accessible to UK exporters, unlike a significant proportion of hydrogen production equipment. Given the immaturity of the market for hydrogen production equipment and stationary fuel cells, the tradability is difficult to establish. However, based on analogous sectors we assume the following:

- **Hydrogen production equipment** is assumed to be as tradeable as combustion equipment for power generation (35%). This implies a tradeable market of approximately £4 billion annually by 2050 (in a high-demand scenario).

- **EPCm Services** related to the design and management of the construction of complex hydrogen production sites are assumed to be 100% tradeable, which implies a tradeable market of approximately £2 billion (in a high-demand scenario). Services such as maintenance are not considered in the analysis as these are typically not traded.

- **Design and advisory services** related to research and development services, including fuel cell systems integration, and technical and business services. These are assumed to be 100% tradable. This implies a tradeable market of approximately £3 billion (in a high-demand scenario).

- **Stationary fuel cells** are assumed to be as tradeable as vehicles produced in the UK (80% traded).[39] This implies a traded market of £15 billion annually by 2050 (in a high-demand scenario).

[38] Akin to the ratio of the value of these services to capex in broader high capex projects in industry (specifically oil and gas).
[39] Based on SMMT data.

Figure 1 **The current and future markets**

Current market for hydrogen and stationary fuel cells

- *Production:* Current industry immature with only niche hydrogen use as an energy carrier.
- *Trade:* Low trade volume driven by small market, with growing trade in advisory services.
- *Markets:* Immature UK and export market, but emerging UK export and demonstration projects.

Tradability of market

- *Goods:* Fuel cells expected to be highly traded; for larger projects a significant share of capex likely domestically supplied.
- *Services:* Engineering, procurement, and construction management (EPCm) contracts are highly traded, with installation, operation and maintenance likely domestically supplied.
- *Trends:* International trade in goods and services is expected to grow sharply as the market grows.

Trends in deployment

- *Global:* Hydrogen and stationary fuel cell production is expected to grow from a minimal base.
- *Growth pattern:* The global market will drive growth rather than the EU market.
- *Uncertainty:* Substantial uncertainty in final hydrogen demand, with some forecasts over 10x others by 2050.

Global and regional market size to 2050

- *Growth trend:* Stronger growth post-2030 as technologies become established, but expected growth is heavily dependent on ambition of forecasts.
- *Key markets:* 10% of global demand expected to be in the EU market, with 90% of global demand located in the rest of the world market.

Source: Vivid Economics

UK competitive position

The UK has growing strength in electrolysis as a means of hydrogen generation. The UK has demonstrated deployment of electrolyser-based refuelling stations and has two of the largest hydrogen refuelling stations by volume in Europe.[40] In addition, UK-based electrolysis companies are competitive overseas and have won contracts to construct major facilities in Europe.[41] These developments demonstrate the UK has the capability to innovate and export hydrogen production equipment. However, workshop evidence and low export volumes suggest that the domestic supply chain is at an early stage of development overall.[42] The speed at which it develops, and its ability to continue innovating, will determine the UK's future competitive position in a growing global industry.

For wider hydrogen generation technology, the UK has relevant research strength in gasification-based routes, and its bioenergy sector may also

[40] E4tech (2016) Hydrogen and fuel cells: opportunities for growth. A roadmap for the UK http://www.e4tech.com/wp-content/uploads/2016/11/UKHFC-Roadmap-Final-Main-Report-171116.pdf
[41] ITM power (2018) World's largest hydrogen electrolysis in Shell's Rhineland refinery http://www.itm-power.com/news-item/worlds-largest-hydrogen-electrolysis-in-shells-rhineland-refinery
[42] Based on COMTRADE data.

support hydrogen competitiveness.[43] As summarised in Table 19, the UK is a significant exporter (and has significant market share) in existing equipment that is applicable to hydrogen production, indicating a good possibility of capturing market share in the future. Specifically, the UK's strengths in the later stages of bioenergy gasification-based routes, such as syngas clean-up, can help the UK establish a competitive position in hydrogen generation equipment, such as biomass gasification. However, there is uncertainty around the split between hydrogen generation technologies that will be used to meet future hydrogen demand. For example, some recent reports have suggested that biomass and coal routes to hydrogen may be substantially less important than natural gas reforming by 2050.[44]

The UK has existing strength in stationary fuel cells. UK firms are well positioned in the EU market, with three UK companies among a relatively small number participating in the stationary fuel cell market.[45] Leading international producers are in strategic partnerships with UK firms, suggesting domestic firms are at the forefront of fuel cell development.[46] The UK supply chain is competitive in specialist fuel cell components such as the membrane electrode assembly.[47] In addition, workshop evidence indicates UK engineering consultancies have recently won sizeable advisory contracts overseas. The above, combined with UK's established research expertise, suggest there is potential for the UK to establish a competitive fuel cell sector, capturing significant market share.

Service exports represent a competitive strength for the UK, creating business opportunities within the hydrogen sector. UK firms have provided engineering, procurement, and construction management (EPCm) services for hydrogen production facilities worldwide, especially for natural gas.[48] Akin to the existing UK EPCm strength in the oil and gas sector, driven by UK firms gaining experience with UK deployment and growing to serve clients globally, UK deployment of hydrogen production technologies could unlock a significant service opportunity for the UK.[49] Our analysis includes an 11% market share for UK EPCm service providers, equal to

[43] Note, the UK is not thought to be competitive in gasification itself but has relevant competitive strength in processes within this conversion route. See the Biomass and Bioenergy sub-theme EINA for more discussion on this.
[44] Energy Transitions Commission (2018) Mission Possible https://www.ineteconomics.org/uploads/general/ETC_MissionPossible_FullReport.pdf
[45] E4tech (2016) Hydrogen and fuel cells: opportunity for growth. Mini roadmaps (appendix to roadmap report).
[46] Ceres Power http://www.cerespower.com/news/latest-news/strategic-partnership-with-bosch/
[47] E4tech (as above).
[48] Amec Foster Wheeler website (this company is now part of another British company, the Woods Group) https://wfww.amecfw.com/sectors/refining/refining-technologies/hydrogen.
[49] Oil and Gas Authority (2016) Supply Chain Strategy https://www.ogauthority.co.uk/media/2834/supply_chain_strategy_1016.pdf

the UK market share in O&G services currently.[50] In addition, we include a 9% market share for design and broader technical services, based on the UK's current market share of these types of services in the world market.[51] Further explanation of our methodology can be found in Appendix 2.

The extent to which existing strengths can be leveraged into large future market shares is uncertain given the sector's immaturity. It partly depends on the type of hydrogen production that is widely deployed**.** Under a scenario with more limited deployment of biomass and coal routes to hydrogen, UK strength in the later stages of gasification-based routes will have a more limited influence on the UK's competitive position in the global hydrogen industry in 2050. More broadly, the immaturity of the overall sector means the UK is well positioned to capture a meaningful market share of EU and global markets. However, unlike some other sectors, the UK's current strength is not based on large established supply chains and could be lost relatively easily as the sector develops.

The key international competitors for the UK are Germany, China, and the US, while Japan and South Korea also have a strong presence.[52] Trade data at the lowest level of aggregation is used, along with expert evidence, to determine the UK's key international competitors.[53] Germany is the leading exporter to the EU market, with key competitiveness in gas generators (e.g. syngas reactors), which is assumed to indicate gasification strength, as well as electrical machinery for electroplating, electrolysis, and electrophoresis, which indicates electrolysis strength. Germany captured a market share of 25% in the EU for this electrical machinery trade category, which compares to a 6% market share for the UK. Germany is also competitive in the rest of the world market, but not dominant, with market shares of between 5%-15% for key technologies. China has strong international competitiveness in electrical machinery for electroplating, electrolysis, and electrophoresis.

[50] EY (2018) Review of the UK oilfield services industry 2018 Link: https://www.ey.com/Publication/vwLUAssets/EY-review-of-the-UK-oilfield-services-industry-January-2017/$FILE/EY-Review-of-the-UK-oilfield-services-industry-January-2017.pdf
[51] This 9% share is across all sectors, based on WTO service trade data.
[52] Market shares use UN Comtrade data for existing technologies that will be applicable to the hydrogen industry. HS codes used are 8405, 841989, 841990, 842139, 730900, 741999, 761100, 854330, 8501, and 850300.
[53] Trade data is not disaggregated at the level of hydrogen production equipment and fuel cells and does not exist for technologies which have not reached commercialisation. Therefore, the HS codes used are for analogous and similar equipment.

Figure 2 **The UK's competitive position in trade in goods**

Current UK competitiveness	**Key competitor – Germany**
• *Shares (NGR, coal gasification, electrolysis, stationary fuel cells):* • EU ~ *7%, 8%, 7%, 2%.* RoW ~ *3%, 4%, 1%, 2%.* • *Strengths:* Strength in stationary fuel cell research and IP, and some areas of gasification. • *Weaknesses:* Unlikely to manufacture finalised fuel cells.	• *Shares (NGR, coal gasification, electrolysis, stationary fuel cells):* EU ~ 31%, 33%, 42%, 20%. RoW ~ *14%, 12%, 14%, 10%.* • *Strengths*: Has a leading position in electrolysis in the EU and rest of the world markets
Competitor–United States	**Competitor–China**
• *Shares (NGR, coal gasification, electrolysis, stationary fuel cells):* EU ~ *5%, 3%, 14%, 4%.* RoW ~ *17%, 18%, 6%, 8%.* • *Strengths*: Gasification strength, which has led to a strong export position in this area. • *Weaknesses:* Limited presence in the EU market for key gasification and stationary fuel cell technologies.	• *Shares (NGR, coal gasification, electrolysis, stationary fuel cells):* EU ~ *3%, 1%, 9%, 14%.* RoW ~ *15%, 14%, 21%, 29%.* • *Strengths:* Growing strength in the stationary fuel cell industry. • *Weaknesses:* Limited gasification goods exports to the EU market.

Note: *Market shares based on analysis of HS Codes: 730900, 741999, 761100, 840510, 840590, 841989, 841990, 842139, 8501, 850300, and 854330.*

Box 9. **Industry workshop feedback on hydrogen business opportunities**

- Attendees felt UK competitiveness will be strongly driven by domestic deployment. Without domestic demonstration of technologies, then retaining competitiveness and innovating will be challenging.
- There was consensus that the UK had to move now if it was going to have good business opportunities in hydrogen and fuel cells. Given developments in other countries, a UK delay would likely mean loss of competitiveness.
- Innovation can unlock good opportunities for IP exports. The UK supply chain may adopt a business model in which the UK licenses offshore manufacturing.
- The UK has strong business opportunities in services, with the UK's leading engineering consultancies expected to offer services in the industry. However, there are also good opportunities to export specialised components.
- There was no consensus on opportunities to export hydrogen fuel. There could be some opportunities to export hydrogen to Europe, but the UK is likely to be a net-importer overall.

Table 19. **Export market shares and innovation impact – hydrogen and fuel cells**

Component	Tradeable market 2050 (£bn)	Current market share of related goods and services	2050 outlook with strong learning by research			
			Market share	Captured turnover (£m)	Captured GVA from exports (£m)	Rationale for the impact of innovation on exports of related equipment and services
Natural gas reforming equipment	**EU: 0-0.2** RoW: 0.1-1.8	**EU: 7%** RoW: 3%	**EU: 15%** RoW: 7%	**Total: 5-150**	**Total: 2-60**	The UK market share increases significantly, to half that of Germany's current market share. Driven by innovating to access cost reductions and the potential to capture high value in this technology from cross-over with commercialisation of carbon capture and storage (CCS).
Coal gasification equipment	**EU: 0-0.1** RoW: 0-1	**EU: 8%** RoW: 4%	**EU: 16%** RoW: 6%	**Total: 2-80**	**Total: 1-30**	The UK market share increases significantly, to half that of Germany's current market share. Driven by innovating to access cost reductions and the potential to capture high value in this technology from cross-over with commercialisation of carbon capture and storage (CCS).
Electrolysis equipment	**EU: 0-0.1** RoW: 0-1	**EU: 7%** RoW: 1%	**EU: 10%** RoW: 3%	**Total: 2-50**	**Total: 1-20**	Driven by the UK leveraging its research strength in electrochemistry and materials design, the UK's 2050 market share increases significantly, to a quarter of Germany's current market share. This increase reflects UK strength but also strength of the competition.
Stationary fuel cells equipment	**EU: 0-1.3** RoW:0.5-14	**EU: ~0%** RoW: ~0%	**EU: 5%** RoW: 3%	**Total: 15-430**	**Total: 4-120**	The UK captures a significant market share, driven by the UK supply chain innovating in specialised components which will enable it to become part of a large global value chain. 5% reflects a quarter of Germany's current market share.

Services						
Natural gas reforming services	**EU: 0-0.1** RoW: 0-0.8	**n/a**	**EU: 11%** RoW: 11%	**Total: 3-100**	**Total: 2-50**	The service opportunity associated with these hydrogen production routes is expected to centre on EPCm services. The UK's ability to capture EPCm-related services is assumed to be similar across different routes. A market share of 11.8% is thought to be feasible, based on the UK's market share for similar services in the oil and gas sector.
Coal gasification services	**EU: 0** RoW: 0-0.4	**n/a**	**EU: 11%** RoW: 11%	**Total: 2-60**	**Total: 1-30**	
Electrolysis services	**EU: 0** RoW: 0-0.4	**n/a**	**EU: 11%** RoW: 11%	**Total: 2-60**	**Total: 1-30**	
Stationary fuel cells services	**EU: 0-0.2** RoW:0.1-2.6	**n/a**	**EU: 9%** RoW: 9%	**Total: 9-260**	**Total: 5-140**	For fuel cells, the service opportunity is expected to primarily revolve around research, design, and wider technical services. Based on the UK's current market share in this category (across all sectors), a 9% 2050 market share is thought feasible.

Note: ***The indicated range for the tradeable market 2050 and impact on UK GVA is based on the IEA ETP 2-degree scenario (low) and the Shell Sky scenario (high).*** *The possible market share of the UK, and rationale for the impact of innovation, are based on stakeholder input gathered in 2 workshops. Key technologies cannot be perfectly matched against trade data because it is not available at the required level of disaggregation. Therefore, current market shares are indicative of the most disaggregated UN COMTRADE category the technology sits within. A subset of the following HS codes was used for each technology depending on applicability: 730900, 741999, 761100, 840510, 840590, 841989, 841990, 842139, 8501, 850300, and 854330.*

Source: Vivid Economics, see Appendix 2 for further methodological notes

UK business opportunities from export markets

Box 10. **Interpretation of business opportunity estimates**
The GVA and jobs estimates presented below are *not* forecasts, but instead represent estimates of the potential benefits of the UK capturing available business opportunities. The presented estimates represent an unbiased attempt to quantify opportunities and are based on credible deployment forecasts, data on current trade flows, and expert opinion, but are necessarily partly assumption-driven. The quantified estimates are intended as plausible, but optimistic. They assume global climate action towards a 2 degree world and reflect a UK market share in a scenario with significant UK innovation activity.[54] More information on the methodology, including a worked example, is provided in Appendix 2, and a high level uncertainty assessment across the EINA subthemes is provided in Appendix 4.

The UK can capture a significant market share, but the business opportunities from hydrogen related export are highly dependent on the future global hydrogen demand. As discussed above, this demand is highly uncertain, with an order of magnitude difference between various credible global energy scenarios. It is possible that the UK develops a competitive industry, and establishes a large market share, but business opportunities from exports remain modest because of a small export market size. The EINA analysis consistently uses IEA ETP scenarios across sub-themes. However, an additional scenario with relatively widespread global hydrogen use is thought credible, and hence business opportunities associated with this (Shell Sky) scenario are presented in parallel below.

In a high-hydrogen scenario, growth of UK exports in hydrogen production equipment, EPCm services, design and expert advisory services, and fuel cells could support around £0.5 billion GVA and 3,600 jobs each year by 2050. Increased final hydrogen demand in 2050 leads to business opportunities in hydrogen production as well as stationary fuel cells (equipment and design and expert advisory services). The opportunities around stationary fuel cells are expected to be the largest, as shown in Figure 3. This is driven by the annual market for stationary fuel cells (see Table 19), which is an order of magnitude larger than the market for various hydrogen production technologies. The presented business

[54] Note, other IEA climate scenarios were also used as a sensitivity. Where the level of global climate action has a meaningful impact on market size, this is highlighted in the market overview section. Full results are available in the supplied Excel calculator.

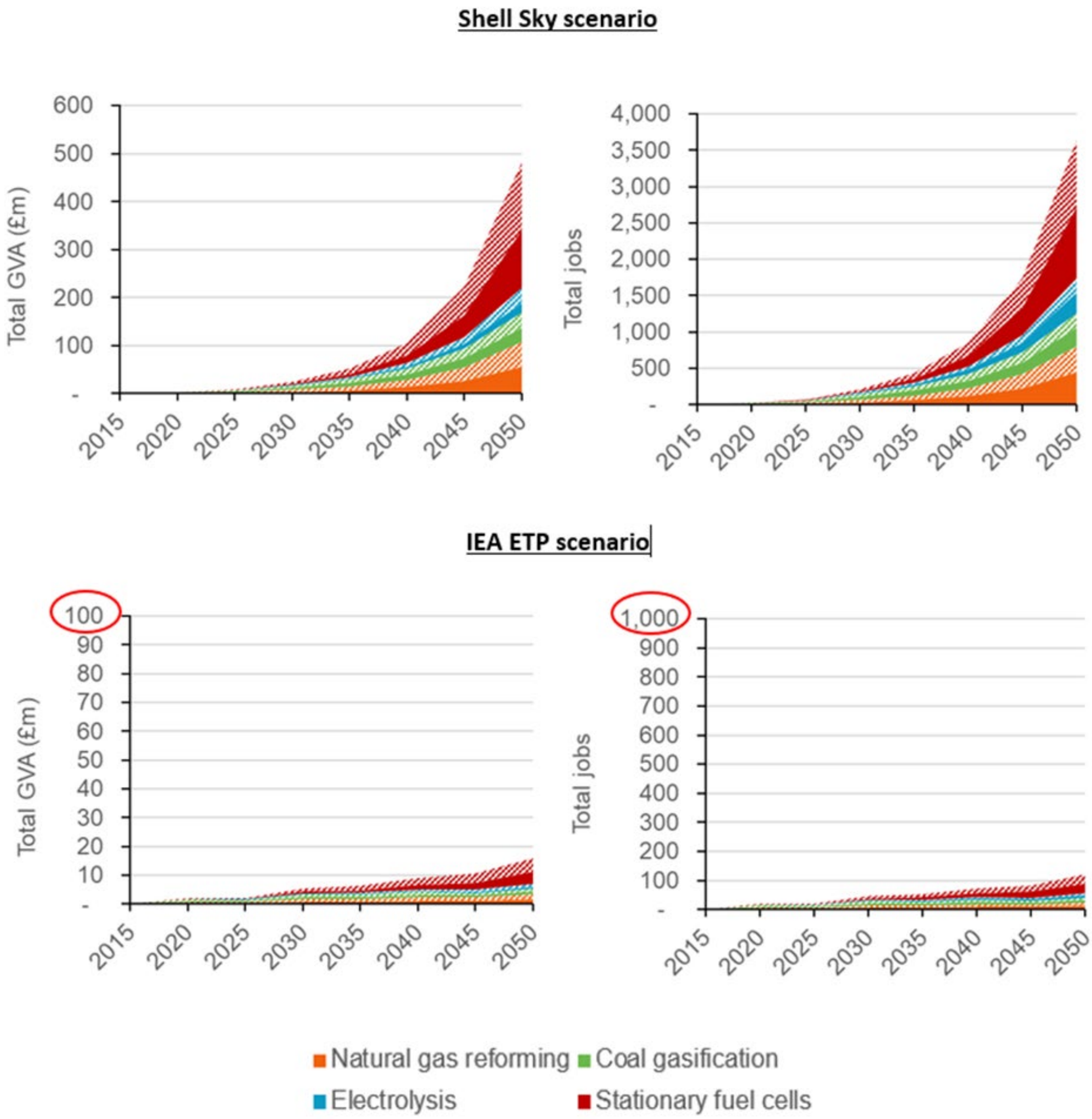
opportunities are also reliant on the UK capturing a significant share of the market, representative of the UK attaining a position as a world leader in hydrogen-related technology.[55]

The business opportunity for service export is approximately half of the overall opportunity. Figure 3 includes the service opportunity within the technologies. As discussed above, tradeable services represent approximately 10%-15% of the overall project value, but given not all capex is traded, services are a relatively larger share of the tradeable market. Furthermore, given the UK's relative strength in services, they are a key part of the final business opportunity.

It is possible that hydrogen business opportunities (from export) are significantly smaller, potentially supporting fewer than 1,000 jobs. The size of the export opportunity is directly dependant on the degree to which other countries develop a hydrogen economy. It is plausible that no European country meaningfully switches to hydrogen use (beyond HDVs in transport). As Europe is the market where the UK is likely able to capture the greatest market share, this scenario implies that UK business opportunities are limited. Figure 3 shows UK export opportunities if global hydrogen demand is as projected in the IEA ETP 2-degree scenario. In this case, the annual opportunity for UK exports is expected to be significantly less than £100 million in GVA.

[55] As a point of reference, the indicated 2050 market shares are half those of Germany's current market shares in similar equipment and likely correspond to the UK as one of the top 5 (top 3 for natural gas reforming and coal gasification) exporters.

Figure 3 **GVA and jobs supported per annum from exports by scenario and components – hydrogen and fuel cells**



Note: ***The solid line represents equipment opportunities, the patterned line represents service opportunities.*** *For hydrogen production equipment, EPCm services are included, while for stationary fuel cells, design and advisory services are included.*

Source: *Vivid Economics*

UK business opportunities from domestic markets

Discussion

The transition of the economy to low-carbon energy carriers and technologies can drive domestic business opportunities in hydrogen and fuel cells. If the UK is to meet the UK Government's net-zero 2050 target,[56] deep decarbonisation is required across all sectors of the economy. As a low-carbon energy carrier, hydrogen can be a key enabler in the transition to low-carbon, with wide-ranging applications across many sectors of the economy including heat, industry, transport and power. The Energy Systems Catapult estimate sizeable hydrogen production of 160TWh in the UK by 2050, equivalent to 10% of the UK's energy consumption in 2017;[57,58] under a net-zero decarbonisation pathway hydrogen production could be greater, especially if used to enable the decarbonisation of heat. This substantial hydrogen production can drive business opportunities for UK firms across production equipment, services, and hydrogen infrastructure.

This report includes natural gas with carbon capture and storage and electrolysis routes to hydrogen, with biomass routes treated in the biomass and bioenergy sub-theme report. Unlike the export analysis, the domestic business opportunities do not include coal gasification routes to hydrogen because coal routes are not included in current government climate strategy. The CCC also indicated that coal gasification is not a viable option for low-carbon hydrogen production in the UK because it offers limited emissions saving compared to reforming natural gas at a significant cost.[59,60]

In addition to the technologies considered in the export analysis, the domestic opportunities include installation and O&M services, and hydrogen infrastructure. The export analysis excludes installation and O&M services because of low tradability. Furthermore, comparable to natural gas, hydrogen will require extensive infrastructure if it is to be highly adopted across the economy. The

[56] CCC (2019) Net Zero The UK's contribution to stopping global warming https://www.theccc.org.uk/wp-content/uploads/2019/05/Net-Zero-The-UKs-contribution-to-stopping-global-warming.pdf
[57] Catapult Energy Systems (2018) Clockwork & Patchwork – UK Energy System Scenarios https://es.catapult.org.uk/wp-content/uploads/2018/10/Options-Choices-Actions-Updated-Low-Res..pdf
[58] BEIS (2018) Energy Consumption in the UK https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/729317/Energy_Consumption_in_the_UK__ECUK__2018.pdf
[59] In the ESME modelling, coal routes to hydrogen with carbon capture and storage comprise less than 10% of overall hydrogen production in 2050. Given the UK's 2050 net-zero target and the government's exclusion of coal routes from future strategy, this analysis transfers all coal gasification hydrogen production in the ESME modelling to natural gas routes. This has a small effect on overall business opportunities.
[60] CCC (2018) Hydrogen in a low carbon economy.

domestic business opportunities divide hydrogen infrastructure into three technology families:

- **The delivery** of hydrogen refers to the transportation of hydrogen from the point of production to the point of consumption. The domestic analysis quantifies the business opportunities associated with new transmission pipelines and compressor stations for a hydrogen transmission network, the repurposing of the existing natural gas distribution network for hydrogen use, and tube trailers.
- **Storage** is focused on the seasonal storage of hydrogen in underground salt caverns.
- **Refuelling stations** refer to road vehicle refuelling stations primarily for hydrogen use in heavy duty vehicles. Uncertainty in future transport hydrogen demand drives uncertainty in refuelling station business opportunities.

Given the cross-cutting nature of hydrogen, several hydrogen end-use opportunities are captured in other sub-themes rather than hydrogen and fuel cells. In particular:

- Hydrogen boilers and heat pumps are covered in the *heating and cooling sub-theme*.
- Hydrogen use for synthetic fuel production is covered in the *disruptive sub-theme report*.

There are wider opportunities associated with a UK hydrogen economy. These are not quantified in this analysis and may not directly support UK jobs. Nonetheless they may be significant. Notable opportunities include:

- **Indirect business opportunities:** The ability to manufacture low-carbon steel, or broader service strengths (such as the supply of financing and insurance for large-scale hydrogen infrastructure projects) may be significant but are out of scope of the EINA analysis.
- **Indirect service opportunities:** The strategic consulting opportunities around repurposing of natural gas infrastructure, or financial services for hydrogen projects, may be available to UK firms. However, these are not directly impacted by technical UK innovation and are not considered in detail.

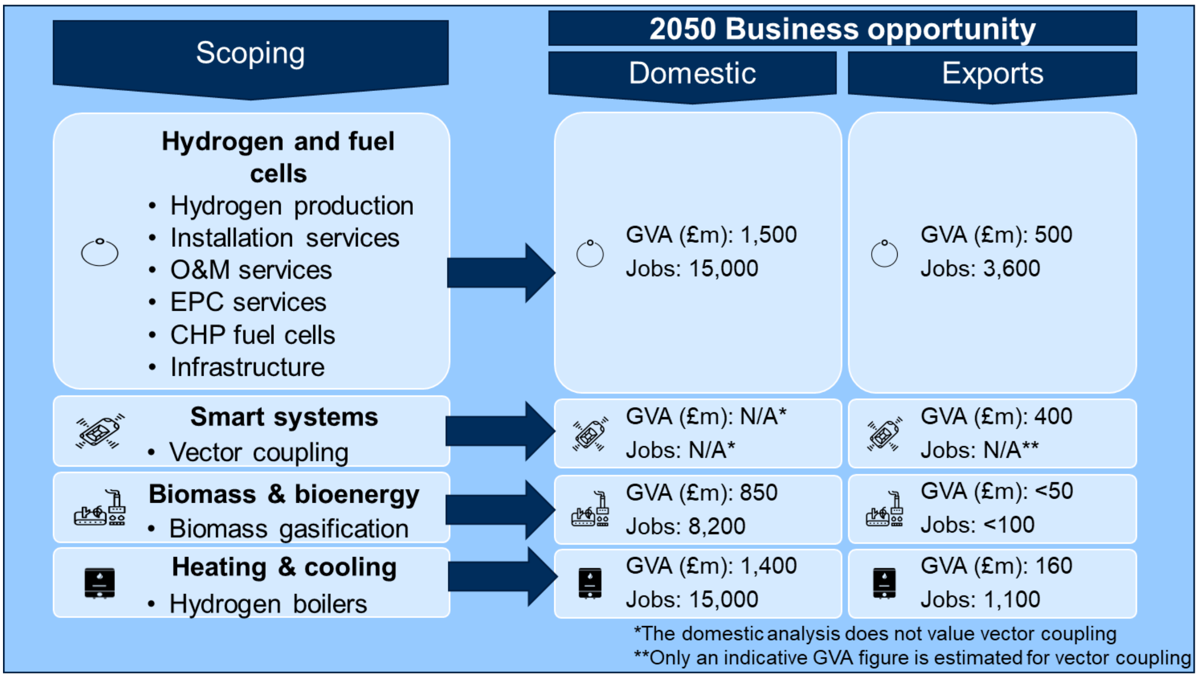
UK firms can build on existing strengths in materials design, CCS technology and niche high-value components to drive domestic business opportunities. The UK can leverage emerging strength in hydrogen technology research to capture a high domestic market share for tradeable technologies, whilst continuing to capture all untraded market value. Across the technologies considered, the shares UK firms capture of the domestic market are outlined in Table 20, and detailed below:

- **Natural gas reforming with CCS equipment:** The UK domestic share for equipment used in the natural gas routes to hydrogen grows from a low base to 47% by 2050, in line with the current domestic share for combustion equipment used in power generation.[61,62]
- **Electrolysis equipment:** The UK domestic share for electrolysis equipment grows from a low base to 78% by 2050, in line with current shares for comparable mature technologies.[63] This UK captured value is comprised of 60% non-traded value and 40% traded.
- **Stationary fuel cell equipment:** The UK domestic share for stationary fuel cell equipment grows from a low base to 73% by 2050, in line with current shares for comparable mature technologies.[64] This UK captured value is comprised of 27% non-traded value and 73% traded.
- **Hydrogen infrastructure equipment:** The UK domestic share of hydrogen infrastructure equipment is 15% by 2050. This domestic share remains constant up to 2050 because the primary suppliers for hydrogen infrastructure equipment operate in mature industries, for example steel used in pipelines in hydrogen transmission and distribution.
- **O&M and installation services:** These services have low tradability; the analysis assumes a 95% domestic market share to allow for minor imports.
- **EPCm services:** The UK captures 77% of the domestic market for EPCm management services across hydrogen technologies, in line with the current domestic share for EPCm services in the oil & gas sector. This market share is assumed to remain constant up to 2050 as leading engineering consultancy strength in the UK continues.

Overall hydrogen and fuel cell domestic business opportunities across all EINA sub-themes can support £3.7 billion in GVA and 37,000 jobs per annum by 2050, as shown in Figure 4. This includes hydrogen and fuel cell opportunities scoped under other sub-themes, for example biomass to hydrogen routes. Hydrogen boilers, especially their installation, drives the largest overall domestic hydrogen and fuel domestic opportunity, supporting £1.4 billion in GVA and 15,000 jobs by 2050. There are also some more speculative opportunities that are not quantified, for example utilising offshore wind for hydrogen production, which if realised, could drive an increase in the overall domestic business opportunity. For a more detailed list of the overall hydrogen and fuel cell business opportunities see Appendix 3.

[61] For the equipment used in natural gas and coal routes to hydrogen, domestic production and trade data codes are not well-matched, leading to an unreliable calculation for domestic market share.
[62] Domestic share for equipment used in power generation combustion equipment uses UK investment in combustion equipment in 2017 (calculation uses BEIS' figures) and subtracts combustion equipment imports using HS codes: 840681, 840682, 841620, 842139, 850161, 850162, 850163, 850164
[63] Uses HS code 854330 and SIC code 28491283. The HS code refers to Electrical machines and apparatus; for electroplating, electrolysis or electrophoresis whilst the SIC code refers to Machines and apparatus for electroplating, electrolysis or electrophoresis.
[64] Uses HS code 8501 (WITS database) and SIC code 27.11 (ONS Business Survey 2017)

Figure 4 **Hydrogen and fuel cell business opportunities across EINA sub-themes**



Source: Vivid Economics

Domestic business opportunities within the hydrogen and fuel cells sub-theme could support £1.5 billion in GVA and 15,000 jobs per annum by 2050, as shown Figure 7 and Figure 8. These opportunities are strongly reliant on the relatively high domestic hydrogen production in the ESME modelling. As discussed in the export analysis, there is great uncertainty around future hydrogen demand. If a low hydrogen scenario is realised domestic business opportunities will be far smaller.

Domestic business opportunities are greater than export opportunities up to 2050, as shown Figure 5 and Figure 6. By 2050, the domestic hydrogen and fuel cell market can support £1.5 billion in GVA and 15,000 jobs each year, which exceed export opportunities of £0.5 billion in GVA and 3,600 jobs.[65] The greater available service value in domestic opportunities drives this increase over exports; equipment contributes around one half of all opportunities in the export analysis, but only a third in the domestic analysis. If domestic O&M and installation services were to be excluded, export opportunities would be double domestic opportunities.

Services are the primary driver of domestic hydrogen and fuel cell business opportunities, supporting £1.1 billion in GVA and 10,000 jobs per annum by

[65] The domestic business opportunities are compared to the export opportunities associated with the Shell Sky scenario. If the IEA ETP scenario is instead used as the comparator, domestic business opportunities would be substantially greater than exports. See the export business opportunities section in the hydrogen and fuel cell sub-theme for a detailed discussion of the Shell Sky scenario versus the IEA ETP scenario.

2050, as shown in Figure 7 and Figure 8. These service opportunities are spread across all hydrogen technologies, with O&M, installation and EPCm services comprising all services value.

Production equipment for the domestic market supports £130 million in GVA and 1,100 jobs per annum by 2050. The smaller market and likely substantial imports for hydrogen production equipment drive the lesser business opportunities in hydrogen production equipment compared to services in the domestic market.

The hydrogen transmission and distribution network can support £330 million in GVA and 3,300 jobs per annum by 2050. Despite the substantial costs associated with the construction of a new hydrogen transmission network and the repurposing of the natural gas distribution network for hydrogen, opportunities in transmission and distribution comprise only around 20% of the overall total. There are three key drivers of these relatively small opportunities:

- **Final hydrogen demand** is around 50% of current final natural gas demand in ESME modelling by 2050; therefore, it's unlikely the hydrogen transmission and distribution network would be completed by 2050, with many infrastructure business opportunities after 2050.
- **UK market share** is relatively low for pipeline components at 15%, reducing business opportunities for UK firms.
- **Construction smoothing** enables the costs of construction and repurposing of infrastructure to be spread over decades, resulting in small annual opportunities relative to the overall lifetime opportunity.

Quantitative results

Table 20. **Domestic market shares and innovation impact - hydrogen and fuel cells**

Technology	Domestic market 2050 (£bn)	Current share of related UK market	2050 outlook with strong learning by research			
			Market share (%) *	Domestic turnover captured (£m)	GVA (£m)	Rationale for the impact of innovation on domestic deployment of related equipment and services
Natural gas reforming with CCS equipment	0.7	N/A	47%	330	120	The UK market shares grows to 47% by 2050, in line with the UK's current domestic market share in combustion equipment for power generation. The UK leverages early-stage strength in carbon capture and storage technologies and high-value manufacturing to innovate in hydrogen production with CCS technologies.
Electrolysis equipment	<0.1	N/A	78%	<10	<10	The UK market share grows to 78% by 2050, in line with current share in comparable mature technologies. UK strength in design, electrochemistry and materials science drives innovation in electrolysis equipment.
Stationary fuel cell equipment	0.1	N/A	73%	60	20	The UK market share grows to 73% by 2050, in line with the current share in comparable mature technologies. The UK leverages early-stage strength in stationary fuel cells, particularly solid-oxide fuel cells

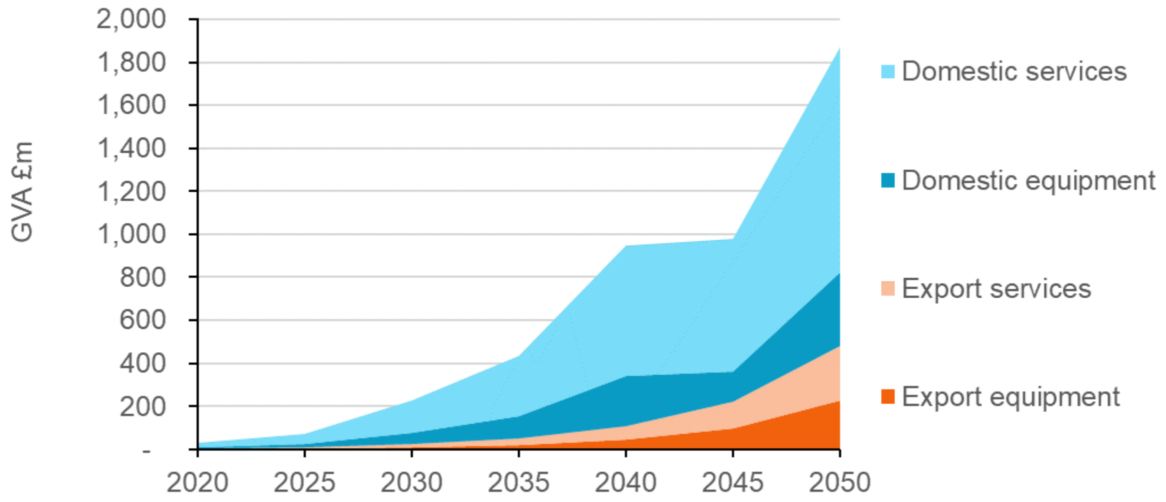
Technology	Domestic market 2050 (£bn)	Current share of related UK market	2050 outlook with strong learning by research			
			Market share (%) *	Domestic turnover captured (£m)	GVA (£m)	Rationale for the impact of innovation on domestic deployment of related equipment and services
						to drive innovation and capture substantial market share in high-value components.
Hydrogen refuelling station equipment	0.1	N/A	15%	20	10	The UK market share grows to 15% by 2050 for hydrogen refuelling station and tube trailer equipment with the UK possessing limited strength in equipment for hydrogen delivery.
Tube trailer equipment	<0.1	N/A	15%	<10	<10	
Underground storage equipment	0.6	N/A	79%	440	180	The UK market share grows to 79% by 2050 for underground storage equipment with the UK possessing strength in equipment for the construction of long-term hydrogen storage salt caverns.
Transmission system equipment	0.2	N/A	15%	35	10	The UK market share grows to 15% by 2050 for the hydrogen transmission and distribution networks with the UK possessing limited strength in equipment for pipeline materials.
Hydrogen distribution network equipment	0.5	N/A	15%	80	20	
O&M services	1.3	N/A	95%	1,200	640	Given the low tradability of these services, this analysis assumes a 95% domestic market share.

Technology	Domestic market 2050 (£bn)	Current share of related UK market	2050 outlook with strong learning by research			
			Market share (%) *	Domestic turnover captured (£m)	GVA (£m)	Rationale for the impact of innovation on domestic deployment of related equipment and services
Installation services	1.1	N/A	95%	1,100	380	Given the low tradability of these services, this analysis assumes a 95% domestic market share.
EPCm services	0.1	N/A	77%	110	60	The UK captures 77% of EPCm services associated with hydrogen technologies, in line with the existing EPCm domestic share in the oil & gas sector. The UK builds on leading engineering consultancy strength to successfully expand into hydrogen technologies.

Note: * Future market shares are not a forecast, but what UK business opportunities could be potentially in the context of the EINAs. The possible market share of the UK, and rationale for the impact of innovation, are based on PRODCOM analysis and additional market research. N/A indicates data is not available.
Biomass gasification routes to hydrogen are considered in the biomass and bioenergy sub-theme; hydrogen boilers and heat pumps are considered in the heating & cooling sub-theme; synthetic fuels are considered in the disruptive technologies sub-theme; vector coupling is considered in the smart systems sub-theme

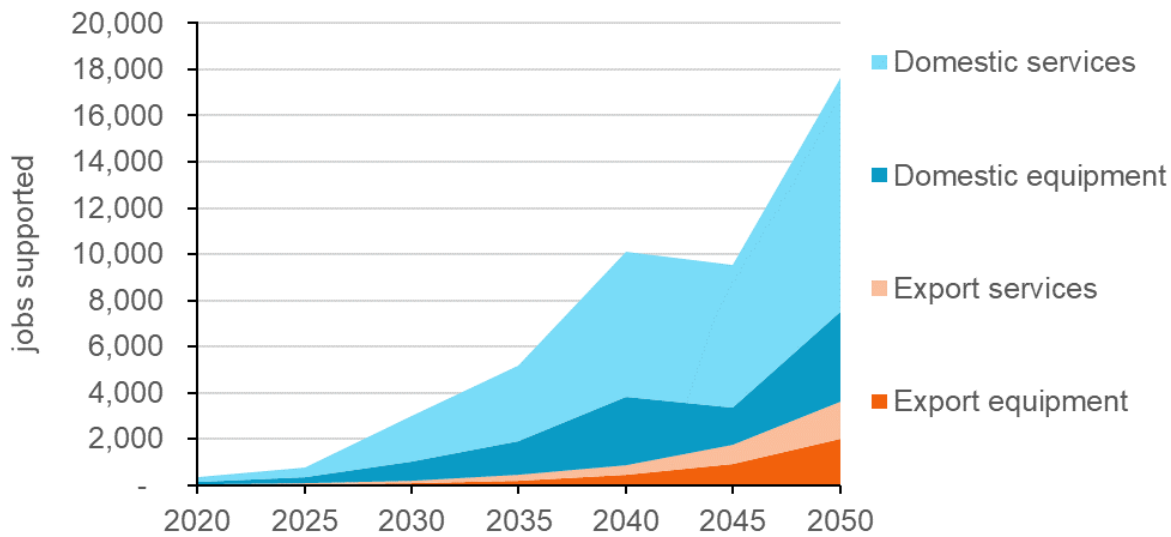
Source: *Vivid Economics*

Figure 5 **GVA per annum from export and domestic markets – hydrogen and fuel cells**



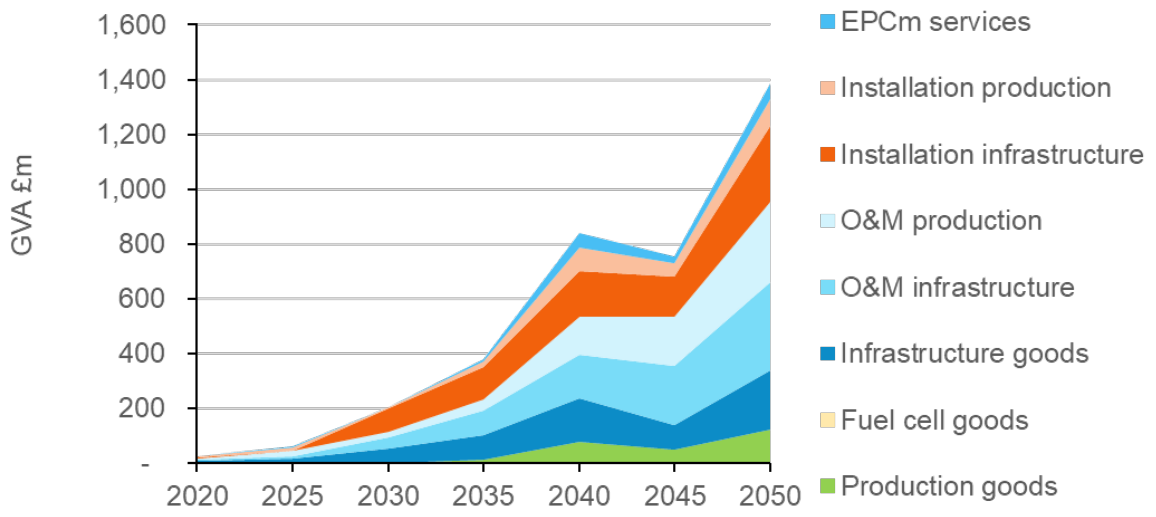
Source: Vivid Economics

Figure 6 **Jobs supported per annum from export and domestic markets – hydrogen and fuel cells**



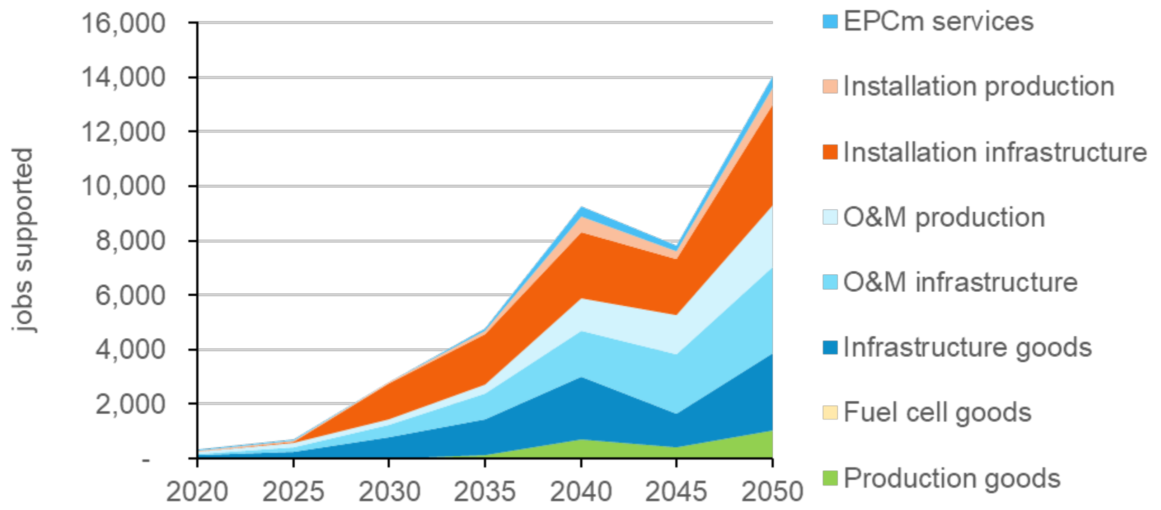
Source: Vivid Economics

Figure 7 **GVA per annum from domestic markets by component – hydrogen and fuel cells**



Source: *Vivid Economics*

Figure 8 **Jobs supported per annum from domestic markets by component – hydrogen and fuel cells**



Source: *Vivid Economics*

Business opportunity deep dive: Stationary fuel cells

Strong expected growth in the global fuel cell market represents a significant business opportunity for the UK supply chain. This is true for both stationary fuel cells and those used in transport. Fuel cells used in transport are covered in the Transport EINA. Given fuel cell technology is in the development and preparation stage globally, innovation is required, especially to reduce capex, for the UK to capture share in a future market.[66] UK companies have already indicated their ability in this area by designing, building, testing, and demonstrating UK-produced fuel stacks.[67] In addition to the fuel cell IP that has been discussed, this capability is a good platform to capture market share as the fuel cell industry matures.

Although the UK supply chain is unlikely to be a big global player in finalised fuel cells, innovation can drive exports of specialised components.[68] The UK has existing strength and IP in specialist components for fuel cells, such as pumps, valves, sensors, and control technologies.[69] These are high-value components which the UK can export internationally, representing a sizeable business opportunity for it if domestic firms can gain access to global value chains.

The UK can leverage its strong engineering consulting base, and fuel cell industry, to supply fuel cell advisory services globally. Traditionally, the UK is competitive in supplying advisory services across all industries, and more recently, fuel cells. UK firms have won contracts abroad, such as in the growing Californian fuel cell market, to offer expert advisory services.[70] Although the international nature of many UK consulting companies leads to GVA and jobs being outside the UK too, it is likely the transfer of knowledge within the company, and reputational boost from winning these types of contracts, will also increase domestic prospects.

UK strengths in catalysis can support UK competitiveness in fuel cell exports. The UK has recognised strengths in catalysis.[71] UK firms already supply catalysts to the processing industry to produce hydrogen from hydrocarbons.[72] The UK can similarly supply to a growing hydrogen industry. Furthermore, experts suggest

[66] TINA (2014) Technology Innovation Needs Assessment Hydrogen for Transport https://www.carbontrust.com/media/593904/h2-for-transport-summary-report.pdf
[67] FCHEA (2019) United Kingdom Fuel Cell Industry Developments http://www.fchea.org/in-transition/2019/2/11/united-kingdom-fuel-cell-industry-developments
[68] E4tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth. A roadmap for the UK http://www.e4tech.com/wp-content/uploads/2016/11/UKHFC-Roadmap-Final-Main-Report-171116.pdf
[69] H2FC Supergen (2017) The Economic Impact of Hydrogen and Fuel Cells in the UK http://www.h2fcsupergen.com/wp-content/uploads/2015/08/J5214_H2FC_Supergen_Economic_Impact_report_WEB.pdf
[70] Ricardo (2018) https://ricardo.com/news-and-media/press-releases/ricardo-helps-toyota-create-second-fuel-cell-electric-zero-emissions-truck
[71] Engineering and Physical Sciences Research Council website https://epsrc.ukri.org/research/ourportfolio/researchareas/catalysis/
[72] H2FC Supergen (as above).

licensing IP internationally may provide a good opportunity for UK firms. This business opportunity is reliant on the UK supply chain being at the forefront of fuel cell innovation.

Market barriers to innovation within hydrogen and fuel cells

Introduction

Box 11. **Objective of the market barrier analysis**

Market barriers prevent firms from innovating in areas that could have significant UK system benefits or unlock large business opportunities. Market barriers can either increase the private cost of innovation to levels that prevent innovation or limit the ability of private sector players to capture the benefits of their innovation, reducing the incentive to innovate.

Government support is needed when market barriers are significant and they cannot be overcome by the private sector or international partners. The main market barriers identified by industry are listed in Table 21, along with an assessment of whether HMG needs to intervene.

Market barriers to innovation for hydrogen and fuel cells

Table 21 lists the main market barriers for hydrogen and fuel cells, along with an assessment of whether the government needs to intervene. For each identified market barrier, an assessment of the need for government intervention is provided. The assessment categories are low, moderate, severe, and critical.

- **Low** implies that without government intervention, innovation, investment, and deployment will continue at the same levels, driven by a well-functioning industry and international partners.
- **Moderate** implies that without government intervention, innovation, investment, and deployment will occur due to well-functioning industry and international partners, but at a lower scale and speed.
- **Severe** implies that without government intervention, innovation, investment, and deployment are significantly constrained and will only occur in certain market segments or must be adjusted for the UK market.
- **Critical** implies that without government intervention, innovation, investment, and deployment will not occur in the UK.

Table 21. **Market barriers**

Market barriers for hydrogen and fuel cells	Relevant for	Need for HMG support
Lack of clear signals, regulatory requirements, and commercial incentives creates uncertainty around the size of the future hydrogen market, which discourages innovation and deployment	All components	Critical
Uncertainty in deployment of CCS is a barrier to low-carbon hydrogen being produced from fossil fuel sources.	Natural gas reforming, coal gasification	Critical
Insufficient infrastructure to respond to market demand. There is a lack of available and functioning hydrogen refuelling stations.	Refuelling stations	Moderate
Limited supply chain capacity for fuel cell production in the UK due to inability to scale up (e.g. time required to produce components reduces ability to respond to market demand, limits deployment)	Fuel cells	Moderate
Perception that hydrogen is unsafe may present a barrier to deploying it at scale in the future (more severe for deployment in heat)	All components	Moderate
High capital costs, unclear route to market, and low investor awareness about potential of hydrogen increases cost of accessing finance and limits opportunities for deployment at scale.	Natural gas reforming	Moderate
Co-benefits, including improved air quality insufficiently incorporated into consumption decisions	All components	Low

Source: Vivid Economics analysis and stakeholder input

Box 12. **Industry workshop feedback**

Industry experts raised several areas that require government support:

- **A consistent and credible policy position is needed to support deployment of hydrogen and fuel cells.** Without certainty, incentives for firms to invest in developing new technology with returns far into the future are low. A coordinated set of signals, regulatory requirements, and commercial incentives would reduce uncertainty about the size of the future hydrogen market. As an example of successful policy support, industry referenced California's policy to provide financial incentives for purchasing alternative-fuel vehicles to stimulate deployment.[73]

- **Uncertainty in deployment of CCS is a barrier to hydrogen production.** Without policy intervention on CCS, investment in low-carbon hydrogen production from gas reforming and coal gasification is unlikely.

- **There is insufficient shared infrastructure in the sector to respond to transport market demand.** This includes a lack of available and functioning hydrogen refuelling stations. This barrier has been recognised by HMG, which provided funding for refuelling infrastructure and hydrogen fuel cell electric vehicles.[74]

- **Supply chain capacity for fuel cell production in the UK is limited, due to its inability to scale up.** The time required to produce components reduces the ability of the sector to quickly respond to increasing market demand.

- **High capital costs, combined with an unclear route to market and low investor awareness about the potential of hydrogen, increase the cost of accessing finance.** Investors have little awareness and understanding of hydrogen in general. Workshop participants reported that this reduces confidence in the sector, contributing to keeping costs high.

- **Perception that hydrogen is unsafe, and insufficient recognition of co-benefits such as improved air quality, are a severe barrier.** They may become more problematic for deploying hydrogen at scale in the future.

International opportunities for collaboration

International collaboration is key to successful technology development programmes. Replacing parallel development of work streams with coordinated R&D efforts can contribute significantly to reducing timescales and optimising resources. This is especially true in times of tight public funding budgets.

International collaboration could allow the UK to share the full cost of innovation with other countries. Currently there is a mix of government- and private sector-led collaborations in hydrogen innovation. HMG is part of international fora on hydrogen including Mission Innovation, Hydrogen Energy Ministerial, Clean Energy Ministerial, and the G20.[75] In the private sector, UK firms collaborate internationally through the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).[76] Potential coordination between domestic and international fuel cell companies could be established by joining supply chains and sharing procurement of materials and components (e.g. refuelling bottles).[77]

Opportunities exist to learn from policy approaches in other countries. For example, tight industry-government coordination resulted in the recent launch of the first hydrogen-powered train in Germany.[78] In Japan, the world's first commercial hydrogen-powered fuel cell car was released in 2014 with government support. South Korea has recently set serious decarbonisation targets and committed to a series of steps that will develop a national hydrogen economy. The hydrogen roadmap presented in January 2019 outlines the South Korean government's strategy in multiple hydrogen sectors, spanning across production, delivery, and utilisation.[79]

Appendix 1: Organisations at expert workshop

- BEIS

[73] Alternative Fuels Data Center (n.d.) Hydrogen Laws and Incentives in California https://afdc.energy.gov/fuels/laws/HY?state=CA
[74] For example, see: ITM Power (2018) £8.8M OLEV funding for refuelling infrastructure and FCEVS http://www.itm-power.com/news-item/8-8m-olev-funding-for-refuelling-infrastructure
[75] Mission Innovation: http://mission-innovation.net/ ; Hydrogen Energy Ministerial: http://web.apollon.nta.co.jp/h2em2018/eng/ ; Clean Energy Ministerial: http://www.cleanenergyministerial.org/ ;
[76] See: https://www.fch.europa.eu/
[77] See: E4Tech (2016) Hydrogen and Fuel Cells: Opportunities for Growth http://www.e4tech.com/wp-content/uploads/2016/11/UKHFC-Roadmap-Final-Main-Report-171116.pdf
[78] WEF (2019) These countries are pioneering hydrogen power https://www.weforum.org/agenda/2019/01/these-countries-are-pioneering-hydrogen-power-d941536b-4206-4fa1-8932-8596d7b856bd/
[79] Fuel Cells Works (2019), Korean Government Announces Roadmap to Become the World Leader in the Hydrogen Economy https://fuelcellsworks.com/news/korean-government-announces-roadmap-to-become-the-world-leader-in-the-hydrogen-economy/

- Cadent
- Ceres Power
- Costain
- Engie
- European Marine Energy Centre (EMEC)
- Imperial College London
- Ineos/Inovyn
- Innovate UK
- Intelligent Energy
- ITM Power
- Johnson Matthey
- Kiwa
- Linde/BOC
- Logan Energy
- National Grid
- Scotia Gas Networks (SGN)
- Siemens
- UK Hydrogen and Fuel Cell Association
- University of South Wales Hydrogen R&D Centre
- Welsh Government

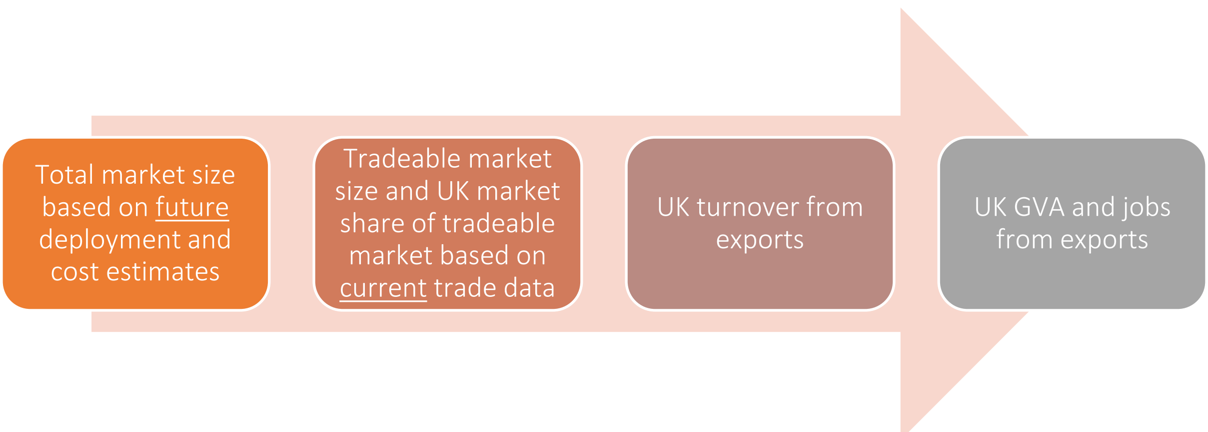
Appendix 2: Business opportunities methodology

Methodology for export business opportunity analysis

In identifying export opportunities for the UK, the EINA process uses a common methodology to ensure comparability of results:

- The **global and regional markets** to 2050 are sized based on deployment forecasts, which come from the IEA when available. For example, deployment of nuclear power is multiplied by costs to obtain annual turnover for the nuclear market.
- The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the global market is likely to be accessible to exports and gives a figure for the tradeable market.
- The UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below.
- The tradeable market is multiplied by the market shares to give an estimate for **UK-captured turnover**.
- The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by productivity figures for that sector to obtain **jobs created**.

Figure 9 **Methodology for assessing export opportunities**



Source: *Vivid Economics*

For all EINA sub-themes, the assessment of the UK's future competitive position is informed by the UK's existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback.

Export business opportunities for goods

- Current market shares of UK goods are evaluated based on existing trade data, where available. If the technology is immature or export levels are low, UK shares are based on trade data from trade in related goods.
- Based on the importance of innovation in unlocking markets, the UK is projected to reach a market share in the EU and RoW by 2050. The potential future market share is intended as an ambitious, but realistic, scenario. It is triangulated using:
    - Market shares of competitor countries, as a benchmark for what is a realistic share if a country is 'world leading'.
    - The maturity of the existing market, which affects the likelihood of market shares changing significantly.
    - The importance of innovation in the technology.
- Market share assumptions are validated at a workshop with expert stakeholders and adjusted based on stakeholder input.

Export business opportunities for services

- The EINA focus on service exports directly associated with the technology and innovations considered within the sub-theme. For example, this could include EPCm services around the construction of an innovative CCS plant, but it will not include more generic service strengths of the UK, such as financial services.
- The EINA methodology does not quantify opportunities associated with installation and operation and maintenance as these are typically performed locally. Exceptions are made if these types of services are specialised, such as in offshore wind.
- The key services to consider are based on desk research and verified through an expert workshop.
- The services considered in the CCUS EINA export analysis are EPCm services, transport and storage services.

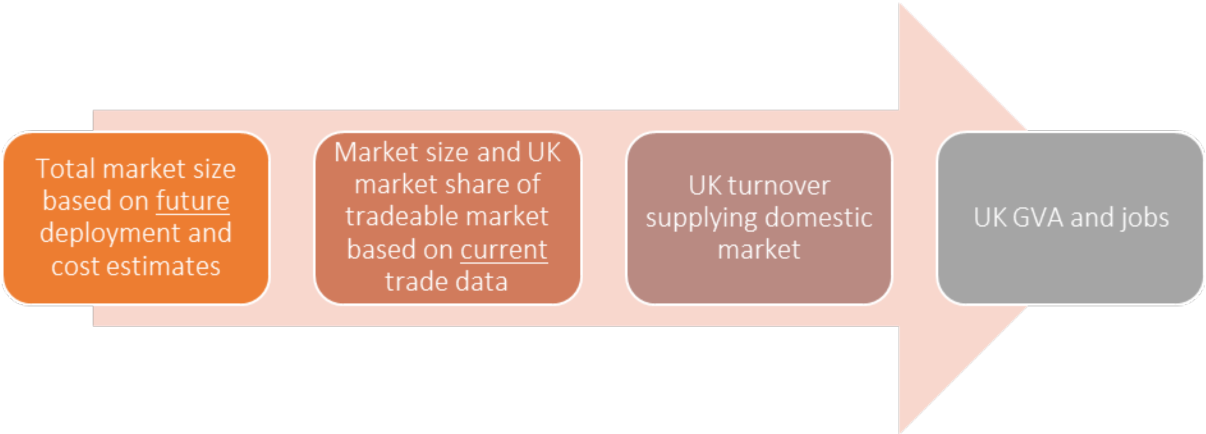
Methodology for domestic business opportunity analysis

To estimate the size of domestic business opportunities for the UK, the EINA methodology, as developed to size export opportunities, is adapted. The domestic analysis leans heavily on insight gleaned from the export analysis, particularly in estimating UK competitiveness and ability to capture market share in its domestic market. To estimate the domestic opportunity, the following methodology is used:

- The **domestic market** to 2050 is sized based on deployment and cost estimates. Deployment estimates are based on ESME modelling used for the EINAs and cost estimates are equal to those from the export work, and based on analysis for each of the EINA sub-themes.[80] For example, deployment of nuclear power is multiplied by costs to obtain annual turnover for the nuclear market.
- The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the UK's market is likely accessible for foreign firms (e.g. electric vehicles), and how much is likely to be exclusively provided by UK companies (e.g. heat pump installation).
- For the traded share of the UK market, the UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below.
- To estimate **UK captured turnover** the traded and non-traded markets are summed.
    - The UK's captured turnover of the UK traded market is estimated by multiplying the tradeable market by the UK's market share.
    - The UK's turnover from the non-traded market is equal to the size of the non-traded market.
- The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by productivity figures for that sector to obtain **jobs supported**.

[80] For detail on cost estimates used, please refer to the Excel calculators provided for each sub-theme, and the individual sub-theme reports.

Figure 10 **Methodology for assessing domestic business opportunities**



Source: Vivid Economics

For all EINA sub-themes, the assessment of the UK's future competitive position is informed by the UK's existing market share of goods and services, the market share of competitors, industry trends, and workshop feedback.

Domestic business opportunities for goods

- Current market shares of UK goods are evaluated based on existing trade (import) and domestic production data, where available. If the technology is immature, UK shares are based on trade data from trade in related goods.
- Based on the importance of innovation in unlocking markets, the UK is projected to potentially increase its market share in its domestic market. This estimate is informed by the previously performed export analysis. It is triangulated using:
    - Market shares of competitor countries, as a benchmark for what is a realistic share if a country is 'world leading'.
    - The maturity of the existing market, which affects the likelihood of market shares changing significantly.
    - The importance of innovation in the technology.

Domestic business opportunities for services

- The EINA focus on service exports directly associated with the technology and innovations considered within the sub-theme. For example, this could include EPCm services around the construction of an innovative CCS plant, but it will not include more generic service strengths of the UK, such as financial services.
- The domestic assessment explicitly quantifies services such as O&M and installation, which are typically not traded but can support a large number of

jobs associated with e.g. heat pumps. For these services, the estimate of potential service jobs supported is based on:
    - An estimate of the total turnover and GVA associated with the service
    - A ratio of GVA/jobs (adjusted for productivity increases) in analogous existing service sectors based on ONS data.
- The key services to consider are based on desk research, verified through stakeholder workshops.

Worked example

1. The **global and regional markets** to 2050 are sized based on illustrative deployment forecasts, which come from ESME when available.[81] For example, deployment of nuclear power (37 GW by 2050) is multiplied by O&M costs (~12% of total plant costs) to obtain annual turnover for the nuclear O&M market (~£2.5 billion by 2050).
2. The **tradability** of the market is estimated based on current trade data, where available, and informed by expert judgement. This determines how much of the global market is likely to be accessible to exports and gives a figure for the tradeable market. In the case of nuclear O&M, tradability is 0% being as it is not tradeable. For the domestic analysis, tradability does not directly feed into our model, but is vital to provide insight on the share of the domestic market UK firms will capture.
3. The UK's **market share** under a high-innovation scenario is estimated based on current trade data, research, and expert consultation. The determination of these shares is discussed in more detail below. For example, for nuclear O&M the UK domestic market share is 100% because the component is not tradeable and therefore foreign firms do not capture some of the value.
4. The tradeable market is multiplied by the market shares to give an estimate for **UK-captured turnover**. For nuclear O&M, market turnover (~£2.5 billion) is multiplied by the UK market share (95%) of O&M to obtain UK-captured turnover (~£2.5 billion by 2050).
5. The captured turnover figure is multiplied by a GVA / turnover multiplier which most closely resembles the market to obtain **GVA**. The GVA figure is divided by labour productivity figures for that sector to obtain **jobs supported**. For example, appropriate Standard Industrial Classification (SIC) codes are chosen for nuclear O&M. This leads to a GVA / turnover multiplier (49%) that is multiplied by market turnover (~£2.5 billion) to isolate GVA (~£1 billion by 2050), which is then divided by labour productivity (~70,000 GVA / worker by 2050) to isolate jobs supported (~16,000 jobs by 2050).

[81] If deployment information is not available from the IEA, alternative projections from, for example, Bloomberg are used. Please see individual sub-theme reports for further detail.

Additional notes

The below lists areas where the analysis under the EINA Hydrogen and Fuel Cells subtheme deviates from the general approach and highlights any major caveats.

Hydrogen refuelling station deployment: ESME forecasts for hydrogen vehicles on UK roads up to 2050 were multiplied by the current ratio of petrol stations to petrol cars in the UK to determine hydrogen refuelling station deployment.[82]

Tube trailer deployment: Given ESME modelling indicates small electrolysis use up to 2050 in the UK, this analysis assumes that a centralised hydrogen production location provides all the hydrogen dispensed at hydrogen refuelling stations. Although this may be a simplification, it results in a relatively small change to the overall business opportunities. In our analysis, either pipelines or tube trailers deliver hydrogen to refuelling stations. Average capacity of a hydrogen refuelling station (200kg/day[83]) is multiplied by the number of hydrogen refuelling stations to determine overall station capacity; this capacity is divided by average tube trailer capacity (500kg[84]) to determine what tube trailer deployment would be in the absence of pipelines. To get actual tube trailer deployment, tube trailer deployment in the absence of pipelines is multiplied by hydrogen transmission and distribution infrastructure as a proportion of existing natural gas infrastructure to get actual tube trailer deployment. Accordingly, as pipelines expand, tube trailer deployment falls.

Underground hydrogen storage deployment: The modelling multiplies final hydrogen demand (TWh) up to 2050 in the UK by the current ratio of underground natural gas storage to final natural gas demand to determine underground hydrogen storage deployment.[85] Underground natural gas storage in the UK is low compared to other European countries, for example Germany. However, there is no prospect of substantial increases, and therefore the ratio of natural gas underground storage to final natural gas demand is deemed appropriate for hydrogen. If hydrogen becomes extensively used to meet peak winter demand, storage requirements and therefore

[82] The Petrol Retailers Association provided the number of petrol cars on the UK's road in 2017 https://www.ukpra.co.uk/en/about/facts-and-figures
Rapleys provided the number of petrol stations in the UK in 2017 https://rapleys.com/news/the-uk-petrol-station-market-whats-happening/
[83] Source E4tech. This capacity is chosen to align with cost estimates used later in the model to ensure consistency.
[84] Hydrogen Europe website https://hydrogeneurope.eu/hydrogen-transport-distribution
[85] Final natural gas demand comes from HMG https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/729395/Ch4.pdf
Underground natural gas storage comes from Ofgem https://www.ofgem.gov.uk/system/files/docs/2019/01/181207_storage_update_website.pdf

deployment may substantially increase. Accordingly, underground storage business opportunities in this analysis should be considered a lower bound.

Hydrogen transmission network deployment: As in other studies, this analysis assumes that an entirely new hydrogen transmission network will need to be built.[86] Hydrogen transmission network (km) in any given year is equal to the ratio of final hydrogen to current final natural gas demand multiplied by the natural gas transmission network (in km).[87]

Hydrogen distribution network: The existing natural gas distribution network can be repurposed for hydrogen. The total capital expenditure to repurpose the natural gas grid is assumed to be ~£22 billion.[88] This cost is divided by final natural gas demand to calculate a repurposing cost/TWh of demand. This ratio is multiplied by final hydrogen demand 5 years into the future to determine deployment of the hydrogen distribution network in any given year. As with the transmission network, a future hydrogen demand is used because infrastructure is likely to lead demand.

[86] Element Energy (2018) Hydrogen supply chain evidence base https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf
[87] The calculation to determine hydrogen transmission network deployment in any given year uses final hydrogen demand 5 years into the future; this assumption is made as infrastructure is likely to lead demand.
[88] Element Energy (2018) Hydrogen supply chain evidence base https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760479/H2_supply_chain_evidence_-_publication_version.pdf

Appendix 3: Overall hydrogen and fuel cell business opportunities

	Technology	EINAs sub-theme/s	2050 domestic opportunity	2050 export opportunity
H_2 production	Natural gas reforming equipment	Hydrogen and fuel cells	GVA: £120m Jobs: 1,000	GVA: £2-60m Jobs: 10-450
	Coal gasification with CCS	Hydrogen and fuel cells	Out of scope for UK	GVA: £1-30m Jobs: 10-260
	Biomass gasification-based routes' equipment	**Biomass and bioenergy**	GVA: £130m Jobs:1,100	GVA: <1-4m Jobs: <100
	Electrolysis equipment	Hydrogen and fuel cells	GVA: £<10m Jobs:<100	GVA: £1-20m Jobs: 10-290
Fuel cells	Stationary fuel cell equipment	Hydrogen and fuel cells	GVA: £20m Jobs:140	GVA: £4-120m Jobs: 30-990
	Transport fuel cells' equipment	**Road transport**	Out of scope	GVA: £600m Jobs: 4,800
Distribution	Refuelling station equipment	Hydrogen and fuel cells	GVA: £10m Jobs: 100	Out of scope[89]
	Tube trailers	Hydrogen and fuel cells	GVA: <£10m Jobs:<100	Out of scope
	Underground storage equipment	Hydrogen and fuel cells	GVA: £180m Jobs:2,400	Out of scope
	Transmission network pipeline	Hydrogen and fuel cells	GVA: <£10m Jobs:120	Out of scope
	Distribution network pipeline	Hydrogen and fuel cells	GVA: £20m Jobs:250	Out of scope
	Transmission network compressors	Hydrogen and fuel cells	GVA: <£10m Jobs:<100	Out of scope
Services	O&M services	Hydrogen and fuel cells **Biomass and bioenergy** **Heating and cooling**	GVA: £2,000 Jobs: 18,000	Out of scope

[89] Hydrogen distribution and transmission network technologies are out of scope for the export analysis because the IEA ETP or other sources did not provide global estimates for the future size of this market.

	Installation services	Hydrogen and fuel cells **Biomass and bioenergy** **Heating and cooling**	GVA: £840m Jobs: 12,000	Out of scope
	EPCm services	Hydrogen and fuel cells **Biomass and bioenergy**	GVA: £120m Jobs: 750	GVA: £10-120m Jobs: 750
	Fuel cell design and advisory services	Hydrogen and fuel cells	Out of scope	GVA: £5-140m Jobs: 30-910
Miscellaneous	Hydrogen boiler equipment	**Heating and cooling**	GVA: £230m Jobs: 2,000	GVA: £170m Jobs: 1,100
	Hydrogen fuel	**Smart systems**	N/A	GVA: £370m (indicative only)
	Total		**GVA**: **£3,700m** **Jobs**: **38,000**[90]	**GVA**: **£1200-1600m** **Jobs**: **6,800-9,600**

[90] The small discrepancy between the jobs supported in Appendix 3 and those presented in Figure 4 is due to rounding.

Appendix 4: Assessment of business opportunities uncertainty

The assessment of business opportunities in the long term, associated with new technologies is uncertain. This assessment does not attempt to forecast what *will* happen. Instead, the business opportunity assessment attempts to provide a realistic and consistent assessment, based on current information, on the business opportunities that *could* be captured by the UK. Whether these opportunities are indeed realised depends on domestic and international developments, political decisions, macro-economic conditions, and numerous other complex variables.

As this assessment is not intended as a full forecast, a formal quantitative sensitivity analysis has not been performed. the below provides a high-level qualitative assessment of the uncertainty associated with the sized opportunity. Note, this is *not* an assessment of how likely the UK is to capture the opportunity, rather it is an assessment of the uncertainty range around the size of the opportunity. The assessment is based on three key factors driving the assessment

1. *The level of future deployment of the technology*. Technologies such as offshore wind are deployed at scale across different energy system modelling scenarios and hence considered relatively certain. In contrast, there is more uncertainty for e.g. hydrogen related technologies. The export analysis is based on 3 IEA scenarios (with numbers provided for the IEA ETP 2 degree scenario). Domestic analysis is based on a single ESME run used across the EINA process.
2. *The potential domestic market share* the UK can capture. This assessment attempts to estimate a plausible market share for the UK across relevant markets. Where this can be based on longstanding trade relationships and industries, this assessment is considered more robust.
3. *Future technology costs and production techniques* are a key driver of the future turnover, gross value added and jobs associated with a technology. For immature technologies for which manufacturing techniques may, for example, become highly automated in future, future costs and jobs supported by the technology may be significantly lower than assessed.

The ratings in the table below are the judgement of Vivid analysts based on the above considerations. The analysts have worked across all sub-themes and the ratings should be considered as a judgement of the uncertainty around the size of the opportunity relative to other sub-themes. As a rough guide, we judge the uncertainty bands around the opportunity estimates as follows:

- **Green**: Size of the opportunity is clear (+/- 20%). Note, this does not imply the UK will indeed capture the opportunity.
- **Amber:** Size of the opportunity is clear, but there are significant uncertainties (+/- 50%).
- **Red:** There are large uncertainties around market structure and whether the technology will be taken up at all in major markets. The opportunity could be a factor 2-3 larger or smaller than presented.

Table 22. **Assessment of uncertainty in business opportunities across sub-themes**

Sub-theme	Uncertainty rating	Comments
Biomass and bioenergy		• **Deployment**: Moderate deployment uncertainty; BECCS can produce negative emissions that have high value to the energy system under a deep decarbonisation pathway; there is moderate uncertainty as to whether BECCS will be used for hydrogen production, as in the ESME modelling, or for power generation. • **UK market share:** Speculative market share for immature traded equipment, but majority of business opportunities associated with certain untraded services and feedstocks. • **Costs and production techniques:** Relatively certain costs with most opportunities associated with labour input rather than immature technologies.
Building fabric		• **Deployment:** Depends on levels of retrofit that greatly exceed those seen to date. • **Market share:** Speculative for traded. However, majority of market untraded, highly likely captured domestically. • **Costs and production techniques:** High share of labour costs (independent of uncertain tech cost).
CCUS		• **Deployment:** Moderate deployment uncertainty; decarbonisation scenarios anticipate rapid uptake of CCUS, though there are few large-scale facilities today. • **Market share:** Moderate market share uncertainty; the UK is likely to be competitive in the storage of CO2 and EPCm services while component market shares are less certain given numerous technology choices and lack of clear competitors. • **Costs and production techniques:** Moderate cost uncertainty; the lack of large-scale facilities today makes estimating future costs difficult.
Heating and cooling		• **Deployment**: Expected to be deployed in most UK buildings by 2050. • **Market share:** some uncertainties, immaturity in markets such as for hydrogen boilers. • **Costs and production techniques:** Relatively certain given relative maturity of boilers and heat pumps. • **Deployment of hydrogen boilers or heat pumps** lead to similar opportunities for UK businesses, while heat networks present a 50 per cent smaller opportunity per household.

Hydrogen and fuel cells		• **Deployment**: Highly uncertain future deployment with a wide-range of 2050 hydrogen demand estimates across scenarios, particularly for export markets. • **UK market share**: Speculative market share for immature traded equipment, but majority of business opportunities associated with certain untraded services. • **Costs and production techniques:** Although deep uncertainty in future hydrogen production costs, for example electrolysis, most domestic costs are associated with labour input rather than equipment.
Industry		• **Deployment**: Relative certainty in deployment as it is based on the 2050 Roadmaps • **UK market share**: Some uncertainty due to poor quality of trade data that may not be representative of technologies within scope. • **Costs and production techniques:** Some uncertainty in costs, particularly for less mature technologies.
Light duty transport		• **Deployment**: Certainty in deployment; low-carbon vehicles will be required in any deep decarbonisation scenario. • **UK market share**: Speculative market share for a relatively immature market; a small number of uncertain future FDI investment decisions generates high uncertainty in overall business opportunities. • **Costs and production techniques:** Highly uncertain future costs, with substantial falls in battery costs a key enabler of BEV uptake.
Nuclear fission		• **Deployment**: Moderate uncertainty in future deployment with some proposed nuclear plants recently cancelled • **UK market share**: Relatively certain market shares based on robust estimates of current nuclear activity; market share growth is dependent on uncertain development of UK reactor IP; however, most business opportunities are associated with untraded activity or areas where the UK has existing strength • **Costs and production techniques:** Uncertain costs for nuclear new build, with dangers of construction overrun; deep uncertainty in costs for immature nuclear technologies, for example SMRs and AMRs.
Offshore wind		• **Deployment**: Offshore wind will be required in any deep decarbonisation scenario, with clear government commitments. • **UK market share**: Expected growth in current market shares given commitments and progress to date. • **Costs and production techniques:** Costs are relatively certain, with clear pathways to 2050.
Tidal stream		• **Deployment**: Global sites for tidal stream are relatively limited, and hence the potential market size well established. • **UK market share**: Although the market is immature, the UK has a an established (and competitive) position. • **Costs and production techniques:** Costs are relatively certain, although the impact of potential scale production is hard to anticipate.
Smart systems		• **Deployment**: High deployment uncertainty given immaturity of smart system market today and evolving business models and regulatory framework. • **UK market share**: Moderate uncertainty given immaturity of the market today and scalable nature of digital smart

		technologies, though there is UK leadership in aggregation services and V2G charging. • **Costs and production techniques**: Moderate uncertainty of cost reductions of batteries and V2G and smart chargers, though costs are expected to continue to fall.

Source: Vivid Economics

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