UK ECONOMIC OPPORTUNITIES FROM THE GLOBAL ENERGY TRANSITION

Final Report

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CONTENTS

EXECUTIVE SUMMARY

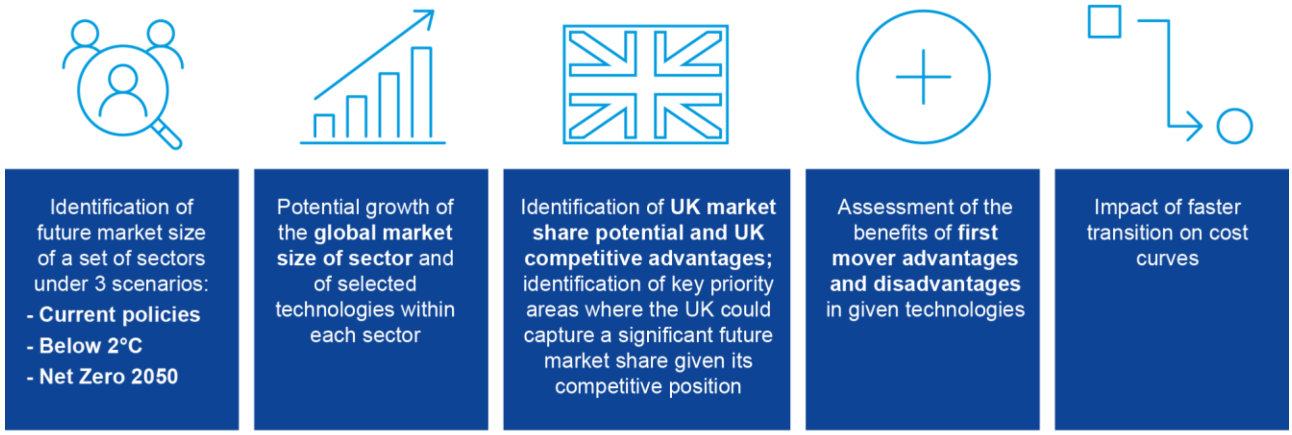
This study aims to provide an overview of the potential market size growth and UK future market share (RQ1) for **seven key sectors for the energy transition** and a selection of technologies within each sector. It reviews and assesses the UK competitive advantages in each sector and technology (RQ2). It also covers analysis of existing evidence through case studies to highlight the benefits and disbenefits of being an early mover in some clean energy technologies (RQ3). Finally, it assesses the impact of a faster transition on cost curves for a selection of sectors (RQ4). The aim is to build the analytical evidence base in these key areas.

Sectors covered under RQ1 and RQ2 are:

1. Renewables
2. CCUS and GGR
3. Hydrogen and biofuels
4. Nuclear
5. Smart systems
6. Heating and cooling
7. Industry

The study has several key objectives which are outlined in Figure ES-1**.**

Figure ES-1: Study objectives



The study covers quantitative analysis at the sector level combined with trade flow and qualitative analysis at the technology level, which is informed by desk research and experts' judgement (see the methodology section for a detailed description of our analytical approach). A summary of the methodological approach is covered in Figure ES-2.

The UK held a general election on 4th July 2024. This report's analysis took place before the election and does not reflect any changes to UK policy since that date.

Figure ES-2: Summary of methodological approach

Quantitative analysis

- At sector level
- Analysis via CGE modelling
- 3 scenarios: Current policies, Below 2°C, Net Zero 2050

Qualitative analysis

- At technology level
- Desk research + expert judgement
- Barriers and enablers, geographical benchmarking

Case studies

- Desk research
- Analysis of historical experiences to draw conclusions valid for the United Kingdom

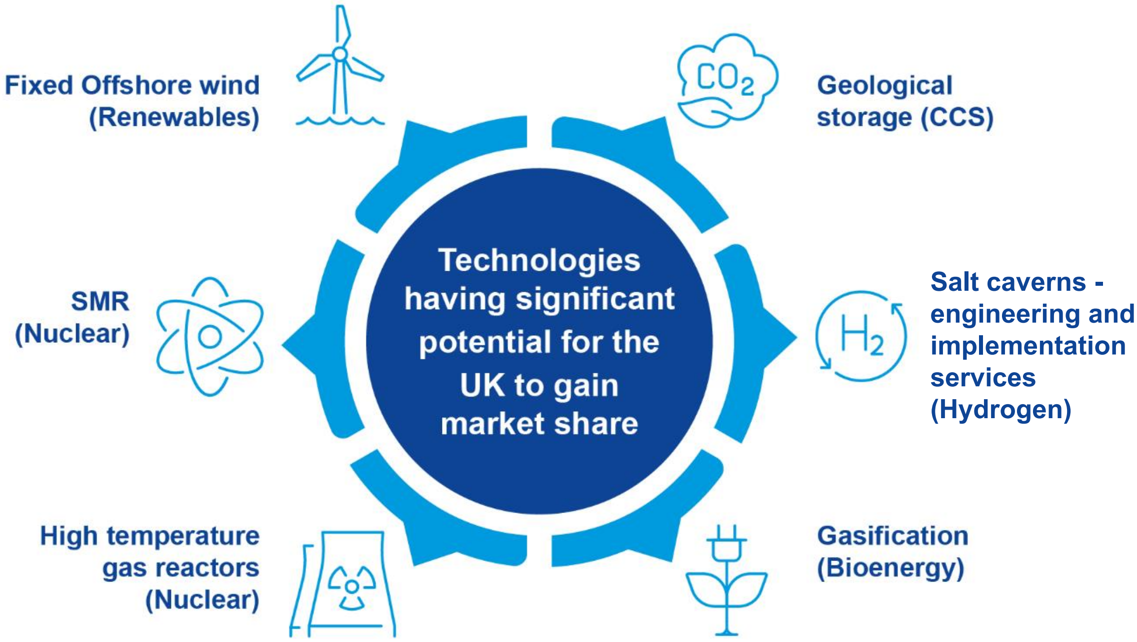
RQ1&2: POTENTIAL MARKET SIZE AND UK MARKET SHARES & UK COMPETITIVE ADVANTAGE – OVERVIEW

Overall, the UK position varies substantially across the technologies and sectors, with the UK in a better position in some compared to others, as expected. While the analysis aims to capture the impact of current policies, some of these are not yet fully implemented or defined, which means it has not been possible to capture their impacts to a substantial level of detail fully. Such instances and their likely impact on the final assessment have been mentioned.

Offshore wind (Renewables), **geological storage (CCS)**, **salt caverns - engineering and implementation services (Hydrogen)**, **gasification (Bioenergy)**, **High Temperature Gas Reactors (Nuclear)**, **and SMR (Nuclear)** were the specific technologies identified as having significant potential for the UK to gain market share given its competitive advantages in these areas.

This assessment is the result of a combination of these technologies being more mature and, therefore, having more developed markets with more certain future growth potential, as well as areas where the UK appears currently to have competitive advantages. Further information on these conclusions and key messages for each sector analysed are reported below. Other technologies analysed show potential and are classified as additional opportunities.

Figure ES-3: Priority focus areas identified



Barriers and enablers of competitive advantage

Regarding general factors that can foster or hamper the UK's relative position across all sectors, international trade plays the most dominant role. Tariff and non-tariff barriers are the main cross-cutting barriers that can impede the UK from gaining important market shares. Conversely, international efforts to overcome trade barriers constitute the most critical enabler.

Below is a list of the most significant barriers and enablers that can affect the broader development & deployment of these technologies at the sector level globally unless explicitly indicated as specific to the UK. Enablers are rated as "green", while barriers are rated as "red" or deemed the most impactful and significant in either direction (supporting a country's development and commercialisation of the technology – enablers. Or hampering a country's ability to increase its exports shares – barriers). This assessment is based on qualitative analysis of available literature and expert judgement. Unless specifically flagged as a UK enabler or barrier, this assessment is at the global level and based on qualitative analysis of available literature and expert judgement.

Table ES-0-1: Key enablers and main barriers at the global sector level

Technology	Key Enablers	Main Barriers
Wind	UK geographical advantage	Slow permitting procedures, vessel shortage, financial instability and contracting risks in offshore wind manufacturing
Tidal	UK geographical advantage	Lack of an immediate route to market, high price differential with other renewable energy technologies, weak financial position of UK companies
CCUS/GGR	Financial incentives, ETS and cost of carbon	Legal and regulatory frameworks, infrastructure for transportation and storage of CO_2
Hydrogen & Biofuels	Decreasing costs and competitiveness	Few offtake agreements, manufacturing capacity bottlenecks in electrolyser technology
Nuclear	Government programs such as the nuclear defence programs	Public perception of safety
Smart systems	Increasing penetration of renewable energy sources into the grid, growing electricity demand, and high offtake of EVs	Data management and cybersecurity concerns
Heating and cooling	Policy and financial support to phase out fossil fuels	Heat pumps are unlikely to be well suited for export markets other than mass-market standardised applications; the UK electricity market has a higher retail power cost than many European competitors
Industry	Installation of pipeline networks for industrial hydrogen use, environmental and climate-change-related commitments, growing environmental awareness of consumers and GDP growth, legal and regulatory frameworks	Challenges in the recycling process, competition from petroleum-based plastics

Research and qualitative analysis, supported by experts' inputs, have shown substantial differences in market size growth and UK market share potential across different technologies within each sector, as their level of maturity and UK competitive advantage are varied.

The report identifies three main dimensions to assess which technologies could be promising for the UK to focus on:

1) the potential growth of the global market size of each technology within each sector (qualitatively) and of the sector itself (quantitively through CGE modelling);

2) the potential UK market share in each sector under each scenario under consideration (quantitatively) and of each technology with respect to the sector average; and finally

3) the assessment, given the UK's competitive advantages and disadvantages with respect to its main competitors, as to whether the UK should or should not consider investing and supporting its industry and exports in each specific technology covered.

The analysis considers three main scenarios: current policies, below 2 ºC, and net zero 2050, which are further described in detail in the methodology section below. This approach by scenario is only applied methodically in the quantitative component of the research. In contrast, for the technology-level qualitative assessment, this has been reported and indicated only if evidence gathered pointed towards substantial differences under any of the scenarios. Still, no differentiation by scenario has been made when assessing individual technologies.

RQ1&2: POTENTIAL MARKET SIZE AND UK MARKET SHARES & UK COMPETITIVE ADVANTAGE – KEY TAKEAWAYS PER SECTOR

Below, we summarise key high-level conclusions for each sector; further details and key takeaways are included under each sector section below in the report.

Renewables

The renewable energy sector, particularly offshore wind, presents significant growth potential globally. Projections from the IEA and IRENA indicate substantial increases in installed capacity, with the UK holding promise in fixed offshore wind due to its established expertise and ambitious government targets. However, global challenges, such as complex permitting processes and supply chain disruptions, hinder growth. Fixed offshore wind is poised for substantial growth, with projections indicating a five to eight-fold increase in market size by 2030. Although less mature, floating offshore wind shows potential for global commercialisation globally by 2026/2027, albeit facing uncertainties.

Carbon capture and storage, and greenhouse gas removal

The UK possesses strengths in mature supply chains and R&D capabilities in carbon capture and storage (CCS) and greenhouse gas removal (GGR). However, technical and implementation hurdles in the UK encompass the absence of proven CO2 injections, high energy costs, and a reliance on expensive offshore CO2 storage. Despite the potential of bioenergy with carbon capture and storage (BECCS), limited biomass resources in the UK pose obstacles to deployment.

Hydrogen and biofuels

The hydrogen and biofuels market is projected to grow substantially, with opportunities for salt caverns (engineering and implementation services) and gasification technologies. While the UK benefits from funding initiatives and expertise, competition from countries like China, Japan, and India poses challenges in market share acquisition. Regulatory support in the UK is robust but must contend with protectionist measures from competitors.

Overall, the UK holds promise in renewable energy and low-carbon technologies, yet must address challenges such as supply chain disruptions and global competition to realise its full potential in these sectors.

Smart Systems

Over the past 50 years, the UK has prioritised strategic growth in sectors like automotive, aerospace, and financial services but has placed comparatively less emphasis on developing modern power electronic-based manufacturing industries for power system applications. While leading the implementation of energy network innovations, the focus has mainly been on implementation and services rather than investing in manufacturing industries for power electronics. International giants have dominated these sectors, making it challenging for new players to enter, especially in areas like converters for HVDC. However, investing in less saturated areas like Vehicle-to-Grid (V2G) technologies may offer strategic opportunities, given the UK's expertise in policy, planning, and regulation.

Nuclear

The UK is actively involved in nuclear technology, particularly High Temperature Gas Reactors (HTGRs) and Small Modular Reactors (SMRs). HTGRs have reached an advanced stage of technical maturity, making them attractive for global investment, while SMRs' commercial viability depends heavily on construction cost reduction. However, none of the experts interviewed expressed optimism regarding the potential of floating nuclear power plants to capture a substantial share of the global market. Russia appears to hold the primary interest in its development, while other regions show limited interest. Floating nuclear power stations, as a concept rather than a proper reactor technology type, demonstrate less flexibility to be deployed outside niche applications to plug off-grid demand and have received considerably less investment.

Heating and cooling

In the heating and cooling sector, the global heat pump market is driven by financial incentives and policy support, with the UK facing intense competition from China, the US, and the EU. Despite challenges, the UK aims to meet domestic demand, focusing on mid-range commercial sectors. However, becoming a global competitor in this market remains a significant challenge for the UK, requiring increased manufacturing capacity, strategic investments, and technological advancements beyond 2030.

Industry

In industry, hydrogen fuel switching presents significant opportunities globally, with the UK offering robust policy and regulatory support and significant government funding and incentives. The UK also shows promise in recycling and recovery, particularly chemical recycling, supported by strong R&D and existing Oil&Gas infrastructure. Moreover, the UK possesses a competitive advantage in bioplastics and bio-based chemicals, leveraging its strong research base and engineering biology sector. However, competition from the EU, China, and the USA remains significant.

Once again, each sector-specific section of the report (chapters 4 to 10) presents further detailed conclusions and information.

RQ3: BENEFITS AND COSTS OF BEING AN EARLY MOVER

The case studies on the early adoption of green technologies offer valuable insights into the benefits and challenges associated with the UK's earlier commitment to further investment in green technologies relative to other countries (being an ‘early mover’). We explored three case studies, which span a range of geographies and time periods, allowing us to draw insights using both historical data and the recent geopolitical context:

- **Morocco**: Concentrated solar power (CSP), mid-2000s onwards
- **Denmark**: 3rd generation heat networks[1], 1970s onwards
- **France**: Nuclear power, 1970s onwards

There is potential for early investment to achieve technology cost reductions that could put the UK in a favourable position in international price competition. The Denmark and France case studies highlight that associated benefits could include the establishment of the UK as a global leader in that technology, creating barriers to entry, restricting access to competitors, and building domestic skills to facilitate longer-term export potential. The Morocco case highlights that this can also stimulate other domestic industries, which could increase competitive advantage in those industries.

However, there is an alternative strategy of allowing other countries to invest first, whereby the UK could import knowledge and expertise learned in different countries and avoid the initial investment costs (and associated low initial production efficiencies). This strategy has the added benefit of preventing technology displacement risk – if other competitor technologies displace the one that the UK has invested in, as renewables have done to nuclear power and solar PV has the potential to do to CSP in Morocco, global focus on cost reduction research skews to the competitor technology, and the UK’s export potential shrinks.

Optimal investment decisions, therefore, depend on long-term national objectives and priorities of governments when deciding whether to pursue early adoption of green technologies. If the goal is to minimise technology costs, importing knowledge and expertise from other countries might be more cost-effective. However, this comes with the risk that other countries will generate barriers to entry, and the UK may have to import those technologies in the future. If the government's priority is establishing the UK as a global leader in manufacturing, creating barriers to entry and stimulating domestic industries, being an early mover may be more advantageous.

The choice of the specific technology is crucial in informing the final judgement on whether being an early mover is advisable. The key factors in the final outcome are whether the technology will be highly adopted internationally and whether IP can be protected.

RQ4: IMPACT OF FASTER TRANSITION ON COST CURVES

The cost curve analysis investigates the link between Research and Development (R&D) expenditures and the cost reduction of clean energy technologies in the UK. The cumulative R&D stock, projected for each scenario up to 2050, shows the impact of heightened decarbonisation efforts on R&D expenditures. This connection, guided by assumed learning rates, signifies that increased investment in R&D results in reductions in production costs through research-driven learning. In other words, more ambitious scenarios requiring

[1] 3rd generation heat networks as defined by (Lund, et al., 2014).

higher deployment of clean technologies globally lead to a stronger effort to channel funds into R&D, leading, in turn, to a decrease in costs.

Across various clean energy technologies, the current policy scenario has the lowest cost reduction. In contrast, the Net Zero 2050 scenario achieves the highest reduction, driven by the need for additional R&D expenditures to meet ambitious decarbonisation targets. The challenge is evident with mature technologies, such as wind equipment, which have already accumulated high R&D stock and have a limited margin to reduce production costs significantly through additional R&D investments. Conversely, immature technologies with a high potential for cost reduction through learning by research, such as EV batteries, demonstrate notable decreases. The reduction in the production cost index is intricately tied to assumed learning rates and the projected R&D expenditures outlined by the GEM-E3 model.

The analysis of different climate mitigation scenarios reveals different trajectories in reducing production costs for key clean energy technologies through learning by doing. The Net Zero 2050 scenario emerges as the most impactful, showcasing significant cost reductions due to the heightened deployment of clean energy technologies. Hydrogen experiences remarkable reductions, driven by widespread adoption in various sectors. Conversely, CCS equipment faces challenges with lower cost reductions, which reflects its slower learning rates and limited deployment.

In the current policy and Below 2 ºC scenarios, batteries take the forefront in achieving significant reductions in production costs. This trend is strongly influenced by the surging battery demand, particularly in the electric vehicle sector. Meanwhile, hydrogen and CCS equipment witness smaller cost reductions in these scenarios, which are closely tied to their lower deployment levels.

These findings show the critical role of technology deployment, learning rates, and contextual scenarios in shaping the cost dynamics of clean energy technologies. Cost reductions were most significant for all technologies considered in the Net Zero scenario.

1. INTRODUCTION

1.1 RATIONALE AND OBJECTIVE OF THE STUDY

The green transition will reshape global markets, offering new opportunities and benefits beyond emissions reduction. It is crucial for the UK not to overlook this opportunity to benefit from the transition. To fully capitalise on these opportunities, a comprehensive understanding of the scale and scope of international markets is essential, supported by reliable data and analysis pinpointing strategic opportunities for the UK.

Due to gaps in the available evidence base, it is challenging to thoroughly address questions regarding the potential economic benefits of the global net-zero transition for the UK and other countries, especially across different transition scenarios. The main objective of this study is to provide a thorough analysis to fill these gaps and support policy development. Specifically, it aims to offer an evidence-based assessment of how the costs and benefits associated with the global transition may vary under different scenarios. This analysis focuses on opportunities up to 2030 while also considering long-term benefits, particularly for emerging technologies extending to 2050.

1.2 RESEARCH QUESTIONS

This study discusses four key research questions:

- RQ1: What potential global market size can the energy transition be associated with under different global transition scenarios, and what market share could the UK gain in each scenario?
- RQ2: In which sectors could the UK have a competitive advantage?
- RQ3: What are the main advantages and disadvantages of being an early mover in new and emerging sectors?
- RQ4: What is the impact of faster transitions (2℃ and 1.5℃ scenarios) on the cost curves of specific technologies?

1.3 IN-SCOPE SECTORS AND TECHNOLOGIES

This study focuses on several sectors and technologies (grouped in technology families), as detailed in the following table. The sectors were decided by DESNZ.

The choice of the in-scope technologies was based on the following reasons:

- DESNZ has provided Ricardo with the list of in-scope technologies for ‘Renewables’, ‘Nuclear’, ‘CCS and GGR’, and ‘Hydrogen and alternative fuels’.
- For ‘Smart systems’, ‘Industry’, and ‘Heating and cooling’, the relevant technologies listed below were selected from a long list by Ricardo sector experts, in agreement with DESNZ. They gave priority to those technologies that, from a preliminary assessment, appeared to be the most promising for the UK.

Table 1-0-1: In-scope Sectors, Tech Families, and Technologies

Sectors	Tech Family	Technologies
Renewables	Wind	Offshore (fixed)
		Offshore (floating)
	Tidal	Tidal stream
Nuclear	Nuclear Gen IV	High Temperature Gas Reactor
	Advanced Nuclear Technologies	Nuclear (SMR)
		Floating Nuclear Powerplants
CCS and GGR	CO_2 capture	Oxy
		Pre-combustion
		Post-combustion

Sectors	Tech Family	Technologies
	CO_2 storage	Geological storage
	GGR	BECCS
		DACCS
Hydrogen and alternative fuels	Hydrogen production	Electrolysis
		Autothermal reforming
	Infrastructure	Hydrogen storage - medium salt cavern
		Depleted gas field storage
		Hydrogen transmission/transport
	Bioenergy	Pyrolysis
		Gasification
Smart Systems	Storage	Thermal energy storage
	DSR	V2G (vehicle to grid)
	Transmission	Power electronics
		HVDC Converters
Industry	Fuel switching	Hydrogen
	Materials	Recycling and recovery
		Low carbon substitutes
Heating and Cooling	Heat pumps	Heat pumps

Key terms used throughout the report are defined in APPENDIX 3: Key terms used in the report.

2. METHODOLOGICAL APPROACH

2.1 INTRODUCTION

The analysis presented in this study is based on a mix of the following methodologies:

(a) **Quantitative analysis**, conducted via E3-Modelling's GEM-E3 model and carried out at sector level only.

(b) **Analysis of trade flows** (source: UN Comtrade database), based on a list of 6-digit HS codes provided by DESNZ and intended to provide an estimate of the current UK's share of global exports.

(c) **Qualitative analysis** is conducted at the technology level based on a combination of desk research and expert judgement by Ricardo sector experts.

(d) **Case studies**, based on desk research and aiming to provide an analysis of historical experiences to draw conclusions valid for the United Kingdom

The methodologies applied for each research question are detailed in the following table.

Table 2-1: Methodology used in this study

Research question	Quantitative analysis	Trade flow analysis	Qualitative analysis	Case studies
RQ1: What potential global market size can the energy transition be associated with under different global transition scenarios, and what market share could the UK gain in each scenario?	✓	✓	✓	
RQ2: In which sectors could the UK have a competitive advantage?	✓		✓	
RQ3: What are the main advantages and disadvantages of being an early mover in new and emerging sectors?				✓
RQ4: What is the impact of faster transitions (2℃ and 1.5℃ scenarios) on the cost curves of specific technologies?	✓			

In the following sections, the various methodological approaches are summarised. A detailed methodology has been provided in APPENDIX 2: Detailed methodology.

2.2 QUANTITATIVE ANALYSIS VIA GEM-E3

The GEM-E3 model is a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium (CGE) model which provides details on the macro-economy and its interaction with the environment and the energy system. The model produces projections for the economic and energy systems extending until 2050, with results presented in five-year intervals from 2015 to 2050. The GEM-E3 model has been used to estimate the global and UK market sizes and share under three scenarios with different ambitions in terms of GHG emissions reduction (RQ1). The model has also been used to identify the key market players in 2050 (RQ2). The scenarios that have been used are the "Current policy", the "Below 2 ºC" and the "Net Zero 2050", which are consistent with 2.8-3.1ºC, below 2 ºC and 1.5 ºC end of century warming accordingly.

For each clean energy sector (wind equipment, CCS equipment, nuclear equipment, hydrogen and alternative fuels, batteries, and advanced heating & cooling appliances), the GEM-E3 model simulates the potential global and UK market size and the contribution of the UK's production to the global market. Furthermore, we present the market shares in the UK and key market players reflecting the relative position of the UK across sectors and scenarios. Since GEM-E3 does not explicitly represent the detailed process/equipment/technologies using hydrogen, it was not possible to cover the market size of these technologies. Instead, we present the hydrogen consumption of the industries at the sectoral classification of the GEM-E3 model.

The GEM-E3 model provides quantified projections of the demand and supply of clean energy technologies within a global closed accounting system, ensuring consistency of transactions globally. Demand for clean energy technologies is mainly driven by the pattern and scale of economic growth and policies/measures/regulations. Technology dynamics and relative cost advantages primarily drive supply.

2.3 TRADE FLOW ANALYSIS

A trade flow analysis is carried out in RQ1 to estimate the current UK's share of global exports in each sector. This is coherent with the approach taken in the original Energy Innovation Needs Assessment (EINA) reports, where estimates of the current market shares were based on an analysis of trade flow codes[2] and an assessment of future market shares was based on expert judgement (gathered via workshops with stakeholders).

The trade flow analysis in the UK market share sections is based on a list of 6-digit HS codes Ricardo received from DESNZ. The list provided details of each code's reference sectors (e.g., Renewables, Hydrogen, etc.). Trade flow data has been downloaded from the UN Comtrade database.

It is essential to acknowledge the limitations of this approach:

- for each sector, not all selected codes are unique to that specific sector, and other relevant codes may not have been captured
- these numbers can only be interpreted as indicative proxies of the UK's share of tradable export markets (in line with the EINA methodology, as discussed in the Appendix Section Trade flows analysis). This is due to differences in the definition of export shares between EINA and this analysis.

To summarise, analysing trade flows provides insight into each country's portion of global exports. However, it is essential to note that global exports do not encompass the entirety of the global market. "Domestic trade," or production serving a country's domestic market, is not accounted for in international trade databases, which, therefore, offer an incomplete picture of the size of global markets.

2.4 QUALITATIVE ANALYSIS

A qualitative analysis is conducted:

- In RQ1 to complement the quantitative analysis of market sizes and UK market shares with evidence at the level of individual technologies;
- In RQ2 to discuss sector-specific barriers and enablers as well as the UK's competitive advantage/disadvantage vis-a-vis other countries (geographical benchmarking).

The qualitative analysis relies on two approaches: (a) desk research and (b) expert judgment. Experts were mainly drawn from Ricardo's teams, who specialise in each sector and, in the case of nuclear, from outside our organisation.

The desktop research/literature review analysed academic papers, industry reports, and grey literature such as company announcements and press releases. In many cases, relevant pieces of literature have been selected based on the suggestion of our sector experts. Experts were consulted using various methods, including data & evidence collection templates, in-depth interviews and brainstorming sessions, and email exchanges. Sector experts were also asked to review, validate, and integrate the findings from the literature review based on their knowledge, as well as to provide or validate the RAG ratings described in Table 2-2.

2.4.1 RAG approach

In both RQ1 and RQ2, for each sector, the discussion of qualitative evidence is complemented and summarised via three tables presenting RAG (Red, Amber, Green) ratings that, based on the assessment conducted in the previous sections within each chapter, classify each technology as detailed in the following table.

These classifications are based on expert judgment (also considering the main results of desk research). Sector experts have not applied a specific framework to arrive at their rating, but the rationale for their choice is provided in the relevant summary tables.

Table 2-2: RAG ratings

RAG rating	RQ	Red	Amber	Green
RAG rating 1	RQ1	Low	Medium	High

[2] Cf. for example Figure 2 at p. 36 of the Biomass and Bioenergy EINA report (2019)

RAG rating	RQ	Red	Amber	Green
Global market size growth potential				
RAG rating 2 Potential to attract significantly higher/lower market shares compared to the sector average[3]	RQ1	Potential to attract lower market share compared to the sector average	In line with the average	Potential to attract higher market share compared to the sector average
RAG rating 3 Competitive advantage rating	RQ2	**Lower potential area**: a technology on which the UK does not appear to have potential	**Further** opportunity: an area where the UK could gain a competitive advantage from positioning itself as a potential early mover	**Primary focus area**: an area where the UK is expected to have consolidated advantage

2.4.2 Case studies

In RQ3, case study analysis is conducted to provide an analysis of historical experiences and draw valid conclusions for the UK regarding the advantages and disadvantages of being an early mover in new and emerging sectors.

Three case studies have been developed:

- **Morocco**: Concentrated solar power (CSP), mid-2000s onwards
- **Denmark**: 3rd generation heat networks[4], 1970s onwards
- **France**: Nuclear power, 1970s onwards

The case studies were developed based on desk research, i.e., a review of the relevant literature for each of the three selected cases. Based on the common results, general conclusions are drawn from the three case studies.

2.4.3 Methodology for RQ4

RQ4 assesses the impact of different GHG mitigation pathways on the capital costs of key technologies and the knock-on effect on production costs and, therefore, competitiveness.

Technologies that are covered in GEM-E3 and are relevant to this study include:

- Alternative fuels (ethanol, biodiesel)
- Batteries
- Equipment for wind power technology
- Equipment for PV panels
- Equipment for CCS power technology
- Hydrogen.

GEM-E3 captures the relationship between cumulative production, R&D expenditures, and reductions in capital costs for each technology. There are two main drivers of these effects:

- **Learning by research:** R&D investment drives productivity improvements and is split between public R&D (which impacts all firms in all regions) and private R&D (which impacts specific firms).
- **Learning by doing:** Gained experience drives productivity improvements, where costs are reduced as production increases.

These effects differ for each technology. The specific productivity rates and model formulas that drive this effect are outlined in APPENDIX 2: Detailed methodology.

[3] The sector average results from (a) the quantitative analysis via the GEM-E3 model and (b) the trade flows analysis. While these values are not exactly the same due to differences in methodology, data sources and time periods, they are normally similar and are taken together to derive an industry average against which the potential UK market share potential is assessed.

[4] 3rd generation heat networks as defined by (Lund, et al., 2014)

3. RQ2: CROSS-CUTTING BARRIERS AND ENABLERS

3.1 INTRODUCTION

Many forces and factors will affect the UK's ability to achieve the anticipated level of market penetration. Some of these factors may impede the UK from attaining the expected market shares in any given sector or technology ("barriers"), while some may facilitate or even support exceeding these market shares ("enablers").

The sections below explore key global forces, unless explicitly flagged as UK, that are expected to influence the assessed UK market shares. They focus on cross-cutting factors affecting multiple sectors associated with the green energy transition. These common forces are in addition to the sector-specific drivers, barriers, and enablers explored in the following sections.

These global barriers and enablers were identified as the most important given (a) the stress placed on them within available literature, (b) the frequency with which they are reported in the literature, and (c) the judgement of Ricardo's sector experts. Regarding (c), each relevant expert was asked to comment on the importance of the barrier/enabler for their industry in the form of a red/amber/green (RAG) rating. They made their assessments based on the guide below, whereby barriers/enablers with high impact that are likely would fall under the red category. In contrast, low-impact and very unlikely ones would fall under the green category.

The same approach was adopted to inform the enablers and barriers at the sector level in each sector-specific chapter in the report, ensuring that the table states global barriers/enablers unless explicitly flagged as UK.

Table 3-1: Guiding matrix for experts' RAG ratings on global cross-cutting barriers and enablers

Barriers

Size of Impact	Likelihood of impact		
	Low	Medium	High
Low			
Medium			
High			

Enablers

Size of Impact	Likelihood of impact		
	Low	Medium	High
Low			
Medium			
High			

3.2 MAIN BARRIERS

Table 3-2 below lists the global barriers identified, unless explicitly indicated as specific to the UK, and provides an explanation of how these practically might impact the UK's market share. As mentioned above, "barriers" are the forces which might impede the UK from attaining the expected market shares. These are accompanied by an RAG rating, which is meant to indicate the level of impact and likelihood the barrier has to influence the UK's capacity to achieve its anticipated market shares in accordance with Table 3-1 above. These are listed in order of importance, starting with the most significant barriers.

Table 3-2: Global cross-cutting barriers to the UK attaining the expected market shares

Barrier	Justification	RAG
Tariff barriers and protectionism	Tariff barriers highly inhibit the international technology spillover effect of trade (Qiao, et al., 2023). Any presence of a price differential can limit the competitiveness of the UK's exports on foreign markets and reduce their capacity to achieve the expected market shares. For example, there is evidence of rising trade protectionism in the renewable energy industry. Disputes have been brought to the World Trade Organisation on countervailing duties, anti-dumping duties, domestic content requirements, or safeguards measures (Karim, Syed, & Islam, 2022). Protectionist measures can be linked to the early development stage of the renewable energy industry, like many of the sectors associated with the energy transition. It is characterised by rapid growth and fierce competition among companies for an export share of the expanding market. Governments play a significant role – the idea of infant industry and strategic trade policy considerations can be used to justify protectionism in this sector. Tariff barriers tend to be higher in developing countries (above 10% in some cases) compared to developed countries (on average at 0.5% with few tariff peaks) (UK Board of Trade, 2021). Considering global populations are concentrated in developing nations, this could restrict the UK's capacity to capture some sections of the global market, especially if tariffs increase for the UK relative to other countries and trading blocs.	
Non-Tariff barriers	Non-tariff barriers (for goods and services) cover any barrier to trade that is not a custom duty at the border and include 'behind the border' regulations, licenses, quotas, and local technical standards (UK Board of Trade, 2021). Differences in standards and regulations between countries, a.k.a. 'Technical Barriers to Trade' (TBTs), account for 34% of the 89,421 non-tariff measures recorded in UNCTAD's database[5] as of 2023 (United Kingdom, 2023). There remains a risk that increasing divergence in regulations and standards between countries can make it more difficult for exporters to comply with multiple export markets. This may increase compliance costs and restrict market access, limiting the UK's capacity to achieve its expected market shares. There is also growing concern that the UK is becoming a less attractive place to invest in the global race to decarbonise in the face of ambitious policy packages introduced elsewhere to support such investments, including the US Inflation Reduction Act and the EU's Green Deal Industrial Plan in particular (Serin E, 2023).	
Diplomatic tensions	The impact of diplomatic tensions on the UK's capacity to attain its potential market shares is illustrated below concerning energy supply. Geopolitical tensions and rising energy prices stemming from (a) Europe's heavy reliance on Russian gas, exacerbated by the Russian invasion of Ukraine in February 2022, (b) Europe's and the US' reliance on Chinese imports, and (c) drought and coal price volatility in Asia, prompted an imperative for ensuring energy security and protecting regional industries. Initially aimed at ensuring the reliability of energy supply, the focus expanded to increase renewable energy targets and encompass the entire energy supply chain, including the regional manufacturing of equipment crucial for energy generation. To elaborate further on point (b) above, heavy reliance on China to manufacture key components of Net Zero Technologies poses a risk to clean technology manufacturers, exposing them to geopolitical tensions and market fluctuations in China. Recent policies, such as export permits for certain products, highlight potential threats to global supplies, impacting industries reliant on Chinese production (IEA, 2023) (IEA, World Energy Outlook 2023, 2023). China also dominates bulk material supply, accounting for around half of global crude steel, cement, and aluminium output, though most is used domestically (IEA, 2023f). In response to these challenges, the U.S. adopted the Inflation Reduction Act (IRA) (2022) to attract supply chain investment by mobilising a massive investment in renewable generation, energy storage and improved grid connections. Europe followed a similar approach with the REPowerEU plan (2022) to reduce reliance on Russian gas and deploy green energy, the European Union's Green Deal Industrial Plan (2023), and the Net-Zero Industry Act to scale up the manufacturing of clean technologies that support the clean energy transition.	

[5] https://trainsonline.unctad.org/home

Barrier	Justification	RAG
	Alongside Europe and the US, China is also committed to further expanding the role of renewables in its energy mix. It aims for renewable energy to contribute more than 80% of total new installed power by the end of its 14th Five-Year Plan (2021-2025). These efforts underscore a broader global trend towards reshaping supply chains and protecting local industries and jobs. Nevertheless, Europe and the US are facing the risk of supply chain shortfalls, as the imperatives to protect local industry and employment pose challenges for maintaining an adequate supply of critical components and materials and jeopardising the sector's ability to keep pace with the accelerating demand for renewable energy. (*Sources*: (Global Wind Energy Council & Boston Consulting Group, 2023) - (Rystad Energy & WindEurope, 2023) - (Global Wind Energy Council, 2023)). More generally, there also seems to be a trend of developing nations (as the world's biggest polluters) pushing back on the 'polluter should pay' principle. In recent global events like the Conference of the Parties (COP), developing nations have been asked to contribute their share of emissions reductions to achieve the Paris Agreement targets. However, they argue that the current status of climate change is primarily a result of historical GHG emissions of now-developed nations and, therefore, that developed countries should provide various kinds of international support, including investment in emissions-saving technologies, to achieve those targets. (Economist, 2022) (Kang S. J., 2020) This reduces the level of investment they are willing to make, which could shrink the total potential size of the world market for green technologies in the shorter term and/or increase trade disputes given that developing nations are relatively worse off from the introduction of carbon taxes and ETS schemes. There is empirical evidence to support this, given that green shares of exports have been falling for developing nations (e.g. China) compared to more developed nations, where they have been rising (e.g. Korea, the U.S.A) (Kang S. J., 2020).	
Critical material availability	The production of critical minerals is highly concentrated geographically, raising concerns about the security of green technology supply chains. According to the IEA, the Democratic Republic of Congo supplies 70% of cobalt today; China 60% of rare earth elements (REEs); and Indonesia 40% of nickel. Australia accounts for 55% of lithium mining, and Chile for 25%. Processing of these minerals is also highly concentrated, with China being responsible for the refining of 90% of REEs and 60-70% of lithium and cobalt (IEA, 2023f). This means that any supply chain reliant on these materials depends on a continuation (or improvement) in bilateral trade and diplomatic relations between the UK and the relevant countries, which remains at risk for reasons outlined in barriers 1-4 above. The prices of materials critical to the renewable energy industry, such as cobalt, nickel and rare earth elements, are also highly variable. Historic sharp price increases and recent plummets in critical material prices have highlighted a worrying scenario for their supply. Due to the lack of geographic diversification in the production of each material, their reliability and affordability are constantly threatened by any economic, political or geopolitical uncertainty (Rystad Energy & WindEurope, 2023) (The Globe and Mail, 2024).	
UK funding gap for early-stage 'cleantech' companies, especially in hardware	UK market share assumptions have been developed based on a current assessment of national competitiveness, but a core differentiator between nations is the capacity to innovate, and this is often delivered through ideas contributed by small startups. Evidence shows that a funding gap exists in the UK at the stage where companies have progressed beyond grant funding and incubator and accelerator programmes but have not yet reached a level of commercialisation where private funding is more readily available (Green Finance Taskforce, 2018) (London Economics, 2023). While the UK has experienced higher growth in the total value of seed rounds and of series A rounds as a percentage of GDP relative to Germany, France and the US between 2017-2021, this is being driven by increasing deal size and conceals a slowing in the total number of deals (London Economics, 2023). Furthermore, clean tech companies may also be less frequently successful in progressing from seed funding to venture funding than other UK technology sectors – 32% of cleantech companies raised venture funding by the end of 2021, compared with 45% for the AI sector and 36% for Biotech (London Economics, 2023). This could indicate that other countries with better funding for early-stage companies may outpace the UK's competitiveness in the future, acting as a barrier to the UK's capacity to gain market share. One recent relevant development is in the US, where they are pivoting towards improving R&D institutional capabilities, and this may distract R&D funding away from the UK.	

Barrier	Justification	RAG
Shortage of technical and STEM skills in the UK workforce	Skilled labour shortages are plaguing many clean technology sectors globally. The lack of plumbers, pipefitters, electricians, heating technicians and construction workers is already restricting the pace of installations of clean energy technologies in Europe and the United States, including solar PV, wind turbines and heat pumps (IEA, 2023). Construction occupations make up nearly half of new energy-related jobs to 2030 on a path to net zero and are facing particularly acute shortages (IEA, 2023). Some fast-growing clean energy sectors are also facing a shortage of the requisite skills needed to scale up output, especially in wind power (IEA, 2023). The energy sector needs higher-skilled workers than most other industries – 36% of energy jobs are within high-skilled occupations by International Labour Organization definitions, compared with 27% in the broader economy. Nearly half of the UK's early-stage cleantech companies surveyed for Tech Nation's Net Zero Report 2021 identified 'team', 'talent' or 'hiring' as one of their top three challenges; this made skills, talent and recruitment the most common challenge for early-stage cleantech companies according to this survey (London Economics, 2023). There is, therefore, a double risk that the UK does not have the domestic skills for the clean energy transition but also that shortages elsewhere exacerbate skills shortages in the UK if the workforce moves abroad.	

3.3 KEY ENABLERS

Acting in the opposite direction than the 'barriers' listed in Section 3.2 above, this section presents the 'enablers', or global factors, unless explicitly indicated as specific to the UK, that could facilitate the UK in attaining (or exceeding) the expected market shares outlined in previous sections. Enablers are listed in Table 3-3 below explaining how these forces impact the UK's market share. These are listed in order of importance, starting with the most significant enablers. RAG ratings are provided here, based on sector expert input and are assessed on the same scale as presented in Table 3-1.

Table 3-3: Global cross-cutting enablers to the UK attaining the expected market shares

Enabler	Justification	RAG
International efforts to overcome trade barriers	Action has been taken unilaterally to reduce tariff barriers. The UK launched its new Global Tariff at the start of 2021, which keeps tariffs at 0% on all environmental goods previously covered by the EU's tariff policy. It also removes tariffs on a further 104 environmental goods (the 'Green 100') to promote the deployment of renewable energy generation, energy efficiency, carbon capture, and the circular economy through recycling and reducing single-use plastics. As a result, the UK now has zero tariffs on around two-thirds of goods covered by the Environmental Goods Agreement (EGA) negotiations at the WTO, including over GBP 2.1 billion of imports by value under the Green 100 (UK Board of Trade, 2021). Action on a unilateral basis can provide confidence in UK investment because it signals to the market an ongoing commitment to zero-tariff trade in clean technologies, which surpasses commitments made by other developed and developing nations and could help the UK maintain its expected market shares. On a **multi-lateral** basis, the UK is a member of the Structured Discussions on Trade and Environmental Sustainability (TESSD) at the WTO and has submitted papers outlining the key goods and services and associated value chains for offshore wind and other environmental goods to highlight both tariff and non-tariff trade barriers and suggest ways forward to overcome them (United Kingdom, 2023) (United Kingdom, 2023). The TESSD is co-sponsored and attended by over 70 nations, providing a promising platform for reducing trade barriers globally. Average global tariffs on 'environmental goods' (based on the OECD's definition[6]), declined from over 3% to below 2% between 2003 and 2016, in part due to targeted efforts by the OECD and the WTO to promote trade in environmental goods by reducing import tariffs multilaterally (United Kingdom, 2023). This suggests that on a global level, tariff barriers to green trade are declining in importance over time. Moreover, action can be taken on a **bilateral** basis. The UK-Australia Clean Tech partnership is a good example of the elimination of tariffs, increased access to a fast-growing Indo-Pacific free trade area, free flow of data provisions, and a ban on data localisation that will allow British SMEs to explore the Australian market without the cost of having to set up local servers (UK Government, 2021). More generally, the UK govt has also expressed that establishing free trade agreements based on liberal green trade principles is a priority (UK Board of Trade, 2021). For the EU market, the EU-UK Trade and Cooperation Agreement (TCA) guarantees zero tariffs and quotas for goods meeting rule-of-origin requirements (ECB, 2023). It was speculated that Brexit would reduce the UK's negotiating power on trade agreements and tariffs. Data is still emerging, and longer-term effects are as-yet unknowable, but IEA analysis suggests that, in general, there has been no real disparity between UK trade with EU and non-EU countries since Brexit (IEA, 2023).	
Countries leading on green policies tend to exhibit higher bilateral green trade levels	The gravity theory of trade models indicates that environmentally progressive policy-making leads to greater levels of green trade. High-income countries with stricter environmental policies (proxied by a ratio of environmentally related tax revenue to GDP) exhibit higher levels of bilateral green exports, similar to high-income countries with greater energy demand (Kang & Lee, 2021). The study also suggests that lower-middle-income countries promote environmental policies and pursue eco-friendly production to be competitive in the global market and keep pace with developed nations. (Kang & Lee, 2021). To the extent that the UK can keep pace with regulatory standards in the EU and the US, this can enable UK industry to capture a higher share of trade with developed nations with strict regulatory standards and increase the appetite for green technologies (i.e. the market size) associated with developing countries.	
The trend towards putting a price on carbon favours low-embedded carbon production	Putting a price on carbon maintains price competitiveness between UK green innovations and 'less green' tech abroad, allowing them to achieve their true societal market share. Emissions trading schemes and carbon border adjustment mechanisms internalise the effects of global warming and increase the relative cost of products with high embedded carbon (Baranzaini, Bergh, & Carattini, 2017). Given the UK's established ETS, it is close behind the EU in pricing its embedded carbon and reporting on such supply chain issues,	

[6] See, for example, the OECD's manual for data collection and analysis for the environmental goods and services industry.

Enabler	Justification	RAG
	providing some advantage over other countries that are not yet fully pricing their carbon. More countries join organised ETSs every year, and this trend will likely continue.	

4. RENEWABLES

4.1 INTRODUCTION

Two technology families are considered within the scope of renewable energies:

- **Offshore wind energy** is the energy taken from the force of the winds out at sea, transformed into electricity and supplied to the electricity network onshore. Offshore wind farms benefit from stronger and more consistent winds than onshore locations, allowing for larger turbines. Within this family, two types of offshore wind energy technologies are considered:
  - **Fixed offshore wind** refers to wind turbines with a direct rigid connection to the seabed, typically installed in water depths up to 60 meters.
  - **Floating offshore wind** (FLOW) involves wind turbines mounted on floating structures. These platforms are anchored to the seabed using flexible anchors, chains, or steel cables. Floating turbines can be deployed further offshore in deeper waters with higher wind potential. (Iberdrola, n.d.).
- **Tidal stream energy** harnesses renewable energy from the regular rise and fall of ocean waters due to gravitational interactions between the sun, Earth, and moon. It captures kinetic energy from fast-flowing water driven by tides. (Graham Research Institute on Climate Change and the Environment, 2023)

Table 4-1: In-scope technologies

Sector	Tech families	Technologies
Renewables	Wind	Offshore (fixed)
		Offshore (floating)
	Tidal	Tidal stream

4.1.1 Key takeaways

Global market trends

- Due to its maturity and affordability, **fixed offshore wind** is poised for substantial growth, with projections indicating a five to eight-fold increase in market size by 2030.
- **Floating offshore wind** faces uncertainties as it is more complex, less mature and more expensive than fixed offshore installations. Predictions indicate that commercialisation will not be reached until 2026/2027 and that its contribution to total wind installations could increase from 0.3% today to 6% in 2032.
- China strategically dominates the global wind supply chain, from rare earth element refining to component manufacturing, with shares of the global market between 54% and 80% approximately. Despite favourable political support, the Western wind turbine industry faces a challenging landscape due to conflicting market forces like declining turbine prices, slow permitting processes, supply chain disruptions, raw material shortages, inflation, and geopolitical tensions.
- Compared to wind, **tidal energy** is a much less mature technology with higher upfront costs. It operates in a harsh environment and faces uncertainties around future growth potential. The predictable and consistent nature of this energy source holds significant potential; however, limited deployment potential exists outside of locations with specific tidal conditions. For this reason, tidal stream generators are not yet mass-produced.
- The expected significant transformation of the energy system needed to achieve the decarbonisation targets leads to a substantial increase in the deployment of wind equipment technologies (both on-shore and off-shore wind). The projected global market size is five times higher compared to the 2020 levels in the net zero scenario (as projected in the GEM-E3 model).

Domestic market size and the UK's competitive advantage

- The UK is a global leader in **offshore wind** deployment, primarily focusing on fixed-bottom wind. This niche is recommended as a primary focus area where the UK is expected to have a consolidated advantage for developing a global market share. A favourable geography coupled with ambitious decarbonisation targets, government policies and supportive investments (such as the recently announced GIGA scheme), competitive auctions, and a growing focus on green skills training contribute to the UK's wind energy success and provide a foundation for future growth. The country is also pioneering floating offshore wind and is poised to become one of the first countries seeking to deploy FLOW at a commercial scale.

- While the UK excels in specific wind energy sectors (like development services, blade manufacture, cables, electrical, offshore services, etc), challenges remain in turbine manufacturing and engineering procurement. Other challenges include competition from other countries with similar advantages (such as China and the US), talent retention and attraction, and a relatively small manufacturing base compared to competitors.
- The UK leads in **tidal energy** development globally, with over half of the world's current operational capacity. This leadership position is underpinned by the UK's numerous tidal stream technology developers. Despite leadership in technology and manufacturing, the UK's tidal energy market remains primarily domestic. While being a market leader creates significant potential for the UK to share expertise and export components, a concrete export market has not yet materialised, and different analyses indicate that it appears likely that most of the UK's manufacturing output will keep being directed to its strong internal market and not for export.
- The UK holds a small share (0.3%-0.4%) of the global wind equipment market. Most wind equipment manufacturers are concentrated in the European Union, holding global market shares between 26% and 31% in the scenarios implemented. China accounts for a significant portion, ranging from 33% to 36%, while the United States holds market shares ranging from 20% to 23%.

4.2 RQ1: POTENTIAL MARKET SIZE AND UK MARKET SHARES

4.2.1 Quantitative analysis at the sector level

4.2.1.1 Market size

This section discusses projections of market size and the UK's market share in the wind equipment industry[7] (tidal stream technology is not considered in this section). The calibration of the wind equipment market size and market shares was based on different reports and sources[8]. UN Comtrade data was used to calibrate bilateral trade transactions.

As of 2020, the global market size stands at approximately USD 58 billion, and the current policy scenario projections indicate an increase over the coming years, reaching around USD 137 billion by 2050, as projected in the GEM-E3 model.

The Net Zero scenario implies a significant transformation of the energy system and sees the highest deployment of clean energy technologies compared to other simulated scenarios. In the Net Zero scenario, the market increases by 5 times in 2050 compared to 2020 (compared to ~2.5 times in the Current Policies scenario and ~4 times in the Below 2 ºC scenario). These results are driven by the increase in the carbon price, which increases the costs of using fossil fuels. Subsequently, there is a substitution towards clean energy fuels and technologies.

Table 4-2: Market size in wind equipment (demand in billion USD)

NGFS Scenario	Geography	2020	2025	2030	2035	2050
Current policies	Global market	58.6	74.8	87.3	99.8	137.2
	Domestic market	1.1	1.2	1.4	1.6	2.2
	Export market	57.5	73.7	85.9	98.2	135.0
Below 2 ºC	Global market	58.6	74.8	87.3	186.6	237.5
	Domestic market	1.1	1.2	1.4	6.2	7.9

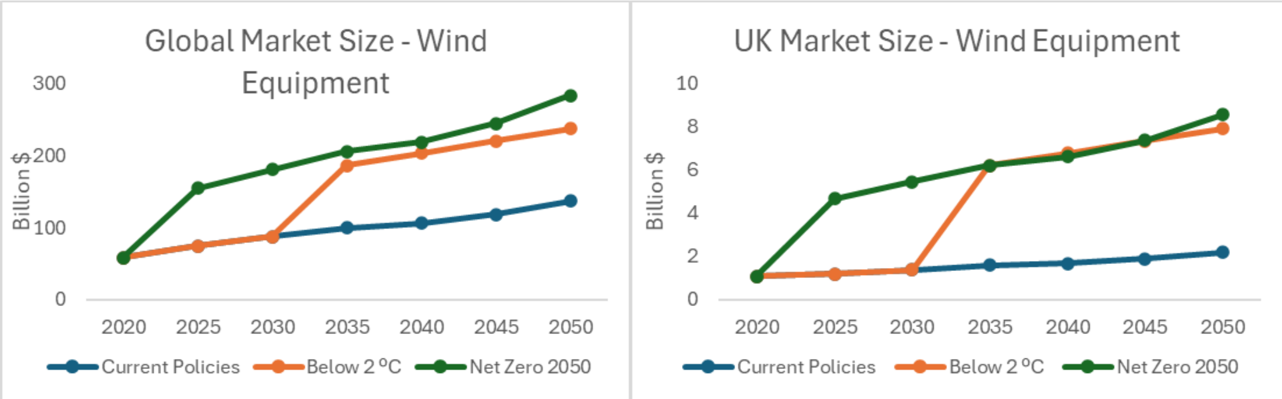
[7] Please note that the wind equipment sector in the GEM-E3 also accounts for equipment of on-shore wind.

[8] Global Wind Energy Council (GWEC) Market intelligence, 2022, (IEA) Energy technology perspectives 2023, Allied Market Research (Wind Turbine Market Outlook – 2030), Statista, UN COMTRADE.

NGFS Scenario	Geography	2020	2025	2030	2035	2050
	Export market	57.5	73.7	85.9	180.4	229.6
Net Zero 2050	Global market	58.6	154.6	180.4	206.2	283.5
	Domestic market	1.1	4.7	5.4	6.2	8.6
	Export market	57.5	149.9	174.9	199.9	274.9

Source: Ricardo analysis based on GEM-E3 outputs

Figure 4-1: Global and UK market size (demand in billion USD)



Source: Ricardo analysis based on GEM-E3 outputs

4.2.1.2 UK market share

The UK currently (2020) relies on imports for approximately 93.5% of its wind equipment. Despite the United Kingdom being a major producer of small-size wind turbines, the market size for these turbines remains small compared to the overall manufacturing of wind equipment. Key EU wind turbine manufacturers are Vestas-Denmark, Enercon-Germany, Nordex-Germany and Siemens-Gamesa-Germany. Countries that can cover the increased demand for wind equipment will contribute significantly to the growing market.

Table 4-3: UK market share in wind equipment

NGFS Scenario	Geography	2020	2025	2030	2035	2050
Current policies	Global market	0.3%	0.3%	0.3%	0.3%	0.3%
	Domestic market	6.5%	6.2%	6.2%	6.1%	5.9%
	Export market	0.2%	0.2%	0.2%	0.2%	0.2%
Below 2 ºC	Global market	0.3%	0.3%	0.3%	0.4%	0.4%
	Domestic market	6.5%	6.2%	6.2%	6.3%	5.8%
	Export market	0.2%	0.2%	0.2%	0.2%	0.2%
Net Zero 2050	Global market	0.3%	0.4%	0.4%	0.4%	0.4%
	Domestic market	6.5%	6.4%	6.3%	6.2%	5.9%
	Export market	0.2%	0.3%	0.3%	0.3%	0.3%

Source: Ricardo analysis based on GEM-E3 outputs

4.2.2 Qualitative analysis: market size

4.2.2.1 Wind: global market size

In its 2023 "Global Offshore Wind Report", the Global Wind Energy Council (GWEC) indicates that the total global offshore wind capacity was 64.3 GW in 2022. Annual offshore wind installations amounted to 8.8 GW in 2022, and new yearly offshore wind installations are projected to reach 30 GW by 2026, 35 GW by 2028, 50 GW by 2030 and pass 60 GW in 2032 (i.e., a sevenfold increase in annual installations between 2022 and

2032). This will result in more than 380 GW of new offshore wind capacity being added over the next decade (2023–2032), bringing total offshore wind capacity to 447 GW by the end of 2032 (Global Wind Energy Council, 2023).

Nevertheless, under scenarios outlined by the world's leading energy institutions, including the International Agency Energy (IEA) and the International Renewable Energy Agency (IRENA), achieving carbon neutrality by 2050 will call for a more rapid growth in offshore wind installed capacity. The IEA's latest roadmap requires offshore wind annual installations to grow ninefold, from 8.8 GW in 2022 to 80 GW by 2030, and then stabilise at 70 GW to be deployed annually between 2031 and 2050. IRENA foresees nearly 500 GW of cumulative offshore wind installed capacity by 2030 in its latest 1.5C-compliant scenario and almost 2,500 GW by 2050 (Global Wind Energy Council, 2023).

Considering cost projections from NREL that indicate a CAPEX for offshore wind of around USD 4,000/kW in 2022, USD 3,500/kW in 2030, and USD 3,000/kW in 2050 (NREL, 2023), the global market size is expected to increase between five and eight times under the previous scenarios:

- Global Wind Energy Council projections: from USD 35.2 billion in 2022 to USD 175 billion in 2030 (fivefold increase).
- IEA's latest roadmap: from USD 35.2 billion in 2022 to USD 280 billion in 2030 (eightfold increase).

It is important to note that these projections refer almost entirely to fixed offshore wind. Please see the box below for a focus on floating wind.

Text Box 41: Floating offshore wind (FLOW)

Floating offshore wind (FLOW) is still in its early stages and needs to transition significant learning to scale up from a handful of demonstration projects to gigawatt-scale developments. Despite 80% of the world's offshore wind resource potential lies in waters deeper than 60m, only 188 MW of net floating wind capacity is in operation worldwide, accounting for 0.3% of total installed offshore wind capacity as of the end of 2022 (Global Wind Energy Council, 2023).

Predictions indicate that the commercialisation of floating wind will not be reached until 2026/2027. Considering the higher cost of floating wind compared with fixed-bottom as well as the expected supply chain bottlenecks in floating wind foundations and port facilities, estimations of floating wind likely to be installed worldwide range between 10.9 GW by 2030 and 26.2 GW by 2032 (Global Wind Energy Council, 2023), which shows how uncertain the current outlook is. In the second scenario, the contribution of floating wind to total wind installations would increase from today's 0.3% to 6%.

The UK, Norway, Portugal, China and Japan are currently the top five markets for total net floating wind installations. By the end of 2030, the UK, South Korea, China, Portugal and Norway will likely be the top five floating markets. As for regional distribution, Europe is expected to contribute 66% of total installations added in 2023-2032, followed by APAC (32%) and North America (6%) (Global Wind Energy Council, 2023).

Potential factors contributing to South Korea replacing Japan in the top five markets may include South Korea's larger potential capacity for floating offshore wind power, estimated at 277 GW compared to Japan's 236 GW. Additionally, South Korea is expected to implement a new site selection and tender system aimed at expediting deployment, potentially surpassing Japan's prolonged development timeline of seven to eight years from project allocation to commercial operations (Global Wind Energy Council, 2023).

4.2.2.2 Wind: domestic market size

The UK is a global leader in deploying offshore fixed wind energy, positioning itself as a primary investment target with consolidated advantages.

With a total of 50 offshore wind farms, the combined capacity of operational and under-construction projects was 20.3GW at the end of 2022 (The Crown Estate, 2022).

- Operational capacity: in 2022, the UK's total operational offshore wind capacity was 13.7 GW, accounting for 24% of global capacity, second only to China, and 45% of the European offshore wind total.
- Projects under construction: as of the end of May 2023, nearly 10 GW of offshore wind projects were under construction, and more than 100 GW of projects were at different stages of development, again only second to China worldwide (Global Wind Energy Council, 2023).

The UK has the ambition to deploy up to 50GW by 2030, with up to 5GW coming from floating offshore wind (Global Wind Energy Council, 2023).

Driven by government policies enforcing strict progress deadlines and a competitive auction process, the UK's success in wind farming is further facilitated by its windy coastal geography along the North Sea, which is relatively shallow to make constructing wind farms easy (The Economist, 2022).

Primarily focusing on fixed-bottom wind, the UK had 14.7 GW of operational capacity in 2023 (DESNZ, 2023), including the world's first, second, third and fourth most significant offshore wind farm projects and largest fleet outside China (Floating Wind Offshore Wind Taskforce, 2023) (DESNZ, 2023). By the end of 2023, for instance, the UK government announced the commitment of nearly GBP 1.1 billion in government investment through the Green Industries Growth Accelerator (GIGA), including GBP 400 million for offshore wind investments (UK Government, 2023).

The country is also pioneering FLOW, with the most significant global deployment at 78 MW, a further approximately 150 MW through planning, and a pipeline beyond 19 GW (DESNZ, 2023). The Government has also signalled its support for FLOW with an ambition of up to 5GW by 2030, viewing the technology as critical to the country's energy transition away from fossil fuels and an opportunity for economic growth and new jobs (Floating Wind Offshore Wind Taskforce, 2023). FLOW has the potential to become a truly enormous global industry, opening up over 80% of coastal seabed unsuitable for fixed-bottom offshore wind. In the context of the ScotWind, INTOG and Celtic Sea FLOW leasing rounds, the UK is poised to become one of, if not the first, country seeking to deploy FLOW at a commercial scale, thereby creating a globally significant library of skills, experience, and intellectual property. The ORE Catapult's Floating Offshore Wind Centre of Excellence has estimated that FLOW has the potential to deliver GBP 43.6 billion in UK GVA by 2050, creating more than 29,000 jobs in the process (DESNZ, 2023). However, seizing this first-mover advantage will be highly dependent on securing investment in appropriate upgraded port capacity (Floating Wind Offshore Wind Taskforce, 2023), (DESNZ, 2023). In 2023, the UK government launched the Floating Offshore Wind Manufacturing Investment Scheme (FLOWMIS) with an allocation of up to GBP 160 million in grant funding for supporting critical port infrastructure to enable the delivery of floating offshore wind (DESNZ, 2023). Components are of such a size that road transport is impossible, and double-handling and transportation are expensive. Therefore, ideally, investment in large component manufacturing should be conglomerated around dedicated offshore wind ports accessible to multiple users (Department for Energy Security and Net Zero, 2023).

The report “Industry Roadmap 2040: Building UK Port Infrastructure to Unlock the Floating Wind Opportunity” highlights that port construction investments of up to GBP 4 billion between 2025 and 2030 would allow the UK to generate approximately 3 to 4 pounds of added value to the economy for every pound invested in port facilities to support the FLOW sector (present Value benefits of 14-18 bn between 2023 to 2040). This scenario would also support around 23,000-30,000 additional FLOW jobs in the UK. Furthermore, further development of existing technology solutions and assets will be necessary to secure the necessary fleet of vessels required for the installation and O&M of FLOW. As demand and scale increase, it is anticipated that next-generation vessels will be built with a dedicated focus on this purpose (Floating Wind Offshore Wind Taskforce, 2023).

4.2.2.3 Tidal: global market size

Cumulative installations of Tidal stream in European countries are 30.2 MW (installed in Europe since 2010), and around 13MW planned (source: Ricardo's expert's judgement).

Tidal energy is a much less mature technology than wind, and its future market size estimates are more uncertain. The predictable and consistent nature of this energy source holds significant potential; however, technological developments have been expected for a considerable period of time but have not yet occurred (source: Ricardo's expert's judgement).

The future of the tidal stream energy market depends on the practical exploitation of natural resources. Estimates indicate a global tidal stream resource exceeding 100 GW, but the realistic global capacity installed by 2030 is expected to be only a few gigawatts (Serin E, 2023). Under high growth scenarios for ocean energy, 2.4 GW of tidal stream capacity could be deployed globally by 2030 (Ibid.). Despite the smaller immediate market, projections suggest a potential annual market value of over GBP 10 billion by 2050, contingent upon achieving a global deployment of 50 GW (achievable under optimistic scenarios) (Ibid.).

4.2.2.4 Tidal: domestic market size

Several pilot projects have been carried out in the UK so far, and the UK stands at the forefront of global tidal stream energy development, with an operational capacity of around 10 MW (2023), representing over half of the world's current capacity in this sector. This leadership position is underpinned by the UK's significant tidal stream generation capacity, both installed and under development, and the presence of numerous tidal stream technology developers (Serin E, 2023).

While the UK faces competition from France and Canada in terms of tidal stream capacity under development, numerous other countries, including China, Japan, the US, Korea, and the Netherlands, are actively engaged in tidal stream energy. Many of these nations already possess existing tidal stream capacity or have projects in development (Serin E, 2023). Consequently, there is potential for these countries to further expand their domestic markets by harnessing the tidal resources in their respective waters.

4.2.2.5 Summary of market size at the technology level

Regarding global market size, fixed offshore is poised to remain at the top of the offshore wind hierarchy by all credible sources and is now a mature and affordable technology with some of the lowest LCOE. Conversely, only locations without easy access to a continental shelf will consider floating offshore a suitable technology, but this may still be a worse investment than other reliable and cheap forms of generating power, e.g., onshore wind and PVs.

Tidal stream has no strategic case for deployment in locations without suitably rough, shallow seas strongly affected by tides. For this reason, tidal stream generators are not yet mass-produced, let alone at a scale comparable to wind turbines. Therefore, it looks unlikely that this technology will grow to anything other than a tiny fraction of wind power, and neither will its market value. Consequently, we consider the growth projections set out by some commercial publications as overly optimistic, and we recommend that these should be treated as a higher boundary rather than a likely outcome.

Table 4-4: Global market size growth potential: RAG rating by technology

Tech family	Technology	RAG rating	Justification
Wind	Offshore (fixed)	High	Very mature, competitive cost of energy. Fixed offshore has a proven track record of falling costs. LCOE of utility-scale offshore wind has fallen by more than 70% in recent years (Global Wind Energy Council, 2023). Considering NREL's cost projections and projected and expected increases in annual installations, the global market size is expected to increase between five and eightfold between 2022 and 2030.
	Offshore (floating)	Medium	They are more complex and less mature than fixed foundations, making them more expensive. They are complementary to fixed foundations in case the depths get too great. Compared to fixed offshore, floating wind farms have the potential to become increasingly competitive in the coming years. According to IRENA, floating wind farms could cover around 5–15% of the global offshore wind installed capacity by 2050 (IRENA, 2019). Still, the outlook is very uncertain in the early stages. Predictions indicate that commercialisation will not be reached until 2026/2027. The contribution to total wind installations could increase from 0.3% in 2022 to 6% in 2032.
Tidal	Tidal stream	Low	Complex technology has higher upfront costs, operating in a harsh environment, then a high energy cost. There is no mature manufacturing ecosystem. Significant uncertainty around the future growth potential. Uncertain estimates of future market size exist in very early stages—a potential annual market value of over GBP 10 billion by 2050.

4.2.3 Qualitative analysis: UK market shares

4.2.3.1 Trade flows analysis

The table below shows the annual average of UK exports (2021-2022) for some selected HS subheading codes (provided by DESNZ) relating to components used in the manufacture of wind energy equipment and parts. This sector's total average is 1.2% of the global tradable market. However, it is essential to acknowledge the limitations of this approach, as not all subheading codes included pertain to wind energy exclusively, and other pertinent codes may not have been captured. Therefore, these numbers can be interpreted as indicative proxies of the UK's share of tradable export markets.

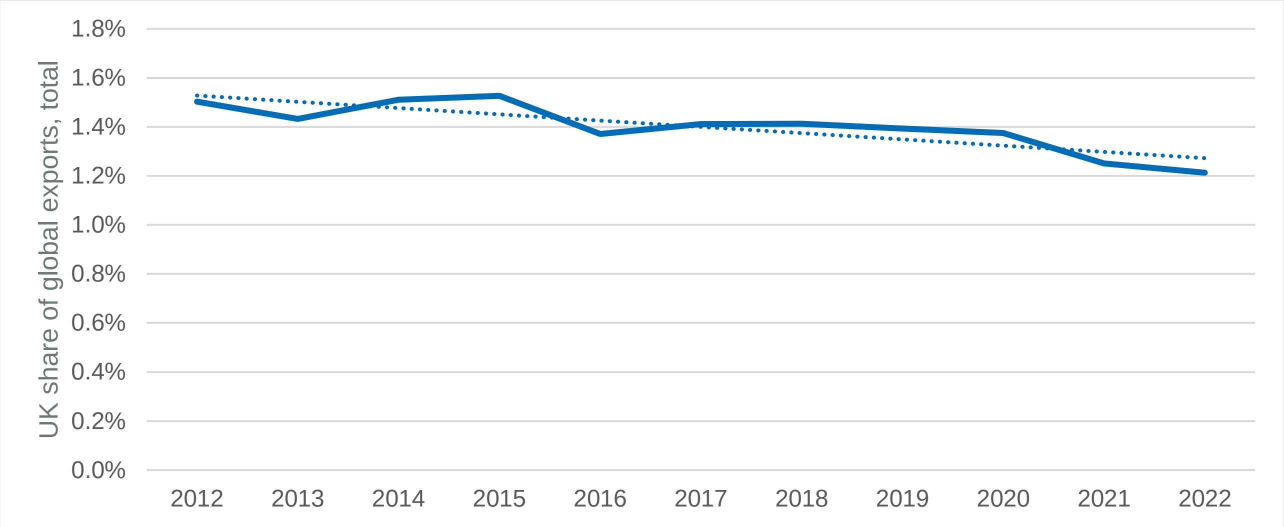
Table 4-5: UK share of global exports, selected HS subheadings, 2021-2022

Group	Subheading included in group	Annual UK exports, average 2012-2022 (nominal)	UK share of global exports
73: Articles of iron or steel	730820 Iron or steel; structures and parts thereof, towers and lattice masts 730890 Structures and parts of structures, of iron or steel, n.e.s. 761090 Bridges and bridge-sections, towers and lattice masts, of aluminium	USD 776 million	1.5%
76: Aluminium and articles thereof	761090 Bridges and bridge-sections, towers and lattice masts, of aluminium	USD 101 million	1.6%
84: Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof	841290 Engines; parts, for engines and motors of heading no. 8412 848210 Ball bearings 848230 Bearings; spherical roller bearings 848340 Gears and gearing for machinery; ball or roller screws; gear boxes and other speed changers 848360 Clutches and shaft couplings, incl. universal joints, for machinery	USD 930 million	1.4%
85: Electrical machinery and equipment and parts thereof	8504 Electrical transformers, static converters (for example, rectifiers) and inductors 850231 Electric generating sets; wind-powered, (excluding those with spark-ignition or compression-ignition internal combustion piston engines) 853720 For a voltage exceeding 1,000 V 854129 Electrical apparatus; transistors (other than photosensitive), with a dissipation rate of 1 W or more	USD 1,772 million	1.0%
90: Optical, photographic, cinematographic, measuring, checking, precision, medical or surgical instruments and apparatus; parts and accessories thereof	903020 Oscilloscopes and oscillographs	USD 67 million	1.7%
Total		**USD 3,646 million**	**1.2%**

Source: Ricardo elaboration on UN Comtrade data

The figure below shows a downward trend in the UK's share of global exports for the total HS codes analysed, from 1.5% in 2012 to 1.2% in 2022.

Figure 4-2: UK share of global exports, 2012-2022



Source: Ricardo elaboration on UN Comtrade data

4.2.3.2 UK market shares: qualitative analysis: wind

The following table reports the global wind supply chain for main components in 2023, according to a 2023 report by Boston Consulting Group for the Global Wind Energy Council.

Table 4-6: Wind turbine market: split by main component

Component	Number of manufacturers (2023)	Collective manufacturing capacity (2023)	Regional distribution (2023)
Turbine gearboxes	18	165 GW per year	80% (133 GW) in China 9% (15 GW) in India 10% (17 GW) in Europe (Germany, Belgium, Spain and Japan).
Turbine generators	27 (22 independent generator producers, five wind turbine OEMs)	156 GW per year	73% (115 GW) in China 5% (8 GW) in India 3% (4 GW) in other APAC countries (Vietnam, South Korea) 16% (25 GW) in Europe (Germany, Finland, Spain, Serbia, Bosnia, France, Austria) 2% (3.5 GW) in South America (Brazil) 1% (1.6 GW) in North America (United States)
Turbine blades	30 (16 rotor blade producers, 14 are wind turbine OEMs)	157 GW per year	64% (101 GW) in China 8% (13 GW) in India 0.4% (0.6 GW) in other APAC countries 13% (20 GW) in Europe (Denmark, Turkey, Poland, France) 8.9% (14 GW) in LATAM (Brazil) 4.9% (7.7 GW) in North America (United States, Canada, Mexico) 0.2% in Africa and the Middle East (Morocco, Iran)
Turbine power converter	18	226 GW per year	82% (185 GW) in China 5% (11 GW) in India

Component	Number of manufacturers (2023)	Collective manufacturing capacity (2023)	Regional distribution (2023)
	(14 independent producers, four are wind turbine OEMs)		1% (2 GW) in other APAC countries 10% (22 GW) in Europe (Denmark, Germany, Spain) 2% (5 GW) in South America (Brazil) 1% (2 GW) in North America (United States)
Turbine towers	50	4,000 towers for offshore wind	54% in China 7% in India 6% in other APAC countries 18% in Europe 3% in South America 11% North America 1% rest of the world

The global wind turbine manufacturing market has seen multiple rounds of consolidation and is now dominated by a selected number of large international players. Despite all major manufacturers in the UK market, these groups tend to use any UK manufacturing facilities to serve their strong domestic demand only. Due to this domestic-centric emphasis, the export opportunities for goods in this sector may be limited, as British companies will prefer to serve domestic demand while other larger manufacturing facilities outside the UK will be available closer to non-UK customers and serve demand outside the UK. A more detailed study on the competitiveness of British companies with an emphasis on exports is presented in Section 4.3.4 of this study, going more in depth into other factors affecting British exports, such as costs and production capacity. The only turbines manufactured in the UK that may be currently exported are roof-mounted or residential-scale, but there is no available literature on this market segment.

None of the leading companies along each supply chain step are UK-headquartered except for some large consultancies. However, it appears feasible that UK designers involved in obtaining patents (e.g. for floating offshore solutions) and engineering consulting companies could retain their world-class expertise and sell their IP.

For example, Ricardo has direct knowledge of several major companies, including engineering designers and power utilities, that design and commission offshore electrical systems from their UK bases for UK and non-UK European projects. However, no credible sources set out the split of UK vs non-UK revenue.

With the Green Industries Growth Accelerator (GIGA), the UK aims to develop its offshore wind sector further. With around GBP 400 million available for the offshore wind sector combined with the ambitious objectives to exponentially increase the amount of offshore energy produced, it should give a boost to British wind turbine manufacturers, promoting domestic industry and helping British companies stay competitive in international markets in part due to their technical expertise arising from their experience in the sector. However, given that details on how GIGA will function and how it will help the offshore wind sector are not yet available, we cannot quantify the exact impact of these investments. It is also worth noting that the EU has, in January 2023, updated its offshore wind production objectives, with countries like Germany, the Netherlands, and Denmark setting out very ambitious plans. The EU will need to scale up installation almost sevenfold by the end of the decade to achieve the combined national targets for offshore wind energy production (Rabobank, 2023). Thanks to the experience of British firms in the sector and good trade relations with EU countries, this could potentially be an opportunity for British companies to export components and technical expertise, ensuring their competitiveness in international markets. As previously mentioned, Ricardo has direct knowledge of these partnerships already happening.

4.2.3.3 UK market shares: qualitative analysis: tidal

The UK tidal energy supply chain is currently world-leading. Of 83 tidal technologies manufacturers, 22 are based in the UK, currently rivalled only by the USA with 19 (EMEC European Marine Energy Centre LTD, 2020).[9] While being a market leader creates significant potential for the UK to share expertise and export components, a concrete export market has not yet materialised, with most of the UK's manufacturing output being directed to its internal market.

Text Box 4-2: UK manufacturers of tidal energy components

Below is a list of manufacturers of tidal energy components based on a preliminary analysis. These entities' GBP 24M combined turnover provides valuable insight into determining their UK market share. This is significantly lower than the estimates found in some market research publications.[10]

Name of the manufacturer	Product	Turnover (if publicly available)	Source
Nova Innovation Ltd	Horizontal Axis Turbines	USD 11 million[11]	(Growjo, s.d.)
Orbital Marine Power	Twin turbines fixed to retractable legs, mounted to a floating platform	USD 8.1 million	(Growjo, s.d.)
Ocean Flow Energy	Horizontal Axis Turbines	USD 4.5 million[12]	(Growjo, s.d.)
SIMEC Atlantis Energy Limited	Horizontal Axis Turbines	GBP 3,194,000[13]	(SIMEC Atlantis Energy , s.d.)
Free Flow 69	Vertical Axis Turbines	USD 3 million	(RocketReach, s.d.)
Current2Current	Vertical Axis Turbines	N/A	--
EC-OG	Vertical Axis Turbines	N/A	--
Flex Marine Power Ltd	Swimmer Turbines	N/A	--
Hales Water Turbines Ltd	Side Drive Turbines	N/A	--
Lunar Energy	Enclosed tips (Venturi)	N/A	--
Nautricity Ltd	Horizontal Axis Turbine		
Repetitive Energy Company	Vertical Axis Turbine		
SeaPower Gen			
SMD Hydrovision,	Horizontal Axis Turbine	[14]	(SMD, s.d.)
Suanders Energy Ltd	Horizontal Axis Turbine		

Evidence in the literature suggests that the UK market share of its domestic market is very high. UK tidal stream projects have maintained a significant domestic content, exceeding 80% in most cases. Developers also intend to maintain high domestic content, aiming for up to 95% in future projects. Frost mentions that "the majority of non-UK content is in the powertrain, for example bearings, gearbox and generator. SKF, a Swedish company, are a key supplier of these components for several turbine manufacturers" (Frost, 2022).

Evidence points out caution regarding the UK's potential to increase its share in the export market. Due to the intrinsic limitations of tidal stream technology, countries without suitable characteristics will generate renewable electricity via different technologies (e.g., onshore wind or PV) and acquire the respective technologies. Another issue, as Serin points out (Serin E, 2023), is that countries with a robust manufacturing base, such as

[9] Other manufacturers count: 2 Sweden, 3 Spain, 6 Norway, 4 Netherlands, 1 Mauritius, 1 South Korea, 2 Japan, 1 Italy, 3 Ireland, 4 Germany, 6 France, 5 Canada, 5 Australia (EMEC European Marine Energy Centre LTD, 2020).

[10] These higher estimates and projections have been nonetheless included in Appendix 2.

[11] Nova consortium has won EUR 20 million of EU funding to install 16 turbine SEASTAR project in Orkney. The SEASTAR project will see more turbines installed than all other current deployments worldwide combined.

[12] It also comprises off shore floating wind turbines.

[13] The group total equity at 31 December 2020 amounted to GBP 81.8 million. Power sales from the MeyGen tidal power project were GBP 3.9 million.

[14] 100M projected turnover by 2025. Unclear the share of tidal.

Germany, are actively pursuing tidal technology development, suggesting competition will not only come from countries with strong internal demand.[15] The main challenge for the UK will be to retain its specialism in high-value components of the tidal steam supply chain, such as hydraulic turbines, if the global tidal stream market were to expand. The analysis highlights that the UK's strengths lie in products of lower complexity and proximity[16], indicating development opportunities.

The UK, which is not a specialised exporter of tidal stream energy products at an aggregate level yet, is found in the same report to have fewer existing strengths[17] in this sector compared to Japan or France but slightly more than Canada. Additionally, the UK trails behind France in terms of proximity. Owing to all these reasons, it appears likely that most of the UK’s manufacturing output will continue to be directed to its strong internal market.

Nonetheless, a study by the Supergen Offshore Renewable Energy (ORE) Hub and the Policy and Innovation Group (P&IG) suggests that exports linked to tidal stream power could accumulate between GBP 2.5–12.7 billion in GVA for the UK economy by 2050 (Serin E, 2023). These projections, however, rely on a potential annual market value of over GBP 10 billion by 2050, contingent upon achieving a global deployment of 50 GW, which represents half of the natural resource and, therefore, represents, in our opinion, an excessively optimistic scenario. To tap into this prospective market, the UK would need to focus on further developing its supply chain. Some sources point to positive prospects for development – for example, according to Catapult, the UK can develop world-leading technology in the global market (Smart & Noonan, 2018).

In conclusion, while it is acknowledged that the UK possesses the potential to leverage its leading expertise in tidal energy, the existing literature presents divergent viewpoints on the potential future trajectory of this industry. On the one hand, realising an export market remains elusive, hindered by the technology's restricted use cases and competition from other countries. On the other hand, some projections offer a more optimistic outlook, suggesting positive prospects for development if the UK continues to enhance its supply chain capabilities. Consequently, the future of the UK tidal energy industry remains uncertain, with contrasting possibilities on the horizon. In the table below, we assess whether there is potential for the UK to capture a market share higher than, in line with, or below the sector average indicated in the quantitative analysis above.

Table 4-7: Technologies that have the potential to attract significantly higher/lower market shares compared to the sector average

Tech family	Technology	Rating	Justification/rationale and key sources
Wind	Fixed Offshore	Higher than average	The UK has a well-developed offshore wind sector, with fixed offshore wind dominating the installed capacity (over 99%). The UK has a well-developed ecosystem around offshore wind, especially around engineering and services, and this can be leveraged and supported to increase capacity and deliver high-value-added exports. Despite relatively low manufacturing activity compared to other countries, the UK has a manufacturing base that meets domestic needs. GIGA could help British companies produce the required components domestically. This would protect Britain’s ambitious national plans for offshore wind energy production from external shocks and supply-chain bottlenecks while promoting domestic industry and creating jobs and wealth.
	Floating Offshore	Average	The UK is one of the pioneers in floating offshore wind, with Hywind in Scotland being the first floating wind farm in the world. As with fixed foundation offshore wind, there is scope to export engineering and services and leverage the sector's expertise and experience.

[15] Most countries actively engaged in deploying or considering the implementation of domestic tidal stream energy, such as China, Japan, and the US, are major exporters of relevant products in this field. Surprisingly, among the top countries specializing in the export of products relevant to tidal stream energy, many lack significant domestic activity explicitly associated with tidal stream energy. Notably, countries like Denmark, Slovenia, and Germany do not possess substantial natural tidal resources or noteworthy domestic initiatives related to tidal stream energy. (Serin E, 2023).

[16] Used in (Serin E, 2023) as the average proximity of a product to all the products that a country is specialised in exporting (i.e. has a revealed competitive advantage in).

[17] Defined as RCA, product complexity, and proximity.

Tech family	Technology	Rating	Justification/rationale and key sources
			Additionally, the UK is investing in low-carbon floating wind installation vessels, which can potentially increase the UK's presence in international markets. GIGA has the potential to help further develop projects related to floating offshore wind, namely by helping British companies scale up their trials for technologies that are in more advanced Technology Readiness Levels (TRLs) but not yet mature enough to be in the market or fully operational.
Tidal		Average	The UK is a leader in this industry due to its great natural resources and significant research conducted in the country. However, Tidal stream remains a small industry due to its inherent challenges and limitations—it is a complex technology operating in a harsh environment, resulting in challenges around reliability and high costs. A potential for export in the tidal stream space is the UK's engineering expertise. However, the difficulties around commercialising the technology will act as a barrier to this and any other form of export.

4.3 RQ2: UK COMPETITIVE ADVANTAGE

4.3.1 Quantitative analysis at the sector level

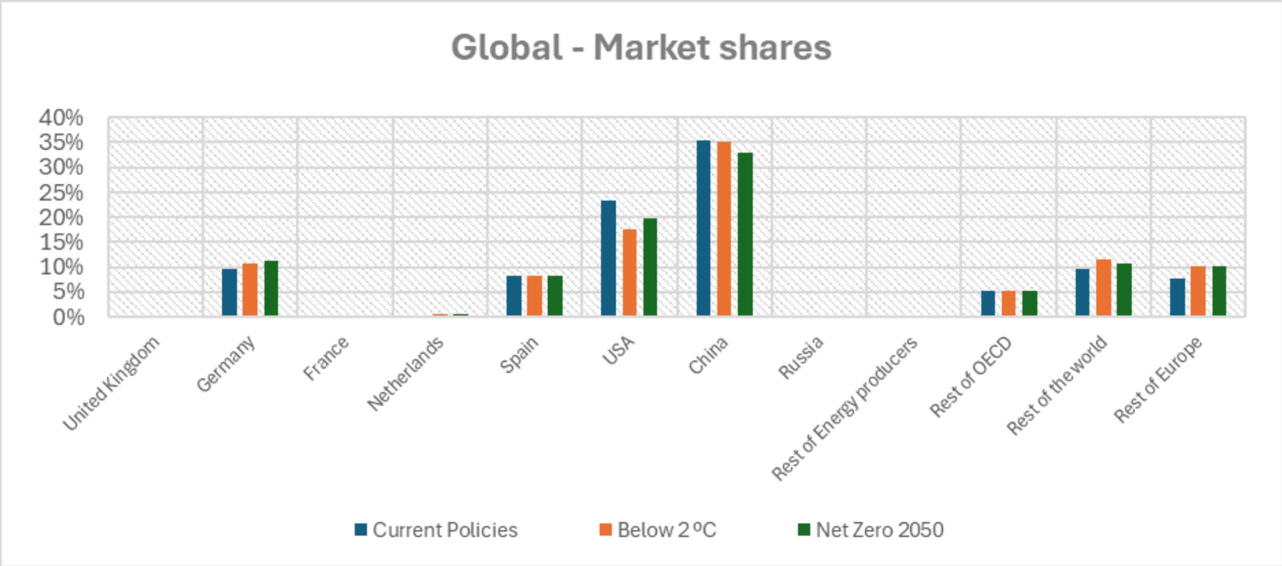
The wind turbine market has transitioned into a mature and competitive industry. Large-scale onshore and offshore wind projects substantially contribute to global energy production.

By 2050, the United Kingdom will hold a small market share (0.3% -0.4 %) in the wind equipment industry. The predominant wind equipment manufacturers are in the European Union, with global market shares ranging from 26% to 31% across different scenarios, and China, accounting for 33% to 36% of the global market across these scenarios.

The heightened commitment to intensify efforts in reducing greenhouse gas (GHG) emissions is expected to drive an increased global demand for wind equipment. In these scenarios (Below 2 ºC, Net Zero) and compared to the current policy scenario, the EU is anticipated to witness a rise in its market share, given its substantial contribution to the export market. The USA is expected to experience a similar trend, but with its production of wind equipment primarily used to satisfy domestic demand.

Changes in market shares across countries depend on countries' capacity to cover the additional wind equipment demand (through investments and R&D) and GHG mitigation efforts that increase countries' domestic demand and affect bilateral trade transactions in the wind equipment sector.

Figure 4-3: Market shares in 2050



Source: Ricardo analysis based on GEM-E3 outputs

4.3.2 Key drivers of competitive advantage

Despite favourable political support for renewable energy, the Western wind turbine industry faces a challenging landscape. The Inflation Reduction Act in the United States and European commitments to increase offshore wind capacity should provide ample opportunities for turbine manufacturers. However, the four major Western turbine makers (GE Renewable Energy, Nordex, Siemens Gamesa, and Vestas) experienced nearly EUR 5 billion combined net losses in 2022. The struggle stems from conflicting market forces: declining turbine prices and a slowed demand due to challenges in obtaining permits.

The race to build larger turbines has intensified the problem as the industry contends with supply chain disruptions, raw material shortages, inflation, higher interest rates, and geopolitical tensions. The prolonged timeline from contract signing to turbine installation exacerbates exposure to market fluctuations. The industry's focus on larger turbines may also pose long-term challenges, potentially impacting maintenance costs and service contract margins.

Chinese turbine manufacturers are rapidly growing, presenting a competitive threat. Western turbine companies must return to profitability to contribute to the decarbonisation goals, possibly requiring government intervention. While recent measures, such as the EU's easing of permissions for new wind farms, are a positive step, more concrete timelines for investments and clearer regulations are needed to ensure the industry's stability (The Economist, 2023).

The following tables discuss sector-specific drivers (classified as barriers or enablers when possible) in greater detail. The methodology for assigning the RAG ratings to enablers and barriers follows the approach detailed in the ‘Cross-cutting barriers and enablers’ chapter above. This applies to all sector-specific barriers and enablers tables across all the following sector-focused chapters.

Table 4-8: Key drivers of energy policy and market developments globally (wind)

Category	Driver	Description	RAG
Drivers	Acknowledged need at the global level to increase global renewable energy capacity	International energy agencies and net zero roadmaps agree on the primary role of wind energy on the road to net zero. IRENA's World Energy Transitions Outlook foresees 3,040 GW of cumulative onshore wind by 2030 and 494 GW of offshore wind by 2030, or about 3.5 TW of total wind installed by 2030. The IEA's Net Zero by 2050 Scenario calls for 2.75 TW of wind installations in 2030, with 320 GW installed in 2030 alone (Global Wind Energy Council & Boston Consulting Group, 2023). In either scenario, global wind growth must rapidly accelerate to meet 2030 targets for a 1.5°C pathway. This would mean ramping up annual global wind installations from the current 110 GW by roughly 3-3.5 times by the end of the decade. Current supply chains only have enough capacity to deliver on growth scenarios that fall short of net zero. Supply chains must scale across all activities and markets to allow the industry to achieve the necessary 2.75 TW of installed capacity by 2030. Global wind growth must rapidly accelerate to meet 2030 targets for a 1.5°C pathway. This would mean ramping up annual global wind installations from the current 110 GW by roughly 3-3.5 times by the end of the decade. (Global Wind Energy Council & Boston Consulting Group, 2023) At the COP28 climate change conference in Dubai, more than 130 national governments, including the European Union, agreed to collaborate to triple the world's installed renewable energy capacity by 2030 (IEA, 2024).	N/A
	Rapid innovation	Continuous technological progress in the wind energy sector has led the industry to reach a new stage characterised by large turbines tailored to specific markets, for instance, market-specific Wind Turbine Generator (WTG) designs to match physical limitations such as highway payload limitations in the USA, environmental requirements in the EU, climate conditions in the Middle East, or grid limitations in Australia. However, this specialisation has made these turbines less suitable for the broader global market. At the same time, the rapid increase in turbine sizes has resulted in several core industry challenges becoming increasingly evident. These include a shortened product development lifecycle that can lead to defects stemming from untested new technology deployments, significant R&D spending for OEMs that they have not been able to recuperate, and a lack of industry standardisation pushing up costs. Source: (Global Wind Energy Council & Boston Consulting Group, 2023)	N/A
Enablers	UK's geographical advantage	Britain's coastline runs along the western shore of the North Sea, one of the windiest places on earth. It is relatively shallow, which makes constructing wind farms easier. Soeren Lassen, head of offshore wind research at Wood Mackenzie, affirms that it is one of the best places in the world to build offshore wind. (The Economist, 2022)	
	UK's announced investments	By the end of 2023, the UK government announced the commitment of nearly GBP 1.1 billion in government investment through the Green Industries Growth Accelerator (GIGA) to accelerate manufacturing in key net zero sectors, including GBP 400 million for offshore wind investments. (UK Government, 2023)	
Barriers	Slow permitting procedures	Slow and complex permitting for both onshore and offshore wind projects globally is delaying future investment decisions by manufacturers. In 2022, around 80 GW of wind installation projects in Europe were stuck in permitting procedures. (IEA, 2023)	
	Vessel shortage	A lack of vessels is looming as a potential future barrier to the scale-up of wind installations in line with countries' climate ambitions. This issue is further exacerbated by the increasing size of wind turbines in recent years, requiring ever bigger vessels and associated adaptations at ports. (IEA, 2023)	
	Financial instability and contracting risks in	The completion of offshore wind manufacturing capacity relies on the financial stability of original equipment manufacturers (OEMs), impacted by tendering and contracting uncertainties. Delays or cancellations in	

Category	Driver	Description	RAG
	offshore wind manufacturing	project awards directly affect manufacturing facilities, potentially jeopardising future investments and causing under-investment across the supply chain. Challenges include risky contract prices leading to bid failures in auctions, underutilisation of existing capacity, and slow permitting processes, contributing to a potential reduction in global manufacturing capacity. (IEA, 2023)	
	Increased steel prices	Russia's invasion of Ukraine pushed up steel prices, an essential input of which both countries are large producers, soaring up wind turbine costs. (The Economist, 2023)	

Table 4-9: Key drivers of energy policy and market developments globally (tidal)

Category	Driver	Description	RAG
Enablers	UK's marine energy resource	The UK has some of the best marine energy resources in the world, and many of the technology concepts have originated from the UK. The UK's 22 tidal stream technology developers, already referenced, are currently rivalled only by the USA, with 19. (Smart & Noonan, 2018)	
Barriers	Lack of an immediate route to market	Worldwide, tidal stream developers lack an immediate route to market to enable volume deployment, standardisation, and the application of existing innovation activity. They also lack ongoing R&D funding to further enhance the technology and solutions available. (Smart & Noonan, 2018)	
	High price differential with other renewable energy technologies	The price differential between tidal stream and other technologies will likely remain high for the foreseeable future. It is unlikely that including non-price factors in the assessment criteria would substantially change the ability of tidal stream projects to secure revenue support outside the ringfence for now. (Serin E, 2023)	
	Weak financial position of UK companies	According to desk research conducted in preparation of this report, some tidal energy manufacturing companies (Sustainable Marine Energy (SME) and Tidal Energy Ltd) are now in administration, and other key players (SIMEC Atlantis Energy LTD) have stopped producing the equipment. They are now exclusively focusing on power generation.	

4.3.3 Geographical benchmarking

Major global market players are strategically positioning themselves to align with ambitious environmental goals and capitalise on the growing demand for clean energy. The United States has released a comprehensive Offshore Wind Energy Strategy and adopted the Inflation Reduction Act (IRA) to reduce reliance on imports and stimulate domestic manufacturing growth. The European Union, committed to climate neutrality by 2050, emphasises industry boost through legislative measures, funding, and supply chain resilience.

China strategically dominates the global supply chain, from rare earth element refining to component manufacturing, signalling intentions for further expansion. India is also emerging as a key player in the global wind supply chain, benefiting from the diversification strategies of European and American turbine OEMs. Australia, with the establishment of offshore wind zones, is also setting targets to attract investment and foster the growth of offshore wind projects.

For decades, Europe has been the world's largest regional offshore wind market in terms of cumulative offshore wind installation. However, it lost its title to Asia-Pacific in 2022 due to strong growth in China in the past five years. APAC's leading position in total offshore wind installations is unlikely to be challenged in the next decade (2023–2032), but Europe is likely to become the largest market for new installations from 2030. North America will remain the third-largest offshore wind market by 2032.

The following table discusses the positioning of key market players (US, EU, China, India, and Australia) in greater detail.

Table 4-10: Major competitors globally (offshore wind)

Country	Description
China	The Chinese wind industry released an initiative during the Global Offshore Wind Summit-China 2022 that calls for 100GW of offshore wind in China by 2025, 200GW by 2030, and 1,000 GW by 2050. (Global Wind Energy Council & Global Wind Organisation, 2023) China is the world's leading wind installer, currently procuring a 64% share of total industry value and an expected 58% share of planned near-term (2023–2025) global wind installations. Supply chain concentration is strongest for rare earth element refining: China has built up its mining – or secured access to mines elsewhere – for most of the materials it needs. Excavations are either within China or supported by Chinese investment in regions such as South America, Asia-Pacific or Africa, where reserves are concentrated. China dominates the refining of neodymium (100% global market share) and dysprosium (88%), both critical to manufacturing permanent magnets for wind and difficult to refine due to environmental concerns. China is also the leading component manufacturer of wind turbine generator components, such as gearboxes (80%), wind power converters (82%), wind power generators (73%) and castings capable of supplying wind (82%), for which the rest of the world is heavily dependent on continued imports. There are clear signals that China intends to keep growing its role as the leading component manufacturer for the global wind industry and further extend its involvement to providing finished wind turbines to international markets (Global Wind Energy Council & Boston Consulting Group, 2023).
EU	After China, the European Union is the second region with the highest manufacturing capacity for key wind energy components. For the more easily traded components – nacelles and blades – China accounts for 64% and 69% of capacity, respectively, whereas the European Union accounts for 16% and 18% (IEA, 2023). Europe has an interconnected supply chain, as the EU Free Trade Agreement helps the movement of goods across member states' borders. Noteworthy European countries in the wind supply chain include Germany, Spain and Denmark, all of which have significant activity linked to producing the main components of wind turbines – blades, nacelles, and towers. In recent years, France has also emerged as one of the key countries, with new blade and nacelle manufacturing plants. The Netherlands, Germany, and Denmark are key producers of offshore wind foundations. Unsurprisingly, these countries are also among the leaders in installed capacity for offshore wind in Europe. (Rystad Energy & WindEurope, 2023). The EU is laying out a multi-pronged approach to boost European industry while achieving energy and climate goals. Renewable energy projects could be given priority permitting in special 'go-to' areas under new provisions being considered in the upcoming revision to the Renewable Energy Directive. At the same time, the REPowerEU package offers renewables a EUR 20 billion funding pot. Additionally, the EU is looking to introduce legislation that would simplify and fast-track permitting procedures for climate-neutral industrial infrastructure to boost Europe's key green industries and their whole value chains. Efforts are also being made to reduce dependence on non-EU sources of raw materials and rare earth elements (REEs). (Global Wind Energy Council, 2023). Recent policies include the Critical Raw Materials Act and the Net Zero Industry Act. While the Net Zero Industry Act aims to support component supply chain sovereignty (with the target of increasing the EU's strategic net-zero technologies manufacturing capacity to at least 40% of annual deployment needs by 2030), the Critical Raw Materials Act aims to ensure the EU's access to a secure, diverse, affordable and sustainable supply of critical raw materials (Rystad Energy & WindEurope, 2023).
India	Since European and American turbine OEMs decided to diversify their supply chains to ensure the security of supply in the aftermath of the COVID-19 pandemic, India, the second-largest Asia-Pacific (APAC) hub for turbine assembly and key components production, has gained an increasingly prominent role in the global wind supply chain (Global Wind Energy Council & Boston Consulting Group, 2023). Government support for domestic manufacturing includes encouraging the manufacturing of various offshore wind installation vessels where a subsidy will be provided under the 'Shipbuilding Financial Assistance Policy' under the label of 'Specialised Vessels' (Global Wind Energy Council & Global Wind Organisation, 2023)
US	Although the US is the world's third largest (after China and Europe) wind nacelle manufacturing hub, North America is generally fully dependent on imported components and is already today experiencing an undersupply of especially components for offshore wind, including offshore towers, foundations and subsea cables. Furthermore, the US critically lacks vessels and ports. (Global Wind Energy Council & Boston Consulting Group, 2023). To reduce reliance upon imports and revive domestic manufacturing capacity growth, the Inflation Reduction Act (IRA) prioritises offshore wind planning and permitting reform legislation, manufacturing, and clean job creation in four ways: tax incentives for wind projects up to 2032; USD 100 million for offshore wind transmission planning; domestic manufacturing tax credit for offshore wind components and an extension of the investment tax credit for vessel construction; and offshore wind development in the southern Atlantic coast and the eastern Gulf of Mexico. Although the full impact of the IRA is still to be seen, the USA market is expected to accelerate sharply. (Global Wind Energy Council & Boston Consulting Group, 2023) (Global Wind Energy Council & Global Wind Organisation, 2023).
Australia	To encourage the offshore wind sector in August 2022, the federal government announced the establishment of several offshore wind zones around the country (Gippsland, Hunter Valley, Illawarra,

Country	Description
	Portland, Northern Tasmania, Perth, and Bunbury). While there are no federal wind targets, the Victoria State Government decided to provide investors with offshore wind business case certainty by setting a target of 2GW offshore wind generation by 2032, 4GW by 2035 and 9GW by 2040. Similarly, the newly elected New South Wales State Government is still considering introducing state offshore wind targets for its Hunter Valley and Illawarra zones (Global Wind Energy Council & Global Wind Organisation, 2023).

Table 4-11: Major competitors globally (tidal)

Country	Description
US	With 19 tidal stream technology developers, the country is currently the only one rivalling the UK tidal developers' fleet. However, the government plans to further invest in tidal energy technologies, as evidenced by adopting the Water Power Technologies Office's Marine Energy Program, which aims to fund research and development in marine energy technologies.
EU	In recent years, the EU has implemented numerous programs to accelerate the transition to a net-zero economy. Notable examples include Horizon 2020, the Innovation Fund, the REPower EU Plan, and the Green Deal Industrial Plan. These initiatives incorporate enabling schemes and consistent funding programs for renewable energy technologies, with the expectation that they will enhance the production of both these technologies and the energy itself. While these plans do not specify the allocation for tidal energy, European countries already investing in tidal stream energy, such as France and the Netherlands, could use these funds to boost their technology production. France and the Netherlands have 7 and 4 tidal technology developers, respectively.
China	The Chinese government has implemented its 14th Five-Year Plan for Renewable Energy Development, which aims to expand tidal stream energy demonstration projects and explore the application of ocean energy systems on islands. China accounts for 17% of the global export volume of products relevant to tidal stream energy. China's rapid rise as a key global exporter began in the '90s when it represented only 3% of global exports. Additionally, China is expected to increase its manufacturing capacity to boost its domestic tidal energy production further, reaching 1.7 MW as of 2023.

4.3.4 UK competitive advantage: qualitative analysis

4.3.4.1 Wind

A study by the Offshore Wind Industry Council & Offshore Wind Growth Partnership states that the UK is strong in development services, blade manufacture, cables, electrical (design, control, monitoring and protection), offshore services (construction, commissioning, and Operations and Maintenance - O&M), crew transfer vessels (CTVs) and moorings and anchors for floating wind.

However, it also highlights some clear areas of weakness. The UK lacks a major wind turbine generator (WTG) manufacturer and, until now, has almost no capability in WTG foundations. The UK also lacks top-tier engineering procurement and construction (EPC) contractors able to manage the supply and installation of major WTGs.

This study calculates that the UK supply chain can capture GBP 92 billion of economic value (Gross Value Add, or GVA) by 2040 if joint government and industry-targeted interventions are focused on the following nine areas of the supply chain in the coming years: cables, substations and electrical design, steel fabrication, floating wind, development services, offshore services, vessels, blades & rotor assembly, and WTG components (Offshore Wind Industry Council & Offshore Wind Growth Partnership, 2023).

While the UK faces stiff competition in established renewable energy sectors like offshore wind, it possesses the potential to develop competitive advantages in emerging technologies and niche areas by 2030 and beyond. Ambitious decarbonisation targets, a supportive policy framework, strong offshore wind infrastructure, advanced grid infrastructure, private sector commitment, and a growing focus on green skills training provide a foundation for future growth. By the end of 2023, for instance, the UK government announced the commitment of nearly GBP 1.1 billion in government investment through the Green Industries Growth Accelerator (GIGA) to accelerate manufacturing in key net zero sectors, including GBP 400 million for offshore wind investments. The package of measures will support economic growth and further establish the UK as one of the best countries in the world to invest in renewables while providing British companies with funding and support to grow. This will drive economic growth and bolster UK exports while removing bottlenecks from the supply chain (UK Government, 2023). However, challenges exist, including competition from other countries with similar advantages (such as China, the US, and Germany), talent retention and attraction, and a relatively small manufacturing base compared to competitors. Given that GIGA aims to target the whole supply chain, there are possible spillover effects in other sectors, making the UK economy more competitive.

Table 4-12: UK competitive advantages

Advantage	Description
Manufacturing of certain components and supporting services	Blade manufacture, cables, electrical (design, control, monitoring and protection), offshore services (construction, commissioning, and Operations and Maintenance - O&M), crew transfer vessels (CTVs), moorings and anchors.
Supportive policy framework	Ambitious decarbonisation targets and offshore wind deployment targets. GIGA committed investments. Growing focus on green skills training.
Existing infrastructure	Strong offshore wind infrastructure and advanced grid infrastructure.

Table 4-13: UK competitive disadvantages

Disadvantage	Description
Limited manufacturing and engineering capabilities	Lack of a major wind turbine generator (WTG) manufacturer. No capability in WTG foundations. Lack of top-tier engineering procurement and construction (EPC) contractors.
Strong competitors	Competition from other countries with similar advantages (such as China, the US, and Germany) and bigger manufacturing capabilities.

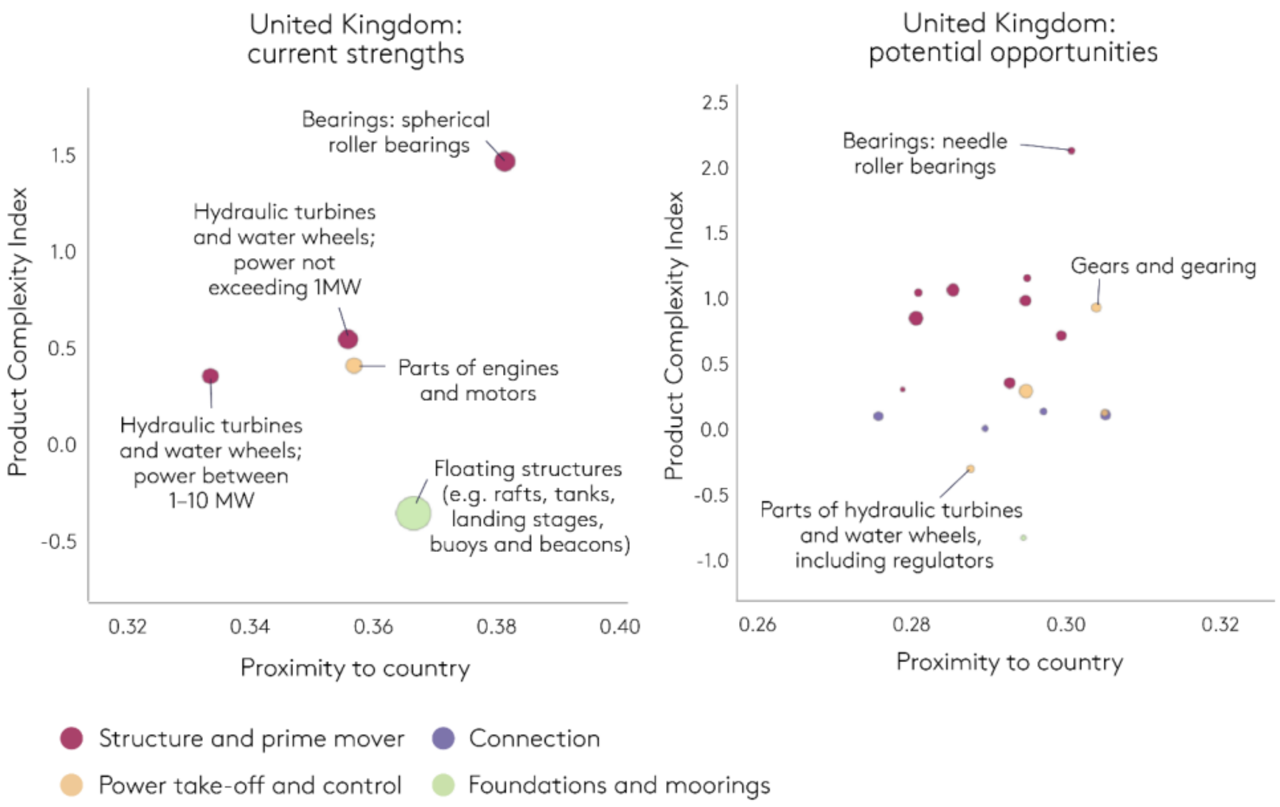
4.3.4.2 Tidal

While tidal stream energy may represent a smaller business opportunity than clean technologies like carbon capture and storage (CCS), nuclear, and offshore wind, it is recognised as a strategic area in the UK's net-zero strategy. The country's 2023 Independent Review of Net Zero highlighted tidal stream energy as an area where the UK is a first mover, suggesting the potential for creating distinct advantages in the future. Explicit policy direction and support are crucial to channel investments into tidal stream energy, ensuring its contribution to the broader clean energy landscape.

The UK has an export specialism in complex products relevant to tidal stream energy, such as hydraulic turbines crucial to the technological foundation of tidal stream plants. Moreover, the UK ranks fifth globally in revealed technological advantage in tidal stream energy innovation, indicating its prowess in research and development. If further supported by strategic investments, this innovation-centric approach can position the UK as a global leader, allowing it to export high-value products and specialised knowledge.

In conclusion, while the tidal stream energy market may currently be smaller than other clean technologies, the UK's leadership position, export specialism, and technological advantage provide a solid foundation for growth. Strategic investments in innovation, coupled with a comprehensive policy framework, can secure the UK's position in the global market, drive regionally balanced growth, and contribute to the country's net-zero goals. The interconnected approach involving tidal stream, offshore wind, and CCS can yield more significant economic benefits than pursuing one area alone, emphasising the importance of a holistic strategy in the UK's renewable energy landscape (Serin E, 2023).

Figure 4-4: Existing strengths and new opportunities for the UK in specific products, tidal stream (2016-2020)



Notes: Each bubble corresponds to a product and is sized by the UK's RCA in that product. RCA, PCI and proximity values are calculated based on average trade values for the products between 2016–2020, the latest five-year period available in our dataset. The products within the overall category defined as relevant for tidal stream energy are broken down into four categories of component types, explained further in Section 2 of the Appendix.

Source: (Serin E, 2023)

Table 4-14: UK competitive advantages

Advantage	Description
Export specialism and innovation	Development of complex products for tidal stream energy, such as hydraulic turbines
Supportive policy framework	Strategic area in the UK's net-zero strategy

Table 4-15: UK competitive disadvantages

Disadvantage	Description
Limited market	Smaller market compared to other clean technologies

4.3.4.3 UK Competitive advantage: key conclusions per technology

In the following table, we classify each technology using an RAG rating methodology as being either:

- A "**primary focus area"**, highlighted in green, i.e. an area where the UK is expected to have consolidated advantage;
- A "**further opportunity**", in yellow, i.e. an area where the UK could gain a competitive advantage from positioning itself as a potential early mover; or
- A "**lower potential"** is in red, i.e. an area in which the UK does not appear to have potential.

Table 4-16: Technologies classification based on UK competitive advantage

Tech family	Technology	Classification	Answer & justification/rationale
Wind	Offshore (fixed)	Primary focus area	The UK already has a thriving offshore wind sector with fixed bottom-mounted turbines. It boasts the world's largest operational offshore wind farm and possesses significant expertise in grid integration, supply chain, and installation. This established advantage in terms of a developed sector and considerable expertise, coupled with ambitious government targets, makes fixed offshore wind a clear primary focus area for the UK. However, the UK offshore wind production plants produce predominantly for the UK domestic market. It appears feasible that UK designers involved in obtaining patents and engineering consulting companies could retain their world-class expertise and sell their IP. With GIGA, UK firms can increase their competitiveness and become more innovative. Keeping British offshore wind companies at the forefront of technological innovation is key to the sector's competitive advantage.
	Offshore (floating)	Further opportunity	The UK has a head start with several pilot projects and research initiatives. By actively nurturing these efforts and capitalising on its existing expertise, the UK can become one of the leaders in this emerging market. GIGA can play a significant role here as it can help scale up new technologies, particularly those in a more advanced stage (higher TRLs), which often have issues finding funding.
Tidal	Tidal stream	Further opportunity	The UK boasts some of the strongest tidal currents in the world, making it a prime candidate for tidal stream energy. However, the technology is still nascent and faces challenges in cost, grid integration, and environmental impact. Nevertheless, the UK's early investments in research and pilot projects position it well to overcome these hurdles and become a leader in this technology as it becomes more commercialised. Note that the commercialisation of tidal stream energy is not guaranteed to happen.

5. CCS AND GGR

5.1 INTRODUCTION

Carbon capture and storage (CCS) refers to technologies that capture CO_2 generated from sources such as fossil fuels before it is released into the atmosphere. The process consists of several stages: CO2 capture, CO2 compression and transport, and finally, the usage or storage of CO_2.

CO_2 capture is divided into three main approaches: oxy-fuel combustion, pre-combustion and post-combustion.

- **Oxy-fuel process** involves the combustion of fossil fuels in a nearly pure oxygen environment instead of air to produce CO_2 and steam, with the released CO_2 subsequently captured.
- **Pre-combustion** methods involve converting the fuel into a gas mixture of hydrogen and CO_2 before it is burnt. Once the CO_2 is separated, the remaining hydrogen-rich mixture can be used as fuel (Grantham Research Institute on Climate Change and the Environment, 2023).
- **Post-combustion** separates CO_2 from the flue gas by using a chemical solvent, for instance, after the fuel is burnt. Chemical absorption using amine-based solvents is the most technologically mature CO_2 separation technique and is applied in the two large-scale projects in operation today (IEA, 2024).

Greenhouse gas removals (GGRs) consist of a range of technology-based and nature-based solutions, with two major novel technology-based solutions consisting of the following:

- **Bioenergy with carbon capture and storage (BECCS)** involves capturing CO_2 from processes where biomass is converted into fuels or directly burned to generate energy. Because plants absorb CO2 as they grow, this is a way of removing CO_2 from the atmosphere (IEA, 2023).
- **Direct air capture (DAC)** extracts CO_2 directly from the atmosphere at any location, unlike carbon capture, which is generally carried out at the point of emissions (IEA, 2023).

The other greenhouse gas removal methods, including methods such as afforestation and reforestation (currently accounting for the majority of greenhouse gas removals) (Smith S. M.-H., 2023). Ocean-based solutions, enhanced weathering, and others are not in the scope of this study.

After capture/removal, the CO2 is compressed and transported by pipeline, ship, rail or truck. It can be used in various applications or stored by injecting CO_2 into deep geological formations. If the CO_2 is permanently stored, the captured CO_2 is permanently removed from the atmosphere and results in emissions reduction (IEA, 2023). With CO_2 utilisation, the CO_2 can either be permanently stored or re-released into the atmosphere, depending on the CO_2 utilisation route. Therefore, for the CO_2 to be considered 'removed' and result in emissions reduction, the CO_2 utilisation route must result in permanent storage. With GGRs, if the CO_2 is permanently removed from the atmosphere and the CO_2 is considered 'removed', there is the potential for negative emissions, hence a net reduction in the overall CO_2 emissions to the atmosphere.

Table 5-1: In-scope technologies

Sector	Tech families	Technologies
CCS and GGR	CO_2 capture	Oxy
		Pre-combustion
		Post-combustion
	CO_2 storage	Geological storage
	Greenhouse Gas Removal	BECCS
		DACCS

5.1.1 Key takeaways

- Today, global capture and storage capacity both culminate at just over 45 Mt CO_2/yr, with a minor discrepancy between the two that is attributed to CO_2 utilisation. The view of the future role and scale of CCS and GGR vary, but recent sources estimate ca. 15-16 Gt CO_2/yr by 2050.

- Technologies used for CCS, resulting in emissions reductions, are generally more mature with higher TRLs than technologies used for GGR, resulting in negative emissions. The IEA's NZE scenario suggests that CO2 capture from fossil fuels would be five times larger than CO2 capture from bioenergy projects in 2030 (IEA, 2021), and a representative database of CCS projects in operation or under development is dominated by projects involving fossil fuels (Global CCS Institute, 2024).
- New technologies and improvements are under development for post-combustion, pre-combustion and oxy-fuel combustion carbon capture systems. It is currently unclear which CCS technologies will most effectively deliver the necessary cost reductions and performance improvements, as several are still in the early development and demonstration stages.
- Regarding carbon removal technologies, the available evidence suggests that the market for GGR could grow in the future, subject to continued policy support and industry coordination efforts.
- The UK market size for carbon removal (GGR) is expected to grow. The technologies need to be deployed in the UK by 2030 for net zero targets to be realised, and they will continue to play an important role beyond 2050. Removal technologies can abate residual emissions in hard-to-abate sectors and create economic benefits from the export of carbon credits.
- The UK market share in CO_2 geological storage is expected to grow significantly, as the UK has one of the largest theoretical CO_2 storage capacities in Europe. This can provide a significant opportunity for the UK to provide CO_2 storage as a service.
- Key drivers of CCS/GGR technologies globally include trends in production costs (for the technologies to become financially viable), the necessity of CCS/GGR deployment in relation to countries' commitments to achieve net zero emissions, and technological progress (also to reduce the costs). The key enablers are financial incentives, ETS and cost of carbon, and corporate ESG policies and sustainable investments. Key barriers globally are the lack of clear legal and regulatory frameworks and confidence in CO_2 storage availability.
- The UK's share in global trade in CCS has been around 5% from 1995 to 2019 (The Centre for Climate Change Economics and Policy (CCCEP), The Centre for Economic Performance (CEP), The Grantham Research Institute on Climate Change and the Environment, The Programme on Innovation and Diffusion (POID), 2021). The UK has introduced several fiscal and policy incentives to support the development of CCS. Other countries are also offering fiscal and policy incentives, such as the Inflation Reduction Act in the US. This may incentivise and attract UK companies to explore overseas opportunities, potentially diverting investments if the incentives may be more attractive elsewhere.
- The UK has several competitive advantages: mature supply chain capabilities and expertise in the Oil&Gas sector, strengths in the manufacturing of measuring, monitoring and verification (MMV) equipment, and strong engineering design capabilities. The UK benefits from a strong R&D ecosystem and is beginning to develop a clearer policy orientation. An additional advantage is the potential to repurpose and reuse existing Oil&Gas infrastructure for the purpose of CO_2 transport and storage.
- On the other hand, technical and implementation hurdles in the UK encompass the absence of proven CO_2 injections, high energy costs, and a reliance on expensive offshore CO_2 storage. However, when coupling offshore CO_2 storage with the ability to reuse existing infrastructure, costs could be driven down, and hence, the UK has significant potential to advance in the CO_2 storage market. Market dynamics present additional hurdles, including a lack of focused CCS suppliers coupled with the prevalence of fragmented markets and project complexity.

5.2 RQ1: POTENTIAL MARKET SIZE AND UK MARKET SHARES

5.2.1 Market size

Today, global capture and storage capacity both culminate at just over 45 Mt CO_2/yr, with a minor discrepancy between the two that is attributed to CO_2 utilisation (IEA, 2023).

The views on the future role and scale of CCS and GGR vary in the net-zero strategies and pathways. The SR1.5 report of the IPCC (2018), which is based on older literature, suggested a total capacity for CCS and GGR of over 20 Gtpa of CO_2 by 2050, while more recent sources (2021) have revised this estimate downwards, to ca. 15-16 Gtpa (Martina Lyons, 2021)[18]. Regarding GGR, IPCC estimates a mitigation potential of DACCS at 5-40 Gt of CO_2 yr^{-1} and of BECCS at 0.5-11 Gt of CO_2 yr^{-1} (IPCC, 2022).

The IEA's NZE scenario suggests that CO2 capture from fossil fuels would be five times larger than CO2 capture from bioenergy projects in 2030 (IEA, 2021), and a representative database of CCS projects in operation or under development is dominated by projects involving fossil fuels (Global CCS Institute, 2024).

Text Box 5-1: Monitoring, measurement, and verification (MMV) technologies

The UK has revealed competitive advantage (RCA) in some key CCS-related products, and a mix of strengths and opportunities, especially in mechanical machinery and MMV instruments. RCA is defined as a given product's share in a country's exports, divided by the product's share in global trade volume (LSE, 2021).

There is potential for significant market growth for monitoring, measuring, and verifying across all technologies discussed below. CO_2 is a molecule that has not traditionally been a focal point for measurement in plant processes, transport, pipelines, or geological storage. Hence, there is a clear need for technological advancements in this domain.

Achieving the ability to precisely measure CO_2 quantities throughout an entire system, facilitating seamless transfer of ownership, and supporting related commercial contracts, payments, and emissions trading systems necessitates accurate and sophisticated monitoring, measurement, and verification technologies.

The development in this area is crucial for enhancing the efficiency and reliability of processes associated with CO_2 management.

In the following paragraphs, we comment on market size trends by tech family and technologies.

5.2.1.1 Carbon capture

Currently, the expansion of carbon capture capacity is ongoing, with emerging technologies being introduced into new markets. More than 140 million tonnes per annum (Mtpa) of additional capture capacity has been announced since 2022, and projections indicate a global capacity of 420 Mtpa by 2035, growing at an 18% compound annual growth rate. This would represent 1.1% of global annual emissions from fuel combustion and industrial processes. While carbon capture and storage (CCS) has traditionally been centred around projects at natural gas processing facilities, there is now a swift diversification into hard-to-abate sectors like cement, iron and steel, and power. The investments in CCS infrastructure amounted to USD 6.4 billion in 2022 and are estimated to have reached USD 5 billion in 2023 (BNEF, 2023).

New technologies and improvements are under development for the carbon post-combustion, pre-combustion and oxy-fuel combustion capture systems. It is currently unclear which CCS technologies will be the most effective in delivering the necessary cost reductions and performance improvements, as several are still in the early stages of development and demonstration (IEA, 2024).

Concerning **post-combustion techniques**, several technological approaches are on the horizon with the potential to improve post-combustion capture, covering the full range of technological maturity. Some of these technologies may be able to outperform solvents over time, but each has its challenges and requires further R&D and demonstration at scale. The emergence of modular carbon capture packages, for example, will be one of the key technologies as the sector develops; however, they are generally at low TRL levels. Amino acid and other mixed salts, water-lean solvents, liquid-liquid solvents, catalysts, polymeric membranes, temperature swing adsorption (TSA), and electro-chemical separation (fuel cells) have been identified as technologies with the highest potential to advance over the next few years. While most post-combustion technologies have some potential to decrease levelised cost of electricity (LCOE) costs, electro-chemical separation has been identified as the technology with the highest potential to lower the LCOE.

5.2.1.2 CO_2 storage

Transport and storage infrastructure for CO_2 is the backbone of the CCS industry. There has been a notable surge in planned capacities for CO2 storage in the last year, with over 370 million tonnes (Mt) of new annual storage capacity announced globally since January 2022. Considering the existing project pipeline, dedicated CO_2 storage capacity is anticipated to surpass 420 Mt CO_2 per year by 2030, aligning the balance between

[18] The IEA Net Zero Emission scenario (2021) and IRENA's 1.5°C Scenarios (2021) envisage total CO_2 capture in the range of 7–8 Gtpa of CO_2, while the IPCC's 6th Assessment Working Group SSP1- 1.9 scenario from 2021 includes 5 Gtpa of BECCS and over 3 Gtpa of DACCS by 2050.

dedicated CO_2 storage supply and the planned demand based on capture capacities on a global scale for 2030 (IEA, 2023).

This positive outlook for the CCS industry reflects enhanced market conditions, primarily driven by policy implementation and operators' coordinated alignment of the CCS value chain. However, it falls short of meeting the approximately 1,200 Mt CO_2 per year target by 2030, as outlined in the IEA Net Zero Emissions (NZE) Scenario (IEA, 2023).

The UK market share in CO_2 geological storage is expected to grow significantly because the UK has one of the largest theoretical CO2 storage capacities in Europe, accounting for approximately 25% of Europe's CO_2 storage potential and which can safely store 78 billion tonnes of CO_2. **This can provide a significant opportunity for the UK to provide CO_2 storage as a service** (UK Department for Business and Trade).

The UK has recently awarded 21 new licenses to companies for CO_2 storage, contributing to the target of storing up to 30 million tonnes of CO_2 annually by 2030. Six licences have already been granted (NSTA, 2023).

5.2.1.3 Greenhouse Gas Removals

The evidence suggests that the market for GGRs could grow, subject to continued policy support and industry coordination efforts. While both BECCS and DACCS may progress at a similar pace in piloting and demonstration phases through the mid-2020s, the BECCS market, benefitting from energy creation, as well as the possibility of retrofitting existing biomass-based facilities, is anticipated to grow significantly faster. An illustrative estimate suggests a growth in the BECCS market of approximately 1000 times in the 2030s, 100 times in the 2040s, and potentially 10 times in the 2050s. In contrast, the DACCS market, requiring higher energy inputs predominantly in the form of electricity, is expected to grow at a comparatively slower pace, according to the judgement of Ricardo's experts; however, growth in the DACCS market is still expected. The deployment of BECCS may also have constraints, mainly related to the availability of land and sustainable biomass as inputs to the process.

The UK domestic market size for GGR, including BECCS and DACCS, is expected to grow:

- Although both BECCS and DACCS currently have high costs[19], **it is acknowledged that GGR technologies need to be deployed in the UK by 2030 and will continue to play an essential role even beyond 2050**. In most CCC scenarios for achieving net zero, half or more of the captured CO_2 in 2050 is attributed to GGR technologies. The demand for GGR at a substantial scale is likely to extend beyond 2050, aligning with numerous IPCC scenarios that propose a need for removing more emissions than are globally emitted in the long term (Centre for Climate Change Economics and Policy, Grantham Research Institute on Climate Change and the Environment, Centre for Economic Performance, Programme on Innovation and Diffusion, & Productive and Inclusive Net Zero, 2023).
- **Removal technologies can abate residual emissions in hard-to-abate sectors and unlock a least-cost pathway to net zero**. A recent study estimated that achieving the net-zero target without BECCS would cost the UK an additional GBP 15 billion, or GBP 17 a year for every household, by 2050 (Baringa Partners LLP, 2021).
- In October 2021, the UK government set a Net Zero Strategy to achieve net zero emissions by 2050. It identified the need for around 80 Mt of CO_2 removal by 2050 using DACCS and BECCS technologies (IEA, 2023). **A pipeline of GGR projects exceeding 10 $MtCO_2$/yr** (CCSA, 2023) **is currently underway, more than double the UK Government's ambition of 5 $MtCO_2$/yr by 2030** (HM Government, 2021). The aviation sector is also displaying a growing interest in these technologies, where it is anticipated that the aviation industry may purchase carbon credits associated with GGR technologies. However, an industry view is that there is a lack of clarity regarding access to CO_2 infrastructure for GGR projects (CCSA, 2023). It is essential to clarify that Ricardo has not received access from DESNZ to any commercial information on CCUS tracks (other than publicly available). This project pipeline faces a notable risk of relocating from the UK, as GGR technologies are more mobile and incentivised in other jurisdictions through appealing and easily accessible subsidy schemes.

[19] Therefore CCS investments made today are crucial for bringing costs down through shared infrastructure, economies of scale and learning by doing.

5.2.1.4 Summary: global market size trends

The following table discusses global market size trends at technology levels in greater detail. For this sector, we have integrated the justification for the ranking assigned to each technology based on two main criteria assessed directly in the table below: Technology Readiness Level (TRL) and Market growth potential.

Table 5-2: Global market size growth potential: RAG rating by technology

Tech family	Technology	Rating	Justification
CO_2 capture	Oxy	Medium	• **TRL:** The technological readiness level is about 5 for the various sub-technologies falling within the oxy-fuel and chemical-looping combustion processes. The majority of these technologies (hereinafter, “Oxy”) have some ongoing pilot-scale demonstrations. Still, there **are no plans for larger-scale demonstrations, and the technology is not being progressed by a commercial partner**. The exception is **oxyfuel gas turbines**, which have commercial backing, and/or large-scale evaluation/ demonstration of the technology is either currently underway or planned (IEAGHG, 2019). • **Market growth potential:** Oxy technologies generally offer lower operational expenses (OPEX) and enhanced efficiency than post-combustion capture technologies. However, integrating these technologies into existing facilities presents challenges that reduce their cost competitiveness compared to post-combustion methods. Therefore, **they are better suited for incorporation into new facilities, particularly in hard-to-decarbonise industries or** addressing residual emissions. However, the prevailing trend in new facility designs, which are more likely to rely on other energy, fuel, and heat generation technologies, means that **Oxy technologies will likely have a medium market growth potential** (Source: Ricardo’s experts’ judgement).
	Pre-combustion	Low	• **TRL:** Pre-combustion technologies’ TRL typically range from 4 to 6 and have not increased significantly since 2014. However, this might change shortly as there is room for cost reduction in the sorption-enhanced water-gas shift technology. While there may be ongoing pilot-scale demonstrations, **there are no plans at present for large-scale demonstrations, and the technology is not being progressed by a commercial partner** (IEAGHG, 2019). • **Market growth potential:** Implementing pre-combustion technologies presents significant challenges, given the substantial modifications required for existing kilns and boilers and the necessity to address NOx emissions inherent in the process. Consequently, research and commercial development are limited **compared to alternative approaches**. Research and development efforts predominantly focus on integrated gasification combined cycle (IGCC) applications (Source: Ricardo’s experts’ judgement).
	Post-combustion	High	• **TRL:** About 40% of the sub-technologies falling within this category (post-combustion capture and high-temperature solids-looping processes) have TRL of 5-6. There is also a technology, ‘aqueous amine’ (falling within liquid absorbents), with TRL 6-9. **Commercial backing and/or large-scale evaluation/demonstration of the technology is currently underway or planned.** Chemical absorption using amine-based solvents is the most technologically mature post-combustion technique for power plants and is applied in the two large-scale projects in operation today (Boundary Dam and Petra Nova). Another 40% of the sub-technologies have some ongoing pilot-scale demonstrations, but there are no plans for larger-scale demonstrations, or the technology is not being progressed by a commercial partner (IEAGHG, 2019). • **Market growth potential:** Post-combustion is the dominant technology in many industries due to its maturity and ease of

Tech family	Technology	Rating	Justification
			retrofitting (resulting in lower CAPEX) compared to alternatives. Post-combustion is the CO_2 capture technology that has advanced most recently. Moreover, there is scope for cost reductions in the future, mainly due to the use of innovative solvents, standardisation of capture units, the emergence of modular carbon capture packages and large-scale deployment leading to economies of scale and learning-by-doing benefits. As a result, **the market growth potential for post-combustion technologies is likely to be greater than for other technologies** (Source: Ricardo's experts' judgement).
CO_2 Storage	Geological storage	High	• **TRL**: In 2022, projects to develop over 210 Mt of new dedicated CO_2 storage capacity were announced globally, more than double the amounts in 2020 and 2021 (IEA, World Energy Outlook 2023, 2023). Currently, over 60 CCS projects have been announced in Europe since 2019, but only three large-scale CCS projects (Norway's 'Longship project', Ørsted 'Kalundborg CO_2 Hub' in Denmark and 'Porthos' in the Netherlands discussed below in the case study) have taken a positive FID and are now under construction (Gas for Climate, 2023). • **Market growth potential**: Whilst there has been a rapid increase in the development of CCS projects and geological storage resources in recent years, it is evident that there is a need for accelerated storage development to effectively contribute to achieving net-zero emissions by mid-century. The current disparity between the geological storage capacity in progress and the geological storage capacity necessary to meet climate targets is significant, representing an order of magnitude. (Global CCS Institute, 2023)[20] Several governments and private entities are actively working towards commercialising these assets as a means to tackle this challenge. However, specific policies, such as the EU's Net Zero Industry Act, fall short of recognising the substantial costs of building storage (BNEF, 2023). This suggests that **the market for these technologies could grow significantly in the future, subject to higher public support and incentives.**
Greenhouse Gas Removals	BECCS	High	• **Market growth potential**: As of 2022, there are three operational commercial facilities, with seven additional in development. The existing facilities are currently capturing 2 million tons of CO_2. **A substantial increase is expected** to approximately 50 million tons annually by 2030. **The BECCS market, benefitting from energy creation and possibly retrofitting existing biomass-based facilities, is anticipated to grow significantly faster than the DACCS market** (Source: Ricardo's experts' judgement). • To promote investment in BECCS, continued development of market mechanisms and policies to create demand is needed. The UK government has acknowledged this and is thereby taking action to develop market mechanisms and policies to support demand. Key examples include plans to integrate GGRs into the UK ETS and develop GGR business models.
	DACCS	Medium	• **TRL**: The current technology readiness level (TRL) is 5, and while some ongoing pilot-scale demonstrations are taking place, there are no plans for larger-scale demonstrations, or the technology is not being progressed by a commercial partner. • **Market growth potential**: ○ Twenty-seven DAC plants have been commissioned to date worldwide, capturing almost 0.01 Mt CO_2/year.

[20] Projections of how much CO_2 must be geologically stored to achieve net zero emissions vary considerably depending upon the assumptions of the scenario or model. For example, the average total mass of CO_2 stored between 2020 and 2050, across the 90 scenarios considered in the IPCC Special Report on Global Warming of 1.5° Celsius exceeds 100 Gt (the annual CO_2 storage rate reaches 10 Gtpa in 2050). In comparison, if all the CCS facilities in the CCS project pipeline commenced operations on time and operated at full capacity, they could theoretically store a total of 12 Gt of CO_2 between now and 2050.

Tech family	Technology	Rating	Justification
			Plans for at least 130 DAC facilities are now at various stages of development.[21] However, most of the facilities announced to date are at very early stages of development, and as with BECCS, cannot be expected to reach final investment decision (FID) and operational status without **continued development of market mechanisms and policies to create demand** for the CO_2 removal service they would provide (IEA, 2023). Market mechanisms and policies also support this to support demand being developed by the UK Government. • Direct air capture is far more expensive than previously thought, costing as much as USD 1,100 per ton today and potentially falling to USD 300-USD 400 per ton by 2030. To realise these cost declines, **the industry will have to coalesce around one or two technologies** and develop the supply chains to bring these technologies to scale (BNEF, 2023).

5.2.2 UK market shares

5.2.2.1 Trade flows analysis

According to the evidence available in the literature, the UK's share in global exports of CCS-related product categories tends to be around or below 5% (with the following shares for specific components: MMV equipment: 5%; Chemicals: 4%; Mechanical machinery: 4.5%; Metal parts and structures: 2%) and declined over the period 1995-2019 (The Centre for Climate Change Economics and Policy (CCCEP), The Centre for Economic Performance (CEP), The Grantham Research Institute on Climate Change and the Environment, The Programme on Innovation and Diffusion (POID), 2021).

We have updated these estimates for 2021-2022 (the last two years available) for some selected HS codes (provided by DESNZ) relating to components related to CCS and GGR equipment production. The table below shows the UK's share of global exports (a proxy for the UK's share of tradable export markets) for the considered HS codes (grouped by HS Chapter).

This sector's total average is 3.6% of the global tradable market.

Table 5-3: UK share of global exports, selected HS subheadings, 2012-2022

HS Chapter	HS Sub-headings included	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
28 Inorganic chemicals; organic or inorganic compounds of precious metals, of rare-earth metals, of radioactive elements or of isotopes	281121 Carbon dioxide	USD 5M	0.9%
29 Organic chemicals	292211 MEA solvent 292217 MDEA solvent	USD 2M	0.3%
38 Miscellaneous chemical products	381400 Organic composite solvents and thinners, not elsewhere specified or included; prepared paint or varnish removers	USD 93M	4.3%
73 Articles of iron or steel	730411 Tubes, pipes and hollow profiles, seamless, of iron (other than cast iron) or steel; of stainless steel	USD 237M	2.0%

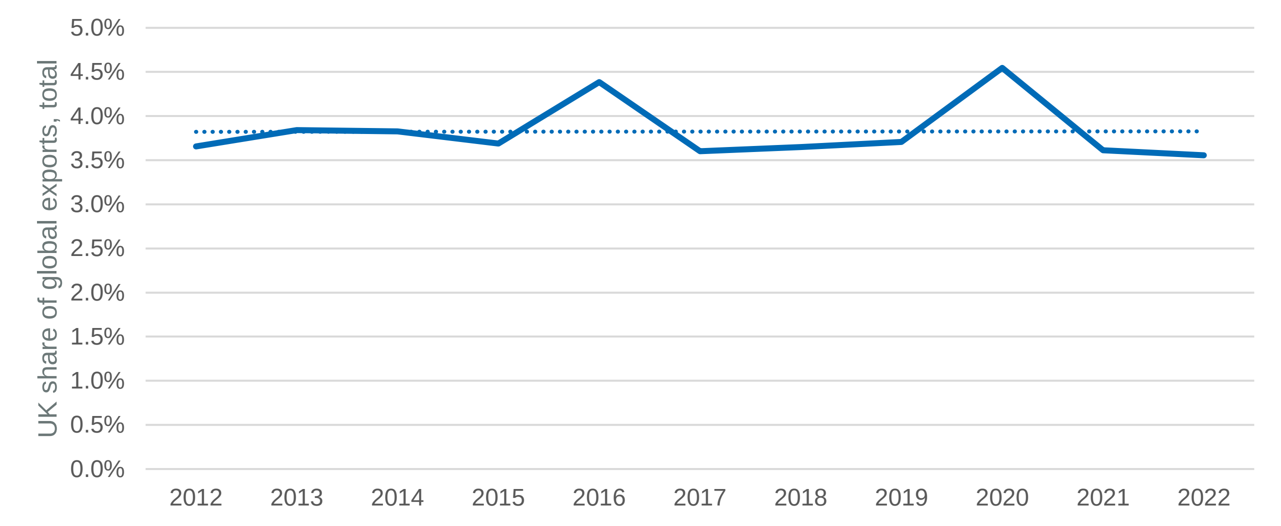
[21] If all were to advance (even those only at the concept stage), DAC deployment would reach the level required in 2030 under the IEA Net Zero Emissions by 2050 (NZE) Scenario, or around 75 $MtCO_2$/year. Lead times for DAC plants range from two to six years, suggesting that deployment in line with the NZE Scenario could be achieved with adequate policy support.

HS Chapter	HS Sub-headings included	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
	730419 Tubes, pipes and hollow profiles, seamless, of iron (other than cast iron) or steel; other 730511 Longitudinally submerged arc welded 730512 Other, longitudinally welded 731100 Steel containers for compressed or liquefied gas 731414 Demister		
84 Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof	841381 CO_2 pump 841480 Hydrogen gas compressor diaphragm 841490 CO_2 compressor 841960 Machinery; for liquefying air or gas, not used for domestic purposes 842139 CO_2 dehydration unit; CO_2 membrane 842199 Centrifuges, including centrifugal dryers; filtering or purifying machinery and apparatus, for liquids or gases; Other parts	USD 3,088M	3.5%
89 Ships, boats and floating structures	890520 Floating or submersible drilling or production platforms	USD 184M	1.6%
90 Optical, photographic, cinematographic, measuring, checking, precision, medical or surgical instruments and apparatus; parts and accessories thereof	901580 Surveying (including photogrammetrical surveying), hydrographic, oceanographic, hydrological, meteorological or geophysical instruments and appliances, excluding compasses; rangefinders; Other instruments and appliances; other 902610 For measuring or checking the flow or level of liquids 902620 For measuring or checking pressure 902690 Instruments and apparatus for measuring or checking the flow, level, pressure or other variables of liquids or gases (for example, flow meters, level gauges, manometers, heat meters), excluding instruments and apparatus of heading 9014, 9015, 9028 or 9032; Parts & accessories	USD 1,465M	5.6%
Total		**USD 5,073M**	**3.6%**

Source: Ricardo elaboration on UN Comtrade data

The figure below shows a stable trend in the UK's share of global exports for the total HS codes analysed.

Figure 5-3: UK share of global exports, 2012-2022



Source: Ricardo elaboration on UN Comtrade data

5.2.2.2 UK market shares

This section provides an overview of the UK's supply side in CCS/GGR technologies manufacturing.

The UK government is working on a plan to position the country as a leading developer in CCS. The strategy involves creating clusters of industries that can store their CO_2 emissions through shared plants. Some examples of clusters are the East Coast Cluster and the HyNet Cluster (Department for Energy Security & Net Zero , 2023). Notably, the Net Zero Teesside Power project in the East Coast Cluster is expected to be built by the UK company NZT Power. This company is responsible for constructing, operating, and decommissioning the gas-fired power station, along with the necessary equipment for CO_2 capture.

To support the early deployment of CCS in the UK, the government has announced funding of up to GBP 20 billion and established a policy environment through the Energy Act 2023, providing a robust regulatory framework for CCS (DESNZ, 2023). The potential economic impact is significant, with a supply chain report estimating that UK CCS could be worth GBP 100 billion to local manufacturing employers (OEUK, 2022).

The UK aims to leverage its expertise and proximity to major northern and western European emissions centres to lead the CCS industry. It estimates a potential for GBP 4 billion to GBP 5 billion in Gross Value Added from UK CCS exports by 2050. The UK also aims to offer potential storage to international emitters, providing additional economic opportunities. The vision is to make the UK a global leader in CCS, fostering a self-sustaining CCS sector that creates thousands of employment opportunities and contributes to emissions reduction on an international scale to ensure a better environment for future generations (DESNZ, 2023).

On GGR technologies, the UK aims to support a mix of these technologies, including BECCS and DACCS. Their modelling assumptions indicate that power BECCS is anticipated to play a significant role as one of the primary contributors to GGR in achieving their net-zero goals (DESNZ, 2023). The expectation is that a variety of GGR technologies will emerge, transforming the sector into a major user of the CO_2 transport network by the mid-2030s, encompassing both CCS and non-CCS technologies.

To bolster advancements in GGR, the UK is committing GBP 100 million to research and innovation initiatives. This includes initiatives like the Direct Air Capture and Greenhouse Gas Removal Innovation Competition (DESNZ , 2023). In July 2022, Phase 2 of the competition was unveiled, allocating over GBP 54 million in government funding to 14 promising demonstration projects. Notably, three of these projects focus on DACCS technologies.

The following table provides a selection of key CCS/GGR equipment manufacturers in the UK.

Table 5-4: Selection of manufacturers of CCS/GGR equipment in the UK

Company	Key information
Baker Hughes	Baker Hughes is a leader in CCS technology and project development, with a long history in the Oil&Gas sector. They are involved in several large offshore CCS projects and have decades of experience in hydrogen technology. They employ over 5,500 people in the UK at more than 30 facilities. They claim to support a network of over 3,000 UK suppliers and spend over GBP 300 million in the UK supply chain annually.
Carbon Clean	The company, which was established in 2009 and is based in London, specialises in affordable carbon capture technology. Its proprietary solvent-based technology captures carbon dioxide emissions from industrial operations, such as power plants and cement factories. The separated and compressed CO_2 can be reused, transported, or permanently stored underground, reducing carbon emissions (Carbon Clean, s.d.).
Aker Carbon Capture	The company is a subsidiary of Aker Solutions and a prominent player in the carbon sequestration sector. It went public in 2020 with a market capitalisation of USD 750.65 million. Originally from Norway, the company has branches in London, Aberdeen, and Reading. Aker Carbon Capture achieved a significant milestone by capturing carbon in 2009 using their Mobile Test Unit. It secured victory in the inaugural UK CCS competition in 2011 (Aker Carbon Capture UK, s.d.).
C-Capture	The Leeds-based company specialises in an inventive carbon dioxide capture design. Their patented solvent-based technology provides a cost-effective method for capturing CO_2 from diverse industries, requiring up to 40 per cent less energy than existing methods. Private investors and the UK Government support it with a total funding of GBP 16.7 million (C-Capture, s.d.). To date, C-Capture's technology deployment has focused on pilot and demonstration scale projects. For example, a demonstration project at Drax power station in the UK used C-Capture's technology to capture one tonne of CO2 per day during a pilot.

There is an opportunity for UK supply chains to develop new capabilities and secure a substantial global market share for CCS technologies. The government is clear that a vibrant and successful UK supply chain is key to creating and sustaining high-skilled, high-value jobs and supporting low-carbon growth in industrial clusters. To achieve this, government and industry must work closely together to address key strategic issues and barriers to investment, enabling UK supply chains to realise the economic benefits of a new CCS sector. CCS can unlock further economic opportunities in industries dependent on CCS technologies, like cement.

However, the highly fragmented markets in the UK, coupled with the involvement of diverse organisations and the management of counterparty risks, contribute to overall project complexity, extending timelines and increasing costs (Source: Ricardo's experts' judgement).

Announced in the Autumn Statement in November 2023, the Green Industries Growth Accelerator is a GBP 960 million package to bolster UK manufacturing capacity and strengthen supply chains in high-opportunity sectors like low-carbon hydrogen, CCS, electricity networks, nuclear, and offshore wind. Throughout 2024, the government will work with industry to carry out market engagement and develop an appropriate delivery mechanism that will maximise the UK's economic opportunity, support key supply chain strategic elements, and sustain jobs across our industrial heartlands.

The CCS industry, through the Carbon Capture and Storage Association (CCSA), published CCS Supply Chain Good Practice Guidance in July 2023, setting out its strategy to build a domestic supply chain for the deployment of the first Track-1 CCS clusters, as well as for the subsequent ramping up of the UK's CCS industry to serve a major and growing international demand. The document sets out a series of industry-led commitments, including its approach to promoting UK supply chain opportunities, creating and sustaining jobs through CCS projects and investment in training and skills. The guidance also sets out a pathway for delivering UK content ambitions in CCS projects consistent with those put forward in the North Sea Transition Deal (NSTD), including a headline voluntary local content ambition of 50%.

In the table below, we assess whether the UK could capture a market share higher than, in line with, or below the sector average indicated in the quantitative analysis above.

Table 5-7: Technologies that have the potential to attract significantly higher/lower market shares compared to the sector average

Tech family	Technology	Rating	Justification/rationale and key sources
CO_2 Capture	Oxy	Lower than average	The UK has been rated as one of the top 5 countries globally for CCS readiness. The UK has significant strengths in

Tech family	Technology	Rating	Justification/rationale and key sources
	Pre-combustion	Lower than average	engineering design and construction and construction management services. This can give the UK good potential to attract high market shares within several CO_2 capture components across the supply chain. Most of the projects deployed in the UK to date are post-combustion carbon capture systems. Hence, it is expected that the UK could have a higher market share in these technologies compared to oxy-combustion and pre-combustion. Oxy-combustion and pre-combustion technologies tend to have a lower TRL and greater plant modifications. However, several components that the UK has experience with will also be present in the supply chain of oxy-combustion and pre-combustion capture, such as process controls, MMV equipment, and compressors. The UK also has advantages in column vessel manufacture, the most significant component of a CO_2 capture plant. However, it is anticipated that the UK will only be able to supply smaller-sized column vessels; therefore, although the UK has an advantage in several components across the CO2 capture supply chain, these generally tend to be for the smaller components and thus, may not result in a higher-than-average share of the market. The GIGA will support the growth of the UK supply chain across all components.
	Post-combustion	Average	
CO_2 Storage	Geological storage	Higher than average	The UK has great potential to attract a high market share in CO_2 storage due to the large geological storage capacity of the North Sea. The UK is also making good progress in developing the environment for this by introducing funding schemes to create the CO_2 transport and storage infrastructure, such as the Carbon Capture and Storage Infrastructure Fund and the GIGA. A business model for CO_2 transport and storage has also been developed, which will provide certainty to those who wish to utilise the transport and storage networks, hence incentivising the use of these.
GGR	BEECS	Average	The UK has highlighted the importance of GGRs towards reaching net zero targets. It has made significant progress in supporting the development of a GGR market, both in terms of UK deployment and developing supply chain capabilities. The GIGA is a key example of this and will support the UK with further developments in the GGR supply chain. A number of the components in BECCS plants will be similar to a CO_2 capture plant, where the UK has an advantage in a number of these components, which can support capturing a portion of the market share. This includes MMV equipment, process control and heat exchangers.
	DACCS	Average	

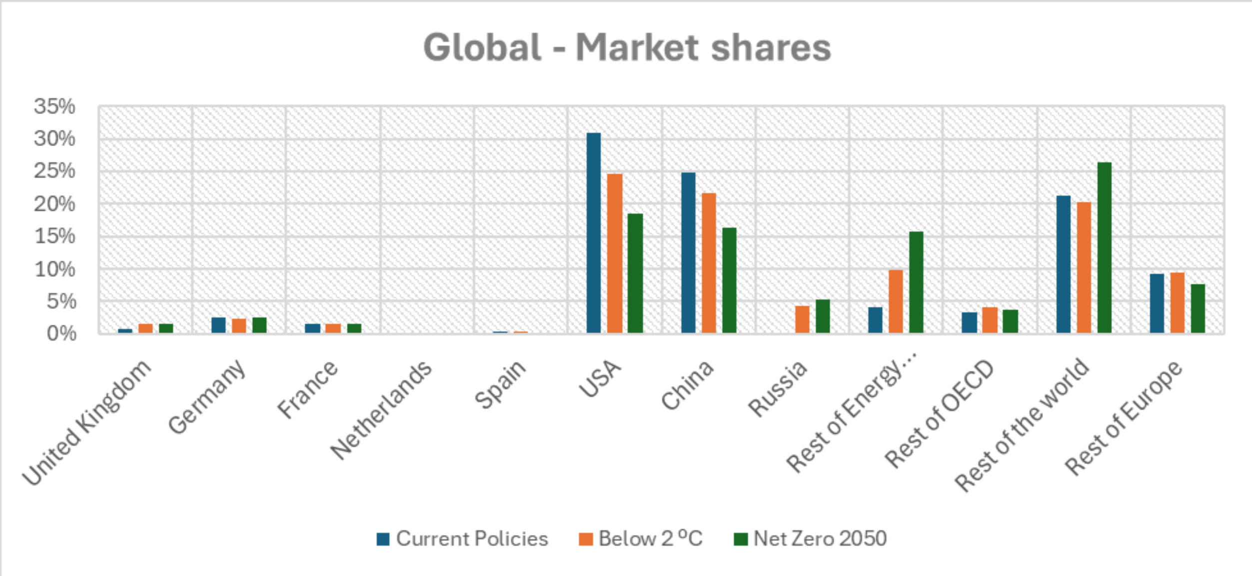
5.3 RQ2: UK COMPETITIVE ADVANTAGE

5.3.1 Quantitative analysis at the sector level

By 2050, the production of CCS equipment is expected to be widespread, with China, the Rest of the World, other energy-producing countries, and the USA emerging as the primary producers.

The market shares of the countries/regions range across scenarios from 20%-26% in the rest of the world region, 15%-25% in China, 18%-31% in the USA and 4%-16% in the other energy-producing countries. The rest of the energy producers and the rest of the world regions experience an increase in market share due to the high potential to use CCS technologies in gas-fired plants. UK market share ranges from 1% to 2%, with a slight increase when there is a higher global mitigation effort.

Figure 5-4: Market shares in 2050



Source: Ricardo analysis based on GEM-E3 outputs

5.3.2 Key drivers of competitive advantage

There are several global drivers of key policy and market developments related to the CCS and GGR technologies. The **costs of these technologies** are still high due to the lack of widespread experience and lack of economies of scale. **Effective legal and regulatory frameworks**, as well as **government support**, can increase investment in CCS. Combined **technology demonstration** and supporting research and development efforts can accelerate technology development and facilitate deployment. The deployment of the CCS/GGR technologies also significantly depends on the **provision of infrastructure and storage of CO_2.**

Table 5-8: Key drivers of energy policy and market developments globally

Category	Driver	Description	RAG
Drivers	Trends in production costs	The successful deployment of CCS technologies depends on establishing a viable business case that ensures investors and facility owners can receive a commercial return. It is crucial for technologies to be sufficiently de-risked and should demonstrate durability to become financially viable. Sustainable CAPEX and OPEX costs also influence the project's bankability. Determining costs for emerging CCS technologies is often challenging, even for leading technologies like amine-based capture processes, due to a lack of widespread experience and large-scale implementation (IEAGHG, 2019). In CCS technologies, the cost can vary significantly by CO_2 source, from a range of USD 15-25/t CO_2 for industrial processes producing “pure” or highly concentrated CO_2 streams to USD 40-120/t CO_2 for processes with “dilute” gas streams, such as cement production and power generation. Regarding GGR, capturing CO_2 directly from the air is currently the most expensive approach. Some CO_2 capture technologies are commercially available, while others are still in development, further contributing to the extensive cost range. There is a significant potential to reduce the costs along the CCS value chain – experience indicates that CCS should become cheaper as the market grows, the technology develops, finance costs fall, economies of scale are applied, and the experience of building and operating the CCS facilities accumulates - a pattern that has been seen for renewable energy technologies in the past (Adam Baylin-Stern, 2021). **The expected falling costs will enable the development of CCS and GGR technologies.**	N/A
	Importance of CCS for reaching the climate commitments	One of the key drivers is the commitment to achieve net zero emissions. Countries, including the UK, are setting ambitious targets and implementing legislation to realise these objectives. Independent bodies like the UK's	N/A

Category	Driver	Description	RAG
		Committee on Climate Change (CCC) also play an essential role in shaping decarbonisation pathways. CCS can strategically contribute to global decarbonisation efforts through various means: first, by lowering emissions in industries deemed 'hard-to-abate'; second, by generating low-carbon electricity and hydrogen for broad decarbonisation applications; and third, by removing existing CO_2 from the atmosphere. (Grantham Research Institute on Climate Change and the Environment, 2023) CCS emerges as the most cost-effective option for decarbonising challenging industries such as iron, steel, and chemicals. Furthermore, in cement production, which accounts for almost 7% of global emissions, CCS stands as the key technological avenue for achieving substantial emissions reductions. Moreover, evidence suggests that implementing GGR technologies will be crucial if global climate change is to be limited to 2°C above pre-industrial levels. To limit warming to 1.5°C and thereby significantly mitigate the associated risks of global climate change, incorporating negative emissions into the mitigation toolbox will become essential (Olle Olsson, 2020). **The relevance of CCS/GGR technologies for achieving net-zero targets is expected to enable further development of the technologies.** On the other hand, there might be other competing decarbonisation options and technologies besides CCS (Carbon Tracker, 2024).	
	Technological progress	The decade between 2010 and 2020 was characterised by cost discovery through studies and the subsequent cancellation or delay in project developments due to economic non-viability (Global CCS Institute, 2023). Currently, several promising technological innovations that have been proposed to reduce CCS costs in various applications, including for power generation, are being demonstrated around the world (IEA, 2023).[22] Although chemical absorption and physical separation stand out as the most advanced and widely used capture technologies, ongoing developments include emerging separation methods like membranes and looping cycles (such as chemical looping and calcium looping). Beyond technological advancements, various trends can potentially enhance the techno-economic performance of CO_2 capture. Examples include the modularisation of capture systems, featuring self-contained plug-in systems, which could decrease land footprint, costs, and lead times for capture retrofits across applications. Additionally, hybridization of diverse capture technologies within capture systems is another trend aimed at boosting capture rates while simultaneously reducing costs and/or energy penalties. **Technological progress will enable further deployment of CCS/GGR technologies and will lead to cost reductions.**	N/A
Enablers	Financial incentives	**Financial incentives,** like the UK CCS Infrastructure Fund, UK Green Industries Growth Accelerator, and the US Inflation Reduction Act**, play a pivotal role in driving change by offering essential funding for CCS initiatives.** In March 2023, the UK announced up to GBP 20 billion to support the initial deployment of CCS (UK Government, 2023). The UK has also been developing a GGR business model, a Contracts for Difference business model that subsidises GGR projects that would otherwise not be financially viable. Additional business models include the Industrial Carbon Capture Business Model, Dispatchable Power Agreement and the T&S Regulatory Investment business model. To enhance the CCS projects	

[22] These include:

- NET Power's 50 MW clean energy plant (commissioned in 2018) is a first-of-its-kind natural gas-fired power plant employing Allam cycle technology, which uses CO_2 as a working fluid in an oxyfuel supercritical CO_2 power cycle, which could significantly reduce capture costs.
- Net Zero Teesside Power in the United Kingdom is expected to come online in 2027 and could become one of the first commercial-scale gas-fired power stations with CCS. The project was named as an investment priority in a UK government announcement in March 2023.
- CCS applied to the industrial sector has also made progress. In 2022 a number of new projects were commissioned:
- One large-scale demonstration project retrofitting CCS to iron and steel production was commissioned in Belgium, bringing the number of large-scale operating CCS projects on iron and steel to two. A smaller pilot also started in France.
- Two CCS projects were retrofitted to chemical production, in the United Kingdom and China.
- A project in China to capture CO_2 emissions from fertiliser production was commissioned.

Category	Driver	Description	RAG
		development pipeline, it is essential to implement supportive policies underpinning more robust carbon values, tax incentives, and facilitating the establishment of CO_2 transport and storage hubs to attract additional local capture projects (Global CCS Institute, 2023).	
	ETS and cost of carbon	The changing CCS landscape is shaped by the existence of the Emissions Trading Schemes (ETS) and the rising cost of carbon. **As the expenses associated with fossil fuel-based energy rise, businesses are incentivised to shift towards cleaner alternatives, thereby fostering the adoption of CCS technologies.** Additionally, in the United Kingdom, suggested changes to the UK ETS involve the incorporation of carbon-removing technologies into the market. This initiative aims to enhance investment in the sector (DESNZ, 2023).	
	Corporate ESG policies and sustainable investments	**Corporate ESG policies and the growing demand for sustainable investments from corporate investors and stakeholders are driving transformative change.** Companies are increasingly aligning their operations with ESG principles, making investments in CCS technologies and sustainable practices more attractive. The UK GGR business model document (DESNZ, 2023) has highlighted the importance of voluntary carbon markets, where the demand for GGR carbon credits on carbon markets has increased in recent years. Therefore, corporate ESG policies are of particular importance, increasing the demand for GGR credits sold in voluntary carbon markets.	
Barriers	Legal and regulatory frameworks	The expansion of CCS technologies requires the establishment of clear legal and regulatory frameworks. These frameworks are crucial for ensuring the responsible management of CO_2 storage sites, safeguarding public health and the environment, and guaranteeing the safety of CCS activities. Additionally, regulatory frameworks play a vital role in defining the rights and responsibilities of various CCS stakeholders, including relevant authorities, operators, and the public. They contribute to providing clarity and certainty to project developers and their investors (IEA, 2022). Highlighting the significance of well-defined legal and regulatory frameworks, including clear MRV framework, standards & methodologies, and robust government backing for CCS/GGR development, the recent growth in CCS project capacity has predominantly occurred in North America and Europe. This trend is attributed to the robust support of policies and/or carbon pricing in these regions. Furthermore, these jurisdictions have enacted comprehensive regulations specifically addressing CCS, showcasing how effective policy and regulation can stimulate investments in CCS (Global CCS Institute, 2023). For example, the European Commission has proposed that Oil&Gas producers take legal responsibility for ensuring the development of European CO_2 storage resources, initially targeting 50 Mt CO_2/year of capacity by 2030. However, **clear legal and regulatory frameworks, providing clarity and certainty to projects developers and investors, are still lacking in many countries, and are thus a barrier to the development of the CCS and GGR technologies.**	
	Setting up infrastructure for transportation and storage of CO_2	**Setting up of infrastructure for transportation and storage of CO_2 is an absolutely crucial component in enabling CCS**, be it fossil-based or bio-based. Both CO_2 shipping and storage infrastructure rely heavily on steel, while storage also requires large amounts of cement. Steel used for CO_2 pipelines in the IEA NZE Scenario makes up only a fraction of the 130 Mt of tubular steel produced annually today. As a result, tubular steel availability is unlikely to limit deployment (IEA, 2023f). While CO_2 infrastructure deployment accelerates in the NZE Scenario, it is **constrained by the required lead times for developing CO_2 storage capacity**. Unlike for critical minerals, fewer assessments have been done to identify CO_2 storage reserves. Confidence in CO_2 storage availability is necessary to assure investment in capture facilities and transport infrastructure, so resources must be assessed as soon as possible (IEA, 2023).	

5.3.3 Geographical benchmarking

This section provides a geographical benchmarking focus on the US, EU, China, and additional key UK competitors, such as Japan, Canada, Saudi Arabia, and Iceland. Although the UK is offering fiscal and policy incentives, other fiscal and policy incentives in other countries, such as the Inflation Reduction Act in the US, other countries with carbon capture ambitions and geological storage potential also attract UK companies to explore overseas opportunities, potentially diverting investments.

We discuss how other key players position themselves in the market both in terms of deployment of CCS & GGR and in terms of export capabilities:

- **Deployment of CCS**: The US is expected to retain its place as the market leader for the deployment of carbon capture, with a 40% market share in 2035. The UK and Canada will follow, at 16% and 12% respectively, while Australia, the Netherlands and China round out the top tier with 3-4% each. However, this lineup could change if China accelerates the deployment of carbon capture in its power sector (BNEF, 2023). A notable moment in global CCS collaboration occurred when the US introduced the Carbon Management Challenge at the Major Economies Forum (MEF). This initiative invited other countries to participate in achieving a collective CCS/CDR target by 2030 (Global CCS Institute, 2023). The objective was to unveil a set of concrete announcements and goals at COP28. While no specific substantive announcements were made at COP28, the established goal is for the nineteen participant countries, along with the European Commission, to collectively manage 1 Gt of CO_2 annually by 2030 (Carbon Management Challenge, 2024).
- **Deployment of GGR**: Countries and regions that have taken an early lead in supporting DACCS research, development, demonstration and deployment include the US, EU, UK, Iceland, Canada and Japan. The vast majority of BECCS capacity is located in North America and Europe. This is expected to stay the same by 2030, according to current plans (IEA, 2023).
- **Export capabilities for CCS-related products**: The UK's share in global trade in CCS has generally been relatively low, around or below 5%, and has decreased over time. Historically, the US and Germany held a dominant position in exporting CCS-related products, but China began surpassing them at the period's end. This shift is partly attributed to China's overall supremacy in global manufacturing exports. Nonetheless, when examining China's strengths and opportunities in CCS specifically, there is evidence of high Revealed Competitive advantage (RCA) and proximity to existing capabilities for many CCS-related products (Centre for Climate Change Economics and Policy, Grantham Research Institute on Climate Change and the Environment, Centre for Economic Performance, Programme on Innovation and Diffusion, & Productive and Inclusive Net Zero, 2023).

The following table discusses each key country in more detail.

Table 5-9: Major UK competitors

Country	Description
US	Since the beginning of 2022, the United States has accounted for 30% of new CCS project announcements. Projections suggest the US will maintain its operational and planned capture capacity leadership, with an increase from 25 Mt CO_2 per year in 2022 to 162 Mt CO_2 per year by 2030. By 2035, the US is anticipated to hold a 40% market share in CCS (BNEF, 2023). The US has mobilised unprecedented government support to support its leading position. Technologies that aid emissions reductions in hard-to-abate industrial sectors are eligible for substantial tax credits. By attracting private capital, these incentives collectively support a doubling in clean energy investment in the US by 2030 over 2022 levels. The more generous tax credits and new grant funding programs are the driving forces behind the announcements of over 100 projects across the CCS value chain since 2022. In 2021, the US approved the Infrastructure Investment and Jobs Act (IIJA), allocating about USD 12 billion for the CCS value chain until 2026. In 2022, the Department of Energy announced substantial funding opportunities under the IIJA, including USD 45 million for CCS in power and industrial applications, USD 820 million for large-scale carbon capture pilot projects, and USD 1.7 billion for carbon capture demonstration projects (IEA, 2023). In April 2023, the US introduced the 'Carbon Management Challenge' ahead of the 28th Conference of the Parties (COP), urging nations to advance global CCS and GGR efforts. Notably, the US presented significant opportunities in 2022 expected to enhance CCS project development, encompassing new funding from the 2021 IIJA and favourable tax credit changes for CCS in the 2022 Inflation Reduction Act (IRA) (IEA, 2023). An analysis of the impact of the US IRA concludes that it could increase CCS deployment in the US by 200 to 250 Mtpa of CO_2 by 2030 (Global CCS Institute, 2023). Regarding GGR technologies, the US has implemented various policies and programs to bolster DACCS, such as the 45Q tax credit and the California Low Carbon Fuels Standard credit. Additionally,

	the IIJA allocates funding (USD 3.5 billion) to create four large-scale DAC hubs along with associated transport and storage infrastructure (IEA, 2023f). Regarding BECCS, the technology has gained support through policies on bioenergy, low-emission fuels, and CCS. While first-generation bioethanol plants may not meet low-emission criteria for IRA tax credits, the IRA could encourage CCS deployment at these plants. This policy environment has led to the US having the largest operational BECCS project, the Illinois Industrial CCS Project, capturing 1 Mt CO_2 annually for permanent storage in a deep geological formation since 2017 (IEA, 2023f).
EU	In March 2023, the European Commission launched the Net Zero Industry Act, recognising CCS as a strategic net-zero technology requiring expanded manufacturing capacity to meet the EU's climate objectives. The Act advocates for an EU-wide target of achieving an annual CO_2 injection capacity of 50 Mt by 2030, with Oil&Gas producers asked to contribute. The Act also outlines clear timelines for permitting CCS projects (IEA, 2023). This might catalyse the CCS deployment. Europe (including the UK) is projected to be ranked second region worldwide in terms of its operational and planned capture capacity by 2030 (reaching 95 Mt CO_2 per year in 2030, up from 2 Mt CO_2 in 2022, when it was ranked third after the US and Central and South America) (Gas for Climate, 2023). Currently, international CCS business models are being developed. In 2023, the first transboundary movement of CO_2 by ship for geological storage was successfully carried out between Belgium and Denmark (Global CCS Institute, 2023). Regarding the GGR technologies, the EU has been supporting DACCS through research and innovation initiatives, such as the Horizon Europe programme and its predecessors, along with the Innovation Fund, initiated in 2020 for the 2020-2030 decade with an initial budget of approximately USD 11.8 billion (IEA, 2023). Corporate and national net-zero commitments and carbon removal policies have primarily driven interest in BECCS. Approximately 10 Mt of biogenic CO_2 capture is planned from heat and power plants, with 80% from dedicated bioenergy facilities and 20% from waste-to-energy plants. In the EU, although carbon removal is not credited under the EU ETS, the initial Communication on Sustainable Carbon Cycles, issued by the Commission in December 2021, recommends removing 5 Mt of CO_2 annually by 2030 from the atmosphere and permanently storing it, utilising technologies like BECCS (IEA, 2023). On February 6th, 2024, the European Commission published a communication on the EU Industrial Carbon Management Strategy. The communication outlines three developmental stages (European Commission, 2024): 1. **By 2030:** The strategic goal is to deploy a CO_2 storage capacity of at least 50 million tonnes per year and the necessary transport infrastructure, including pipelines, ships, rail, and roads. 2. **By 2040:** Regional carbon value chains should become economically viable to align with EU climate objectives. CO_2 is envisioned to become a tradable commodity within the EU's single market. Up to one-third of captured CO_2 is anticipated to be utilised. 3. **After 2040:** Industrial carbon management is expected to integrate fully into the EU's economic system. Biogenic or atmospheric carbon is projected to become the primary source for carbon-based industrial processes or transport fuels. The strategy does not prescribe specific sectors for applying carbon capture at the national level, leaving such decisions to individual Member States. The Commission plans to support carbon capture and storage by creating a platform for demand assessment, an investment atlas for CO_2 storage, and guidance for permitting processes. For carbon capture and use, the Commission will assess options to increase sustainable carbon utilisation in industrial sectors. Objectives aligned with the EU's climate goals will be established to promote industrial carbon removals, along with policy options and support mechanisms (Ibid). This includes potential accounting for carbon removals in the EU ETS and increased support for research and innovation in novel industrial technologies under Horizon Europe and the Innovation Fund (European Commission, 2024).
Norway	Norway is a pioneer in CCS efforts. The first large-scale CO_2 capture and injection project with dedicated CO_2 storage and monitoring was the Sleipner offshore gas field storage in 1996, which has a storage capacity of 1 Mt/year, and until now, it has stored more than 20 MtCO2. For technical and commercial reasons, the CO_2 must be removed from the gas before it can be sold. A CO_2 tax on offshore Oil&Gas activities introduced by the Norwegian government in 1991 made the project commercially viable. Besides the Sleipner CO2 storage project, Norway is currently deploying another large-scale project, the Snohvit CO2 storage project, with a capacity of 0.7 Mt/year (IEA, 2023).
Iceland	Iceland currently employs two DACCS plants with storage: Climeworks Orca and Mammoth, with 0.004 $MtCO_2$/year and 0.036 $MtCO_2$/year capacity, respectively. Orca is the world's first direct air capture and storage (DAC+S) plant, launched in 2021, and Mammoth is expected to be completed in May 2024 (Climeworks, 2022).
Japan	In January 2023, Japan issued a CCS roadmap outlining an annual CO_2 storage goal of 6-12 million tons (Mt) by 2030 and an ambitious target of 120-140 Mt per year by 2050. The roadmap, detailed under the CCS Long-Term Roadmap for Japan, emphasises the initiation of the first commercial

	facilities by 2030, with a progressive trajectory aiming to achieve a substantial 240 million tons per annum (Mtpa) of CO_2 storage by 2050 (Global CCS Institute, 2023). In 2020, the first retrofitting of a large-scale biomass-fired power plant with CO_2 capture took place, although no storage site for the CO_2 has yet been identified (IEA, 2023).
Canada	In Canada, the 2022 federal budget proposed an investment tax credit for CCS projects between 2022 and 2030, valued at around 60% for DAC projects when CO_2 is stored at an eligible permanent sequestration site (IEA, 2023).
Saudi Arabia	Jubail Industrial City, one of the largest CCS hubs globally, is set to commence operations by 2027. In its initial phase, it will have a capacity of up to 9 million tons per annum (Mtpa) of CO_2. This will support Saudi Arabia's goal to extract, utilise, and store 44 Mtpa of CO2 by 2035 (Global CCS Institute, 2023).

5.3.4 UK competitive advantage: qualitative analysis

Regarding the export capabilities for CCS-related products as a whole, the UK finds itself at a slight disadvantage compared to some of its counterparts like Germany and the United States. Nevertheless, given that countries specialise differently in various products and no single nation has achieved complete dominance across the entire product portfolio, plentiful opportunity remains for the UK (Centre for Climate Change Economics and Policy, Grantham Research Institute on Climate Change and the Environment, Centre for Economic Performance, Programme on Innovation and Diffusion, & Productive and Inclusive Net Zero, 2023)

The UK has several competitive advantages for specific activities related to the CCS and GGR technologies. The UK has mature **supply chain capabilities** and expertise in the Oil&Gas sector, which can provide transferable skills and opportunities for repurposing to support the CO_2 storage market. It also has strengths in the manufacturing of measuring, monitoring and verification (MMV) equipment, which are essential products in the CCS and GGR sector, as well as strong engineering design capabilities. Additional areas that may provide high potential for the UK include column vessel manufacture, assembly and internals, heat exchanger manufacture and assembly, and packaged CCS provisions. The UK has committed to GBP 960 million for the Green Industries Growth Accelerator (GIGA), which will support by leveraging investment and accelerating advanced manufacturing in net zero sectors, including CCS (DESNZ and The Rt Hon Claire Coutinho MP, 2023). The UK Treasury's Spring Budget allocated an additional GBP 120 million for the GIGA, bringing the total investment to nearly GBP 1.1 billion (Energy Live News, 2024). Additional advantage for the UK is the potential to repurpose and reuse existing Oil&Gas infrastructure for the purpose of CO_2 transport and storage.

The UK has a **substantial estimated CO_2 storage capacity**, which could be provided to the neighbouring countries. The UK benefits from a strong **Research, Development, and Deployment (RD&D) ecosystem**. It is beginning to develop a clearer policy orientation, which can promote investment in implementing and manufacturing CCS and GGR technologies. The UK can also benefit from its **global presence and recognition** and has the potential to **align and learn from neighbouring countries** developing CCS.

On the other hand, the UK has some competitive disadvantages. In the policy landscape, challenges arise from **limited engineering appreciation among decision-makers**. Technical and implementation hurdles encompass the **absence of proven CO_2 injections**, **high energy costs**, and a reliance on **expensive offshore CO_2 storage**. Market dynamics present additional hurdles, including a **lack of focused CCS suppliers**.

Competitive advantages and disadvantages are discussed in greater detail below.

Table 5-10: UK competitive advantages

Advantage	Description
Supply chain capabilities	• **Oil&Gas**: The UK has long-standing experience in the Oil&Gas, process and energy supply industries, which can provide transferable skills in engineering, procurement and construction management in the CCS and GGR sector (Departments for Business, Energy & Industrial Strategy, 2019). However, additional upskilling and training may be required. The UK Government has therefore launched the CCS Task and Finish Group within the Green Jobs Delivery Group. This will gather evidence of the potential skills gaps and feed into the Green Jobs Plan, published in 2024 (DESNZ, 2023). The UK's existing Oil&Gas pipelines provide an opportunity for repurposing to support a CO2 storage market: the rich infrastructure in the North Sea, much of which is nearing the end of its Oil&Gas lifecycle and which is well suited for re-purposing for CCS transportation and storage within the next 10-20 years. The UK has a mature

Advantage	Description
	offshore and sub-surface supply chain, as well as mature offshore infrastructure, which can be leveraged to provide a competitive advantage in CO_2 storage (Department for Energy Security and Net Zero, 2023). • **MMV equipment**: The UK has existing strengths in measuring, monitoring and verification (MMV) equipment and mechanical machinery, which are essential products in the CCS and GGR sector (Centre for Climate Change Economics and Policy, Grantham Research Institute on Climate Change and the Environment, Centre for Economic Performance, Programme on Innovation and Diffusion, & Productive and Inclusive Net Zero, 2023). This also extends to process control equipment, providing significant opportunity due to the requirement for monitoring across the CCS chain and the importance of balancing demand on the system. The UK is also developing its own MRV standards for GGRs, providing opportunity for the UK to lead in this area. • **Engineering Design: Engineering design is a significant economic opportunity for the UK. It utilises the nation's strength in high-value technical design and builds on active national onshore and offshore** energy industries. This draws on the skills of the 5.6 million people employed in the UK engineering sector, of which an estimated 330,000 are employed in the advanced fuels and chemicals sector. • **Column vessel manufacture, assembly and internals:** The manufacture of column vessels is well suited to the current UK manufacturing sector capabilities. This can, therefore, provide an opportunity for the UK with the CCS and GGR sectors, where the column vessels are often the largest part of the process plants. However, it should be noted that large volumes of orders within the UK may result in a bottleneck as there are only a limited number of locations within the UK where the column vessels can be manufactured. Currently, the UK is also unlikely to be able to produce enormous column vessels. However, UK off-site fabrication shops could support production for average plants (Nuclear AMRC / HVM Catapult, 2022). • **Heat exchanger manufacture and assembly:** Many companies in the UK design, manufacture, and install heat exchanger products. CO_2 capture plants require various heat exchanger technologies tailored to the plant's specific needs. This can, therefore, provide a significant opportunity for the UK. Additionally, as reboilers are very similar to shell and tube heat exchangers, there is also potential future growth within this area in the UK (Nuclear AMRC / HVM Catapult, 2022). This is an essential aspect of amine CO_2 capture plants. • **Packaged CCS provisions:** Several UK companies already offer CCS packages, including Carbon Clean and C-Capture (Global CCS Institute , 2023). UK Government funding of GBP 5 million has supported accelerating the commercialisation of Carbon Clean's technology, which has now been installed at 38 facilities globally (UK Department for Business and Trade). This provides a significant opportunity for the UK to grow within this space and grow the number of products and companies providing packed CCS provisions (ARUP, 2023).
Storage capacity	The UK boasts very high theoretical storage capacity in the UK Continental Shelf (UKCS), particularly in the North Sea, offering the potential to store CO2 for hundreds of years (including significant storage contingency in case of individual site failures). According to Ricardo's experts, the UK could import CO2 from other nations with no geographical storage capacity to store it in UK geological storage areas. Certain European countries, including Germany, Estonia, Ireland, Finland, Slovenia and Lithuania, prohibit the geological storage of CO2 altogether, providing further opportunity for the UK to provide 'CO_2 storage as a service' (European Commission, 2023). Global CO2 storage capacity estimates range from 8,000-55,000 Gt. CO2 storage capacity estimates in Europe are approximately 450 Gt (however, this does not factor in policy and regulatory factors), with around 80 Gt of this being located in the UK (Clean Air Task Force, 2021) (DESNZ, 2023). Some European countries have limited CO2 storage potential (Estonia, Finland, Luxembourg); hence, the UK can position itself and provide CO_2 storage as a service to neighbouring countries. On the other hand, offshore storage is considerably more expensive (possibly around four times more expensive) than comparable onshore systems in countries such as the US or Canada (Source: Ricardo's experts' judgement).
R&D initiatives	Early exploration and engagement in CCS in the UK have led to a high level of awareness among stakeholders, fostering a conducive environment for technological advancements. The UK benefits from a strong Research, Development, and Deployment (RD&D)

Advantage	Description
	ecosystem, with institutions like UKCCSRC, SCCS, Industrial Decarbonisation of Clusters, and BGS supporting advancements in the sector. The UK Government also facilitates R&D by offering several funding opportunities, including the DAC and GGR Innovation Programme, the Industrial Strategy Fund, and the Net Zero Innovation Portfolio.
Integrated policy landscape and public support	Committing to a Net Zero policy, carbon budgets, and well-organised stakeholder organisations with aligned policies creates a solid foundation for CCS and GGR sector growth. The UK is beginning to develop a clearer policy orientation, which can promote investment in both the implementation and manufacturing of CCS and GGR technologies. UKCS CCS is licensed by the North Sea Transition Authority, providing alignment of stakeholders and instilling investor confidence with a clear and mature legislative framework for CCS (Source: Ricardo's experts' judgement). Government support to date has predominantly focussed on addressing barriers related to high capital and operating costs. The Government has also started to develop models to support GGR (such as the GGR business model), including CO_2 transport and storage, which can support the development of a market for CO_2 storage as a service. Moreover, the UK benefits from a stable regulatory regime and active and deep capital markets (DESNZ, 2023). The Green Industries Growth Accelerator has been developed to enhance UK manufacturing capacity and strengthen supply chains. CCS is a key sector in the overall GBP 1.1 billion support package (Energy Live News, 2024). This will allow the UK to leverage private investment and seize growth opportunities presented by the sector's growth. Funding will be available from 2025-2030, supporting the future growth of CCS-related product manufacturing and supply chains in the UK (GOV UK, 2023).
Global presence and recognition and international coordination	The UK energy and Oil&Gas industry's global reach and active participation in international CCS initiatives showcase the nation's influence and contribution on a global scale. Moreover, the UK can potentially align and learn from neighbouring countries developing CCS, benefiting from similarities in geology, supply chains, costs, and regulatory environments. Finally, the UK is recognised for developing new technologies in a safe and environmentally conscious manner. Its culture emphasises high standards, reliability, safety, and environmental consciousness, earning appreciation from other market players.

Table 5-11: UK competitive disadvantages

Disadvantage	Description
Incomplete policy direction	A clearer political direction is emerging from the UK Government, such as through the CCUS Vision published in December 2023, which shows the route that CCUS projects can take beyond 2030, with a vision to make the UK a global leader in CCUS (DESNZ, 2023). However, challenges still arise regarding long-term certainty for investors, reducing the likelihood of investment in the CCS and GGR sectors. Further finer details of the policies are needed. Further clarity is also necessary for unsuccessful projects in the Track-1 cluster sequencing process. Several projects currently under development in the UK have highlighted that they may consider moving their developments overseas if they cannot access CO_2 infrastructure and are unsuccessful in obtaining CCS funding support (CCSA, 2023).
Lack of proven CO_2 Injections	One notable disadvantage is the absence of actual CO_2 injections in the UK to demonstrate injectivity, containment, and storage operation costs. Although there are expectations of similarities to Norway, the lack of tangible evidence may pose uncertainties in the effectiveness of storage operations. (Source: Ricardo's experts' judgement).
High energy costs	The UK grapples with high energy costs, a significant factor contributing to overall CCS costs (and highest for DACCS). (Source: Ricardo's experts' judgement).
Limited engineering appreciation among decision-makers	Key decision-makers in the UK often have limited appreciation of engineering aspects. With few investors or politicians possessing experience in manufacturing, geology, or large plants, investments in the sector can be erratic and poorly aligned. (Source: Ricardo's experts' judgement).
Limited number of focused CCS suppliers	Due to a lack of large chemical engineering projects in the UK, a limited base of UK Tier 0, 1, and 2 suppliers could supply the largest items of kit within a CCS facility (Source: Ricardo's experts' judgement).

5.3.4.1 UK Competitive advantage: key conclusions per technology

In the following table, we classify each technology as being either:

- A "**primary focus area**", highlighted in green, i.e. an area where the UK is expected to have consolidated advantage;
- A "**further opportunity**", in yellow, i.e. an area where the UK could gain a competitive advantage from positioning itself as a potential early mover; or
- A "**lower potential"** area, in red, i.e. an area on which the UK does not appear to have potential.

Table 5-12: Technologies classification based on UK competitive advantage

Tech family	Technology	Classification	Answer & justification/rationale
CO_2 capture	Post-combustion	Further opportunity	Post-combustion capture has the advantage over pre-combustion and oxy-combustion capture of being able to be retrofitted onto existing plants with much fewer modifications needed. To date, most CO_2 capture projects deployed are post-combustion capture projects. The UK also has significant expertise in manufacturing components relevant to post-combustion CO_2 capture systems, including column vessels, MMV equipment, heat exchanger manufacture and assembly and packaged CCS provisions. This can allow the UK to develop the manufacturing sectors to supply equipment for CO_2 capture plants (Source: Ricardo's experts' judgement). The GIGA will support the UK with further CO2 capture supply chain developments.
	Oxy	Further opportunity	Many equipment items for oxy-fuel combustion CO_2 capture plants and pre-combustion CO_2 capture plants may be similar to those of post-combustion plants (such as MMV equipment, pumps, etc). The UK can, therefore, build on the existing manufacturing industry to be involved in the global trade of CO2-related equipment. However, implementing oxy-fuel and pre-combustion capture systems is more complex, with lower TRLs across the board. This may mean that the demand for these technologies will not increase as much as post-combustion capture systems, hence potentially providing a lower potential for global market size for the UK to be involved in.
	Pre-combustion	Further opportunity	
CO_2 storage	Geological storage	Primary focus area	The North Sea geological storage capacity is indicated to be greater than the UK's requirement for CO_2 storage. Therefore, several CCS clusters are reporting potential for CO_2 import, potentially positioning the UK as an importer of CO_2 from countries with no geological storage ability. This provides a significant opportunity for the UK to provide 'CO_2 storage as a service' (Source: Ricardo's experts' judgement).
GGRs	BECCS	Further opportunity	To date, the deployment of BECCS and DACCS in the UK has focused on pilot and demonstration scale projects. However, the UK Government's ambition is to deploy 5 $MtCO_2$/yr by 2030 (HM Government, 2021). In order for DACCS to sufficiently result in negative emissions, the electricity used to power the plant must come from low-carbon sources. The UK has significant quantities of wind and solar power that can support this. Over recent years, the UK has also published several policies relevant to GGRs, which can
	DACCS	Further opportunity	

Tech family	Technology	Classification	Answer & justification/rationale
			provide certainty to inventors interested in investing in the technologies. However, there are still some barriers to the deployment of BECCS and DACCS, most notably high costs and large energy requirements. In the case of BECCS, a major constraint also relates to the availability of biomass (Source: Ricardo's experts' judgement). The GIGA will also support the UK with further developments in the GGR supply chain.

Source: Ricardo's experts' judgement

6. HYDROGEN AND ALTERNATIVE FUELS

6.1 INTRODUCTION

This chapter analyses the hydrogen and alternative fuels market and its associated technologies.

- **Hydrogen** is an energy carrier with many applications within the energy transition. Since hydrogen is an energy carrier and not an energy source, it also has applications as a molecule in chemical and industrial processes that could be decarbonised using hydrogen from a renewable origin. Currently, hydrogen is mainly used in refineries and industrial processes, and it is sourced from a fossil fuel origin, primarily methane, which is very carbon intensive.
    - **Low-carbon hydrogen**, as it will be reviewed in this chapter, could either come from electrolysis using electricity from renewable sources such as wind or solar ('green hydrogen') or carbon-intensive processes to reform hydrogen from natural gas, like autothermal reforming[23] (ATR) complemented by carbon capture, use and storage (CCS) technologies ('blue hydrogen'). From this point of view, electrolysers will be crucial equipment to produce low-carbon hydrogen while contributing to the energy transition (IEA, 2023). Blue hydrogen is widely regarded as a stepping-stone technology on the path to net zero and the dominance of green hydrogen. Within the technology pathways to produce low-carbon hydrogen, ATR with CCS will compete with the implementation of CCS to already established steam methane reforming (SMR) plants.
    - The physicochemical properties of hydrogen require high-pressure and low-temperature conditions for storage and transportation, which involves energy-intensive processes. For this reason, 90% of hydrogen currently used worldwide is produced on-site and not stored or shipped to consumption sites (IEA, 2023). With the energy transition applications advancing, new opportunities for storage and transport technologies arise in future markets where hydrogen cannot be produced on-site. This section analyses the uprising market trends for salt caverns and depleted gas fields as storage technologies. Despite the low fraction of hydrogen not used on-site, hydrogen transmission and transport technologies exist and range in the more local or national applications from pipelines to tube trailers. Transmission and transport solutions for international trade or longer distances include facilities to produce ammonia, methanol and other liquid organic hydrogen carriers (LOHC).

Bioenergy – Methodological note

The comparison of the different energy transition technologies assessed in this study with the bioenergy technologies (gasification and pyrolysis) is difficult since these are not standalone technologies for the production of biofuels. The process of producing biofuels (via gasification or pyrolysis) involves additional technologies – typically licenced by major Oil&Gas companies. These processes are usually not developed by a single technology licensor, but the process itself uses different licensors. Sections of both processes are similar to other chemical plants, therefore the same technology licensor could deliver the same product to different fields (e.g. manufacturing and pharma), effectively not contributing entirely, with its sales, to the gasification market share. This makes the estimation of the market share even more difficult at a quantitative level. Therefore, to be comparable, the analysis should identify each technology licensor or manufacturer involved into the implementation of these processes and identify for each of them what is the % of market they are covering and for which application.

- Finally, in the context of this report, the term **bioenergy** covers only the biofuels (liquid and gaseous) produced via gasification and pyrolysis[24] of secondary biomass sources (e.g. energy crops,

[23] Natural gas contains methane (CH_4) that can be used to produce hydrogen with thermal processes, such as steam reforming and partial oxidation (U.S. Department of Energy, n.d.). Autothermal reforming (ATR) combines steam reforming and partial oxidation processes. ATR creates a thermally neutral process by utilising steam reforming to boost hydrogen production while using the partial oxidation to generate heat. This process does not require an external heat source for the reactor because ATR includes partial oxidation which is exothermic (Manna, 2024).

[24] Gasification produces gas by breakdown of solid biomass at high temperature with the presence of an oxidant like oxygen, pyrolysis does not need an oxidant to generate gases and liquid organic products as result of the process at medium temperatures (IEA, 2023).

lignocellulosic residues, industrial and municipal solid wastes). The use of these technologies for heat and power is not considered.[25]

Table 6-1: In-scope technologies

Sector	Tech families	Technologies
Hydrogen and alternative fuels	Hydrogen production	Electrolysis
		Autothermal reforming
	Hydrogen infrastructure	Hydrogen storage - medium salt cavern
		Depleted gas field storage
		Hydrogen transmission/transport
	Bioenergy	Pyrolysis
		Gasification

6.1.1 Key takeaways

- The market size for hydrogen-related technology will experience a significant increase in the next 25 years (global annual market value of USD 120-135 billion by 2050), while it is not expected a similar rise in demand for technologies for bioenergy. For hydrogen, the leading technologies with a high growth potential are electrolysers (global annual market value of USD 50-60 billion by 2050) and transmission/transport technologies (global yearly market value of USD 53-67 billion by 2050). Regarding bioenergy-related technologies, despite their expected low level of growth overall, gasification has higher potential in market size than pyrolysis in relative terms.
- Hydrogen and alternative fuels are essential components in achieving decarbonisation. According to projections in the GEM-E3, the global market size for hydrogen fuel in 2050 is anticipated to increase from USD 377.6 billion in the current policy scenario to USD 3142.1 billion in the Below 2 ºC scenario. In the net-zero scenario, the market size is projected to further increase to USD 3677.2 billion by the year 2050.
- According to the projection from the GEM-E3 model, the UK holds approximately 1.1-2.1% market share in the global market for hydrogen and alternative fuels across scenarios and over time. The main producers of hydrogen and alternative fuels are Latin America and Asian countries, holding a market share of approximately 30% to 36%. The USA has a market share ranging from 17% to 23%, and China has a market share of around 15% to 20% across scenarios in 2050.
- Note that the above points refer to hydrogen production as a fuel, while the technology-level analysis conducted in this chapter relates to the manufacturing of equipment for the production and transmission of hydrogen.
- The UK has high potential in terms of market share in equipment manufacturing for gasification and for engineering and implementation services for salt caverns. Gasification has a wide range of applications in the UK. Given its flexibility and capacity to generate sustainable aviation fuel (SAF) and hydrogen, gasification technologies manufactured in the UK can potentially attract a future high market share (5% of the global demand for SAF in 2035).
- The demand for hydrogen- and bioenergy-related technologies is mainly driven by the demand for the final products, i.e. hydrogen and bioenergy. Technology manufacturing is boosted by funding mechanisms such as the US Inflation Reduction Act and the EU Innovation Fund. Nevertheless, the development and the growth of markets for these technologies could be hampered by production bottlenecks and a low number of offtake agreements that could destabilise the demand for hydrogen and bioenergy.

[25] Heat and power generation is covered by the BECCS technology, given the latest market trends that associate the production of heat and electricity from bioenergy with carbon capture and storage.

- Besides the US and the EU, market competitors are China, India and Japan. China is expected to possess 25% of the global electrolyser manufacturing capacity by 2030. In addition, along with Japan and South Korea, China is one of the three countries where shipbuilding yards build liquefied gas tankers for hydrogen transport. In addition, Japan has patented the largest number of hydrogen technologies between 2010 and 2020, positioning itself as a technology leader in the sector. Finally, India will account for 6% of global electrolyser manufacturing capacity in 2030 and has adopted several programs to finance research in hydrogen- and bioenergy-related technologies.
- The UK has a regulatory and policy framework that could support an industrial landscape with the technology and expertise needed to manufacture hydrogen- and bioenergy-related technologies. Nevertheless, it is falling behind due to a surge of competition from other countries. Protectionist economic and regulatory measures fuel this competition. The UK can reap some benefits, but it will attract smaller market shares than the shares of the other players.
    - The UK enjoys some competitive advantages. Several fundings were adopted for hydrogen-related technology, reaching a funding greater than GBP 600 million (Hydrogen Supply Competition, Net zero Hydrogen Fund, Hydrogen Allocation Rounds and Industrial Hydrogen Accelerator competition). In addition, the UK could position itself as a key player in gasification and pyrolysis because both technologies are closely linked to the Oil&Gas sector, and the UK presents a long history of technical development of O&G technologies.
    - The UK has to deal with competitive disadvantages, too. In particular, several gasification projects have been ended in the UK due to technical and management issues. This has generated poor confidence for investors and local authorities, hindering a full commitment to developing these technologies.

6.2 RQ1: POTENTIAL MARKET SIZE AND UK MARKET SHARES

6.2.1 Quantitative analysis at the sector level

6.2.1.1 Market size

Under the current policy scenario, the global market size for hydrogen and alternative fuels will rise from USD 213 billion in 2020 to USD 377.6 billion in 2050 (+77%).

However, in the Below 2 ºC and Net Zero scenario for 2050, the global market experiences a substantial surge, reaching USD 3142.1 billion (a 15x increase) and USD 3,677.2 billion (a 17x increase), respectively. This underscores the need to utilise hydrogen and alternative fuels to achieve decarbonisation.

In the GEM-E3 model and for the scenarios considered, the change in the fuel mix is mainly affected by the carbon prices and policies and measures. As the cost of fossil fuels rises due to carbon pricing and renewable energy sources (RES) deployment rate increases, there is an increase in the demand for hydrogen and alternative fuels. Higher carbon prices incentivise a shift towards cleaner energy sources, and RES deployment requires additional storage, impacting the overall composition of the fuel mix. In the Net Zero scenario, the UK market share of hydrogen and alternative fuels is lower than the current policy scenario as the contribution of UK exports to the total export market is relatively small.

Table 6-2: Market size (demand in billion USD)

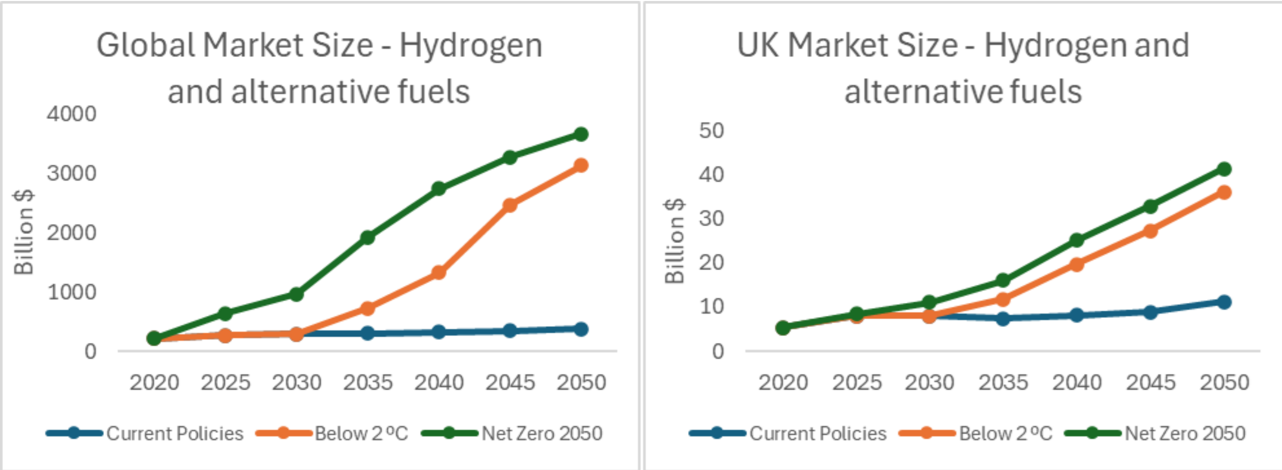
NGFS Scenario	Geography	2020	2025	2030	2040	2050
Current policies	Global market	213.0	267.5	292.6	305.0	377.6
	Domestic market	5.3	8.0	8.0	7.4	11.2
	Export market	207.6	259.5	284.6	297.5	366.4
Below 2 ºC	Global market	213.0	267.5	292.6	727.8	3142.1
	Domestic market	5.3	8.0	8.0	11.8	36.2
	Export market	207.6	259.5	284.6	716.1	3105.9
Net Zero 2050	Global market	213.0	642.4	966.0	1928.0	3677.2
	Domestic market	5.3	8.4	11.1	16.1	41.4

NGFS Scenario	Geography	2020	2025	2030	2040	2050
	Export market	207.6	634.0	954.9	1911.9	3635.9

Source: Ricardo analysis based on GEM-E3 outputs

The following figure depicts the global and UK market sizes for hydrogen and alternative fuels. In the Net Zero scenario, these fuels exhibit substantial increases, reaching their peak by 2050. The UK market size escalates from approximately USD 5 billion to around USD 41 billion in 2050.

Figure 6-1: Global and UK market size – Demand



Source: Ricardo analysis based on GEM-E3 outputs

6.2.1.2 UK market share

The UK holds approximately 0.6-2.1% market share in the global hydrogen and alternative fuels market across scenarios and over time.

In 2020, domestic production covered 43.6% of the domestic demand, peaking at 87.1% in the Net Zero scenario in 2050.

Table 6-3: UK share of each market

NGFS Scenario	Geography	2020	2025	2030	2040	2050
Current policies	Global market	1.3%	1.3%	1.2%	1.1%	2.1%
	Domestic market	43.6%	33.4%	32.6%	35.3%	64.7%
	Export market	0.2%	0.3%	0.3%	0.3%	0.2%
Below 2 ºC	Global market	1.3%	1.3%	1.2%	0.9%	1.0%
	Domestic market	43.6%	33.4%	32.6%	44.9%	84.5%
	Export market	0.2%	0.3%	0.3%	0.2%	0.1%
Net Zero 2050	Global market	1.3%	0.7%	0.8%	0.6%	1.0%
	Domestic market	43.6%	42.7%	55.6%	62.3%	87.1%
	Export market	0.2%	0.2%	0.2%	0.1%	0.1%

Source: Ricardo analysis based on GEM-E3 outputs

6.2.2 Qualitative analysis: market size

Based on recent literature findings, the technologies analysed are very likely to experience positive market size growth in the future.

- **Hydrogen**: Based on the estimates by Ludwig et al. (2021), the global annual market value could reach USD 120-135 billion by 2050 when considering the hydrogen technologies covered here. The hydrogen business will be more competitive and less profitable than Oil&Gas. Clean hydrogen will not generate returns comparable to those of Oil&Gas. Hydrogen is a conversion, not an extraction business, and has the potential to be produced competitively in many places. This will limit the possibilities of capturing economic rents akin to those generated by fossil fuels (IRENA, 2022).

- **Bioenergy**: Although some sources, including IRENA (2022), indicate that modern bioenergy can make up a significant share of total energy use in industry by 2050 (20%), the manufacturing of equipment at the technology level appears to be quite limited.

For hydrogen technologies, equipment manufacturing could reach USD 113-141 billion (Ludwig, et al., 2021). This estimate includes production, transport and storage technologies. However, according to IRENA (2022), the hydrogen business will be less profitable and highly competitive. Indeed, hydrogen is a conversion business; hence, it can be produced competitively in many places.

According to BCG analysis, production technologies such as electrolysers and autothermal reforming (ATR) combined may constitute a global annual market valued between USD 53 billion in the worst-case scenario and USD 67 billion in the best-case scenario by 2050, while infrastructure market size – e.g. storage, transmission and transport – could reach a value of USD 55-63 billion by 2050 (Ludwig, et al., 2021). Existing estimates, including at specific technology levels, differ significantly, though, with BSG figures appearing to be at the lower end of the spectrum, but they all point to substantial future growth in all technologies explored. Estimates tend to differ, but the most significant technologies in terms of absolute future market size potential appear to be electrolysis (USD 50-180 billion between 2032 and 2050) and hydrogen transmission (USD 53-67 bn by 2050).

6.2.2.1 Hydrogen

Hydrogen production technologies include electrolysers and autothermal reforming (ATR). Electrolysers manufacturing could account for almost 45% of global annual market value for hydrogen technologies (Ludwig, et al., 2021). Considering the technology readiness level of electrolysers, this potential can be exploited soon. Indeed, PEM, alkaline and solid oxide electrolysers are in the market uptake stage (IEA, 2023). They are a step before being considered a mature technology. The large gap in market potential between electrolysers and ATR can be due to the fact that large-scale hydrogen production with CCS requires equipment – e.g. compressors, pumps, fans, heat exchangers, separation columns and storage tanks – already used in other industries such as Oil&Gas, chemicals and power generation (IEA, 2023). The partial presence of these technologies can explain why the market potential for manufacturing ATR is lower than in the case of electrolysers. In addition, there is no current real market size as ATR is a relatively new technology. Although it shows promising performance for hydrogen production (coupled with CCS), the standard SMR is the incumbent technology and still the ‘standard’ according to the judgement of Ricardo’s experts.

- **Electrolysis**: The market size is expected to grow substantially, but there are different estimates. According to Polaris Market Research (2023), the electrolyser market size will reach a value of USD 181.09 billion by 2032, while BCG (Ludwig, et al., 2021) estimates a global annual market value of USD 50-60 billion by 2050. Considering that the market size was USD 5.69 billion in 2022 (Polaris Market Research, 2023), the growth potential can range between an extra USD 44 billion and USD 175 billion. Two opposite forces can affect the demand for electrolysers. On the one hand, the pressure is on electrolyser manufacturers to further develop their technologies, standardise their systems for large-scale applications, and increase their manufacturing capacity. In addition, the increasing access to cheap renewable electricity attracts interest in low-emission hydrogen production using electrolysers (IEA, 2023). On the other hand, the uncertainty of the market can hamper the potential market size (DNV, 2022). The challenges are the growth of the supply chain, the use of precious materials (especially for PEM), and the absence of qualified personnel. Additional challenges are the readiness for large-scale electrolysis design and the development of inherently safe designs for ever-larger concepts (DNV, 2022).
- **ATR**: The market is expected to grow, but estimates differ significantly. BCG (Ludwig, et al., 2021) estimates that the global annual market value for capture technology used for hydrogen production will be USD 5-7 billion by 2050. These values include both SMR with CCS and autothermal reforming (ATR) with CCS. Instead, Dataintelo (2021) expects a market size value of USD 2.06 billion for ATR.

The large gap in market potential between electrolysers and ATR can be due to the fact that large-scale hydrogen production with CCS requires equipment – e.g. compressors, pumps, fans, heat exchangers, separation columns and storage tanks – already used in other industries such as Oil&Gas, chemicals and power generation (IEA, 2023). The partial presence of these technologies can explain why the market potential for manufacturing ATR is lower than in the case of electrolysers. In addition, there is no current real market size as ATR is a relatively new technology. Although it shows promising performance for hydrogen production (coupled with CCS), the standard SMR is the incumbent technology and still the ‘standard’ according to the judgement of Ricardo’s experts.

Hydrogen infrastructure will account for almost 46% of the global annual market value for hydrogen technologies (Ludwig, et al., 2021). However, the maturity of these technologies and, hence, their market uptake vary (IEA, 2023). Trucks and ammonia tankers are mature technologies, given their deployment for other uses. Pipelines for hydrogen and repurposed gas pipelines are also in the market uptake stage. Nevertheless, technologies enabling hydrogen transport for long distances are at the demonstration stage (IEA, 2023). On the one hand, technologies such as hydrogen blending, liquified hydrogen tankers, hydrogen turbo compressors and liquified organic hydrogen carriers have to demonstrate their possible market application. On the other hand, large prototypes for hydrogen de-blending have to be tested (IEA, 2023). These readiness levels can postpone the full deployment of technologies in a global annual market valued at USD 35-40 billion (Ludwig et al., 2021). In addition, their postponed deployment could fragment the global hydrogen market because these technologies can enable the transport of hydrogen over long distances. Hydrogen suppliers would not have access to a global market but to local ones due to pipelines range limits. Hence, local markets would be satisfied by local hydrogen production plants. The increase in hydrogen suppliers in each geography would increase demand for hydrogen production technologies. Therefore, market fragmentation could positively affect production technology manufacturers.

- **Medium salt cavern**: BCG (Ludwig, et al., 2021) estimates the global annual market value for hydrogen storage will be USD 5-7 billion by 2050. These projections do not distinguish between salt caverns and depleted gas fields. However, based on announced projects, the storage capacity based on salt caverns will be 4TWh (80% of the total storage capacity) in 2030 and 14TWh (45% of the total storage capacity) in 2050 (IEA, 2023). These estimates highlight that a large share of the market value of hydrogen storage could be due to salt caverns. Should the wide-scale adoption of green hydrogen happen as predicted, then large-scale storage will be required to meet seasonal demand variation. Moreover, according to Ricardo's experts, decarbonising electricity supply and increasing renewable supply will necessitate seasonal storage.
- **Depleted gas field storage**: BCG (Ludwig, et al., 2021) estimates the global annual market value for hydrogen storage will be USD 5-7 billion by 2050. These projections do not distinguish between salt caverns and depleted gas fields. However, based on announced projects, the storage capacity based on salt cavern will be 1TWh (20% of the total storage capacity) in 2030 and 14TWh (45% of the total storage capacity) in 2050 (IEA, 2023). According to Ricardo's experts, there is no current market, and one is unlikely to be created until well after 2030. However, similar to salt caverns, if seasonal hydrogen storage is required, repurposing gas fields is a potential option. Regarding potential market size, each country will not need many gas field storage facilities, assuming there will be a national transmission network to distribute the hydrogen.
- **Hydrogen transmission and transport:** BCG (Ludwig, et al., 2021) estimates the global annual market value for hydrogen transmission and transport will be USD 53-67 billion by 2050. In particular, BCG distinguishes between the different technologies related to these activities.
  - For pipelines, the expected value is USD 2-5 billion. Reached economies of scale, pipelines will become the cheapest option for hydrogen transport up to a distance of 2,000-2,500 km, particularly in the case of repurposed pipelines (IEA, 2023).
  - Regarding compression and other distribution modes, the forecasted value is USD 16-22 billion: USD 5-7 billion for compression and USD 11-15 billion for other distribution modes.
  - BCG (Ludwig, et al., 2021) expects a value of USD 35-40 billion for conversion and recapture technologies. Indeed, hydrogen can be transported more easily as ammonia or carbon-based compounds such as methanol, but it needs to be reconverted. The ammonia technology market is expected to be valued at USD 21-25 billion, while the carbon-based compounds technology manufacturing will amount to USD 16-20 billion.

6.2.2.2 Bioenergy

Bioenergy technologies cover pyrolysis and gasification technologies manufacturing.

- **Pyrolysis[26]**: The global pyrolysis oil market is estimated to reach over USD 449 million by 2030 (Data Bridge Market Research, 2022). According to the judgement of Ricardo's experts, it is likely that pyrolysis will be deployed to contribute more to the waste management sector than to energy-related use, as witnessed in the US and the EU. According to his opinion, fuels developed by pyrolysis technologies will be mainly the process's side-products rather than the technology's central focus (non-biogenic feedstock recycling). Therefore, if only energy-related applications are considered, the real

[26] The focus is on the market size of the product rather than the technology itself because there is no public data available for pyrolysis market. It is also important to highlight that the pyrolysis oil market considers plastic feedstocks amongst others, therefore it does not refer to bioenergy only.

growth rate will likely be minimal. No specific data related to the UK market are currently available (Source: Ricardo's experts' judgement).

- **Gasification**[27]: The global biomass gasification market in 2022 was estimated at USD 29 million (MarketsandMarkets, 2022). According to different sources (MarketsandMarkets, 2022; Dimitriadou & Lavinsky, 2022), the annual growth rate for the gasification market can be 8.9% or 7.2%. The former is the estimated growth rate from 2022 to 2027 (MarketsandMarkets, 2022), while the latter is the estimated growth rate of the demand for sustainable aviation fuel (SAF) from 2025 to 2050 (Dimitriadou & Lavinsky, 2022). Assuming that demand for gasification technologies was to grow at the same rate as SAF demand, the global market size would reach USD 3.16 billion by 2050. However, it is essential to note that this assumption is not backed by evidence or expert judgement and, therefore, must be interpreted as an optimistic scenario. Assuming both growth rates allows us to estimate global market size ranges for gasification technologies in 2030 and 2050.[28] The market for gasification technologies could reach a value of USD 50.6-57.4 million in 2030 and USD 2.03-3.16 billion in 2050.

6.2.2.3 Summary: global market size trends

The following table summarises global market size trends at the technology level.

Table 6-4: Global market size growth potential: RAG rating by technology

Tech family	Technology	Rating	Justification/rationale and key sources
Hydrogen production	Electrolysis	High	In 2022, the market size was USD 5.69 billion (Polaris Market Research, 2023). According to sources reviewed (Polaris Market Research, 2023; Ludwig, et al., 2021), the growth potential can range between USD 44 billion and USD 175 billion. In addition, three electrolysis technologies (PEM, ALK, and SOEC) are in the market uptake stage according to their technology readiness level (TRL 8-9) (IEA, 2023). This technology maturity could foster the reaping of the early-mover benefits.
	Autothermal reforming	Medium	In 2022, the total market size was approximately USD 1.02 billion. It is expected to grow by a further USD 1.04 billion between 2022 and 2030, reaching an estimated worth of USD 2.06 billion by 2030 (Dataintelo, 2021). Two technologies (ATR and ATR – GHR) are tested as large prototypes (TRL 5) (IEA, 2023). However, according to Ricardo's experts' judgement, the longevity of blue hydrogen technologies is questionable. Large-scale technologies are at risk of being irrelevant in 26 years as they are incompatible with Net Zero due to the inherent release of GHGs at the flue and upstream. Also, emissions from upstream gas extraction will be inherently associated with natural gas usage. Although this technology has global potential, it will have limited market uptake in the UK.
Hydrogen infrastructure	Hydrogen storage - medium salt cavern	Medium	Based on announced projects, the storage capacity based on salt caverns will be 4TWh in 2030 and 14TWh in 2050 (IEA, 2023). Salt caverns are assessed as a mature technology (TRL 10) while fast-cycling salt caverns are tested as large prototypes (TRL 5) (IEA, 2023). In addition, according to Ricardo's experts' judgement, given the fugitive emissions in the case of depleted gas fields, a more controlled, dedicated salt cavern would be the preferred technology.

[27] The biomass gasification market size refers to the total market value of biomass gasification systems, which are used to convert biomass feedstocks such as wood chips, agricultural waste and municipal solid waste into a synthesis gas and includes all applications of the synthesis gas: conversion to biofuels as well as combined heat and power production.

[28] The main caveats are the stability of growth rates over time and the use of market size in 2022: prices can change due to inflation and decreasing manufacturing costs.

Tech family	Technology	Rating	Justification/rationale and key sources
			However, recent research (Peterse, Kühnen, & Lönnberg, 2024) highlights that the potential investment cost for a salt cavern will be EUR 900/MWh on average.
	Depleted gas field storage	Low	Based on announced projects, the storage capacity based on depleted gas fields will be 1TWh in 2030 and 14TWh in 2050 (IEA, 2023). Depleted gas fields should start testing as large prototypes (TRL 4) (IEA, 2023). Furthermore, recent research (Peterse, Kühnen, & Lönnberg, 2024) highlights the potential investment cost for the depleted gas field will be EUR 450/MWh on average. Nevertheless, their geographical location is limited, and significant questions remain on how fugitive emissions can be eliminated (Source: Ricardo's experts' judgement).
	Hydrogen transmission/transport	High	Concerning transmission and transport, TRL varies according to the technology (IEA, 2023): • Mature (TRL 11) – trucks and ammonia tanker; • Market uptake (TRL 9-8) – new pipelines and repurposed gas pipelines; • Demonstration (TRL 7-6) – H2 blending, liquified H2 tanker, H2 turbo compressor, liquified organic hydrogen carrier; • Large prototypes (TRL 4) – H2 de-blending. Whenever hydrogen transport by pipeline reaches economies of scale, it will become the cheapest option for hydrogen transport up to a distance of 2,000-2,500 km, particularly in the case of repurposed pipelines (IEA, 2023). Hence, an increase in demand for hydrogen pipelines could occur. IEA (2023) expects the global hydrogen transmission pipeline length to be 20,000 km and 220,000 km in 2030 and 2050 in the Net Zero scenario. At least 70% of those lengths will be due to new H2 pipelines (IEA, 2023). In addition, according to Ricardo's experts' judgement, the transmission pipeline sector will be essential in moving hydrogen from production centres to demand centres and supporting international trade. It will grow and be crucial to any industrialised nation. This will be a globally competitive sector, and the UK should consider focussing on its strengths – offshore/subsea pipelines. Regarding transport, there are currently no commercially available tankers for shipping liquefied hydrogen, and only a few shipbuilding yards are building these tankers in Korea, Japan, and China (IEA, 2023).
Bioenergy	Pyrolysis	Low	Pyrolysis for biogenic feedstocks and tyres as feedstock is ready for market uptake (Panoutsou, et al., 2021). Given the multitude of pyrolysis applications available, a clarification is needed. The current use of pyrolysis technologies in the UK, at a commercial scale, is mainly focused on the production of both pyrolysis oil and biochar from waste biomass resources, deemed suitable and compliant with the Biomass Sustainability Criteria as summarised in the national biomass strategy (2023). However, globally, the pyrolysis technology suppliers mainly focus on the waste management market, particularly the plastic-to-plastic circular loop, which would exclude the technology from energy-related applications. Therefore, if considering the energy market alone, the pyrolysis market will most likely reduce, with a few notable exceptions, while its use in the recycling sectors will substantially increase. Despite this scenario, the energy-related use of pyrolysis might also be affected by the new discussion at the policy level regarding the use of allocation methods (chain of custody methods) in the industry. If a more lenient allocation method is adopted, then pyrolysis technologies could still be deployed for

Tech family	Technology	Rating	Justification/rationale and key sources
			energy use, particularly fuel production (e.g. Naphtha). However, the impact of these methods is still unclear, especially in the UK, where the mass-balance discussions have not been formalised yet (Source: Ricardo's experts' judgement).
	Gasification	High	Biomass gasification technologies have reached the demonstration stage (TRL 7-8) (IEA, 2023; Panoutsou, et al., 2021). Both UK and EU have set relevant targets for the use of Sustainable Aviation Fuel (SAF) in the aviation industry (SAF mandate). To be adopted as drop-in fuel, SAF should be manufactured via specific pathways, certified by American Society for Testing and Materials (ASTM). According to the judgement of Ricardo's experts, gasification represents one of the most promising production pathways for SAF, from either biogenic or non-biogenic resources (e.g. Municipal Solid Waste).

6.2.3 Qualitative analysis: UK market shares

6.2.3.1 Trade flows analysis: hydrogen

The table below shows the annual average of UK exports (2021-2022) for a number of selected HS subheading codes (provided by DESNZ) relating to components related to the production of hydrogen production equipment. These numbers can be interpreted as proxies of the UK's share of tradable export markets. The total average for this sector stands at 2.3% of the global tradable market.

Table 6-5: UK share of global exports, selected HS subheadings, 2021-2022

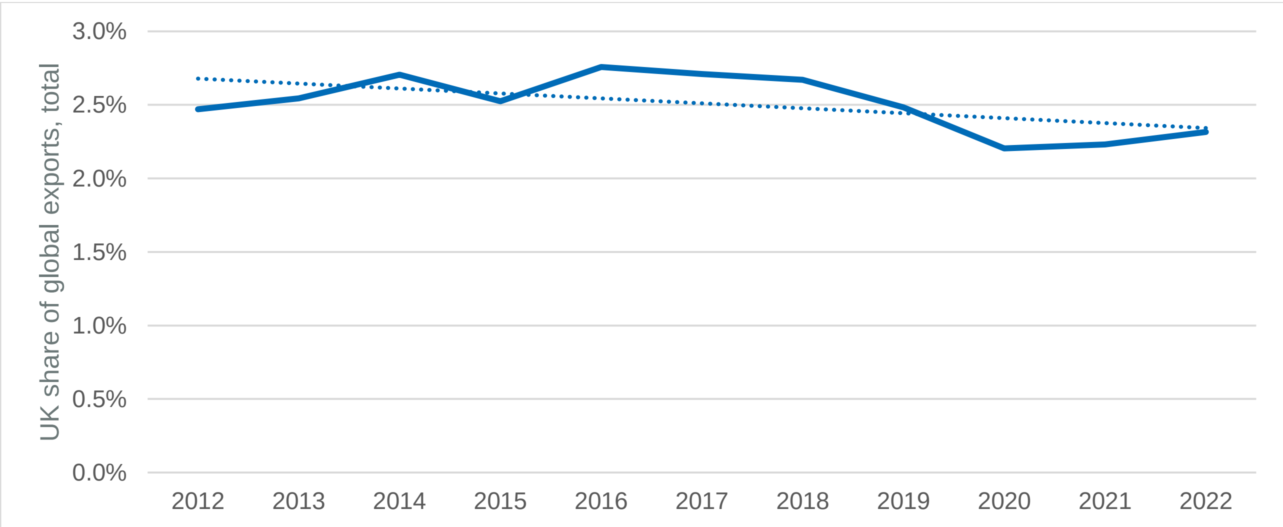
Group	Subheading included in group	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
28 Inorganic chemicals	280410 Hydrogen	USD 3M	1.0%
73 Articles of iron or steel	730900 Reservoirs, tanks, vats and similar containers for any material (other than compressed or liquefied gas), of iron or steel 731100 Steel containers for compressed or liquefied gas	USD 216M	2.3%
74 Copper and articles thereof	741999 Copper; articles n.e.c.	USD 27M	1.3%
76 Aluminium and articles thereof	761100 Aluminium reservoirs, tanks, vats and similar containers, for any material (other than compressed or liquefied gas) 761300 Aluminium containers for compressed or liquefied gas	USD 115M	12.4%
84 Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof	840510 Producer gas or water gas generators, with or without their purifiers; acetylene gas generators and similar water process gas generators, with or without their purifiers 840590 Producer gas or water gas generators, with or without their purifiers; acetylene gas generators and similar water process gas generators, with or without their purifiers - Parts 841440 Hydrogen compressor 841480 Hydrogen gas compressor diaphragm 841989 Machinery, plant or laboratory equipment, whether or not electrically heated, for the treatment of materials by a process involving a change of temperature such as heating, cooking, roasting, distilling, rectifying, sterilising, pasteurising, steaming, drying,	USD 2,480M	3.6%

Group	Subheading included in group	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
	evaporating, vaporising, condensing or cooling: other machinery, pant and equipment 841990 Machinery, plant or laboratory equipment, whether or not electrically heated, for the treatment of materials by a process involving a change of temperature such as heating, cooking, roasting, distilling, rectifying, sterilising, pasteurising, steaming, drying, evaporating, vaporising, condensing or cooling: parts. 842139 CO_2 dehydration unit; CO_2 membrane		
85 Electrical machinery and equipment and parts thereof	8501 Electric motors and generators (excluding generating sets) 850300 Parts suitable for use solely or principally with the machines of heading 85.01 or 85.02. 854330 Electrical machines and apparatus; for electroplating, electrolysis or electrophoresis	USD 1,076M	1.2%
Total		**USD 3,917M**	**2.3%**

Source: Ricardo elaboration on UN Comtrade data

The figure below shows an increase in the UK's share of global exports (for the total HS codes analysed) between 2012 and 2016 (from 2.5% to 2.8%), followed by a decline to 2.2% in 2020 and a rebound to 2.3% in 2022.

Figure 6-2: UK share of global exports, 2012-2022



Source: Ricardo elaboration on UN Comtrade data

6.2.3.2 Trade flows analysis: bioenergy

The table below shows the annual average of UK exports (2021-2022) for some selected HS subheading codes (provided by DESNZ) relating to components related to bioenergy production equipment. These numbers can be interpreted as proxies of the UK's share of tradable export markets. The total average for this sector stands at 4.0% of the global tradable market.

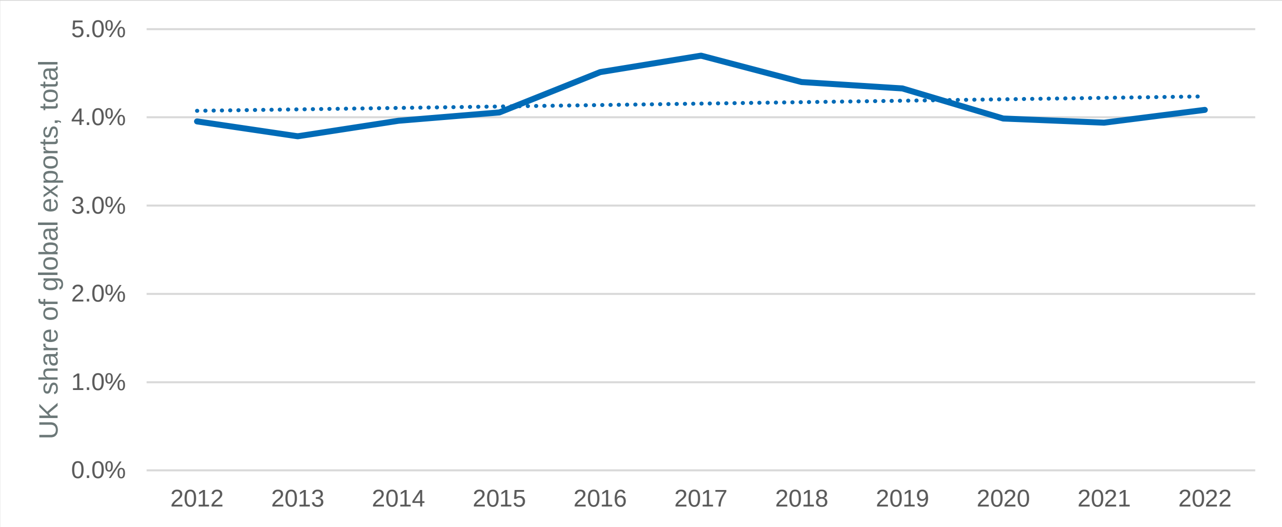
Table 6-6: UK share of global exports, selected HS subheadings, 2021-2022

Group	Subheading included in group	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
73 Articles of iron or steel	730900 Reservoirs, tanks, vats and similar containers for any material (other than compressed or liquefied gas), of iron or steel 732119 Cooking appliances and plate warmers, other, including appliances for solid fuel	USD 144M	2.3%
74 Copper and articles thereof	741999 Copper; articles n.e.c.	USD 27M	1.3%
76 Aluminium and articles thereof	761100 Aluminium reservoirs, tanks, vats and similar containers, for any material (other than compressed or liquefied gas)	USD 9M	3.9%
84 Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof	8405 Producer gas or water gas generators, with or without their purifiers 840211 Boilers; watertube boilers with a steam production exceeding 45 tons/hour 840212 Boilers; watertube boilers with a steam production not exceeding 45 tons/hour 840219 Boilers; vapour generating boilers, including hybrid boilers n.e.c. 840290 Steam or other vapour generating boilers: parts. 840410 Boilers; auxiliary plant, for use with boilers of heading no. 8402 or 8403 (e.g. economisers, super-heaters, soot removers, gas recoverers) 841181 Turbines; gas-turbines (excluding turbo-jets and turbo-propellers), of a power not exceeding 5,000kW 841182 Turbines; gas-turbines (excluding turbo-jets and turbo-propellers), of a power exceeding 5,000kW 841490 CO_2 compressor 841931 Dryers; for agricultural products, not used for domestic purposes 841940 Distilling or rectifying plant; not used for domestic purposes 841960 Machinery; for liquefying air or gas, not used for domestic purposes 841989 Machinery, plant or laboratory equipment, whether or not electrically heated, for the treatment of materials by a process involving a change of temperature such as heating, cooking, roasting, distilling, rectifying, sterilising, pasteurising, steaming, drying, evaporating, vaporising, condensing or cooling: other machinery, plant and equipment 842129 Filtering or purifying machinery and apparatus for liquids 842139 CO_2 dehydration unit; CO_2 membrane 847990 Machines and mechanical appliances; parts	USD 4,286M	4.2%
Total		**USD 4,467M**	**4.0%**

Source: Ricardo elaboration on UN Comtrade data

The figure below shows an increase in the UK's share of global exports (for the total HS codes analysed) between 2012 and 2017 (from 4.0% to 4.7%), followed by a decline to 3.9%% in 2021 and a rebound to 4.1% in 2022.

Figure 6-3: UK share of global exports, 2012-2022



Source: Ricardo elaboration on UN Comtrade data

6.2.3.3 UK market shares: qualitative analysis

Future UK market shares for the technologies analysed are most likely to experience positive trends, despite currently being fairly low. The UK may satisfy a small share of an increasing technology demand (Wood/Optimat, 2022). The potential market is quite similar among the technology families. The UK is projected to satisfy around 3% of the global demand for electrolysers and 7% of the demand for ATR technologies by 2050 (Wood/Optimat, 2022). On the other hand, regarding hydrogen infrastructure, the UK market share will only cover a tiny fraction of global demand, according to the judgement of Ricardo's experts (see the table below for more information).

Table 6-7: UK market share: likely trends by technology

Tech family	Technology	Answer
Hydrogen production	Electrolysis	UK technology manufacturing will satisfy 2% and 3% of the global market, respectively, in 2030 and 2050 (Wood/Optimat, 2022).[29] These estimates are supported by the planned expansion projects currently available. Among the announced expansion plans of key electrolyser manufacturers, only one plan is expected to occur in the UK. ITM Power plans to expand its manufacturing capacity to 1.5 GW by 2030 (IEA, 2023). This expansion represents almost 4% of the planned manufacturing capacity expansion at the global level by 2030. This slight future increase in manufacturing capacity can explain why the UK market share will slightly increase.
	Autothermal reforming (ATR)	UK technology manufacturing will satisfy 5% and 7% of the global market in 2030 and 2050 (Wood/Optimat, 2022).
Hydrogen infrastructure	Hydrogen storage - medium salt cavern	The global underground hydrogen storage is expected to reach up to 50TWh by 2030 (Research and Markets, 2023). Based on hydrogen demand in the UK hydrogen strategy, up to 3.1TWh of salt cavern storage will be needed by 2030, which is 6% of the total hydrogen storage in 2030. (Source: Ricardo's experts' judgement)

[29] The assumptions of Wood and Optimat report (2022) behind the three scenarios are multiple deployment rates of hydrogen. These different paths are partially consistent with the assumptions under GEM-E3, guaranteeing the reliability of the estimates provided by Wood and Optimat (2022).

Tech family	Technology	Answer
	Depleted gas field storage	The hydrogen sector could require up to 3.4TWh of large-scale hydrogen storage by 2030. Depleted hydrocarbon fields with existing infrastructure are considered a promising option for offshore storage. The potential of hydrogen storage in depleted gas fields is 2700TWh. Although it is difficult to predict the percentage will be fulfilled by depleted gas fields in 2030. (Source: Ricardo's experts' judgement)
	Hydrogen transmission/transport	Most hydrogen transport will be long-distance pipeline transportation in China and North America, with some international pipelines in Europe. The breakdowns of UK domestic and import shares for hydrogen in 2030 remain unclear. Assuming domestic production fulfils 80% of the hydrogen demand, with the rest met by imports, transport would be just 0.32 million tonnes, representing less than 2% of the total hydrogen transport (Source: Ricardo's experts' judgement).
Bioenergy	Pyrolysis	Whatever the global demand scenario can be in the future, the UK industry is currently underdeveloped compared to other geographical areas, like the EU. (Source: Ricardo's experts' judgement)
	Gasification	The current sustainable aviation fuel (SAF) production capacity in the EU is estimated to be around 0.24 million tonnes. The UK production is still in its infancy. Figures regarding the actual production of SAF in the UK are still unclear, given the country's actual low production rate (Source: Ricardo's experts' judgement). However, 20 planned SAF plants are present in the UK, with a forecasted production of over 800 kt/y of SAF, representing a market share between 3% and 5% of the global demand in 2035. Currently, the most significant worldwide proportion of SAF production adopts the Hydrotreated Esters and Fatty Acids (HEFA) process, which uses oils and fats as feedstock. Given the environmental issues associated with this feedstock, alternative technologies are currently being developed in the UK, most of which adopt gasification as a key technology.

The evidence presented makes it possible to draw some conclusions on the future UK market share in manufacturing specific technologies and its potential in attracting higher shares (see the table below for further information). In particular, the UK has a high potential for producing two technologies: autothermal reforming (ATR) and gasification. ATR will satisfy a lower market share of the demand for production technology than electrolysers (IEA, 2023). Nevertheless, the UK is expected to catch a higher share than the average (Wood/Optimat, 2022). Instead, gasification has a wide range of applications in the UK, according to the judgement of Ricardo's experts. Its feedstock acceptance flexibility and capacity to generate sustainable aviation fuel (SAF) and hydrogen drive current investors' interest in the market. Hence, the UK has the potential to attract higher market shares. In the table below, we assess whether there is potential for the UK to capture a market share higher than, in line with, or below the sector average indicated in the qualitative analysis above.

Table 6-8: Technologies that have the potential to attract significantly higher/lower market shares compared to the sector average

Tech family	Technology	Rating	Justification/rationale and key sources
Hydrogen production	Electrolysis	Lower than average	In the Net Zero scenario for 2030, two-thirds of the hydrogen produced (100 Mt out of 150 Mt) will be used for traditional demand uses in the industry and refining sectors (IEA, 2023). Low-carbon hydrogen (which includes electrolysis and ATR combined with CCS) will account for 14% of the consumption (5 Mt) in refining and 31% of demand (22 Mt) in industry by 2030 (IEA, 2023). The demand for low-carbon hydrogen in refining (5 Mt) and industry (22 Mt) will be covered by electrolytic hydrogen mostly (4 Mt in refining and 9 Mt in industry). Even though it can appear that electrolytic hydrogen will satisfy a lower demand than fossil fuels combined with CCS, it has to be underlined that ATR and SMR will contribute together. In the context of this report that analyses electrolysis and ATR, this distinction implies that the market size for ATR will be lower than the demand for electrolysers. Despite the increasing global demand for electrolysers, the UK market shares are expected to be lower than the sector average in

Tech family	Technology	Rating	Justification/rationale and key sources
			2030 and 2050. UK market shares for ATR will be greater than the sector average (Wood/Optimat, 2022). Indeed, in 2022, the UK accounted for 0.74% of the electrolysers manufacturing capacity worldwide (Energy and Climate Change Directorate, 2022). The same results do not change if GIGA policy is considered according to the judgement of Ricardo's expert. Indeed, even if GIGA boosted the manufacturing capacity by two- or three-fold compared to the estimations of Wood/Optimat (2022), the UK market share of electrolysers production would still be a marginal participation globally. Instead, GIGA will reinforce the UK market share for ATR because it is already higher than the average in the current policy scenario (Wood/Optimat, 2022).
	Autothermal reforming (ATR)	Higher than average	See above. In addition, ATR has the potential to be more popular than SMR. However, according to the UK government's hydrogen strategy, blue hydrogen is only seen as a stepping stone (Source: Ricardo's experts' judgement). UK technology manufacturing is expected to satisfy 5% and 7% of the global market, respectively, in 2030 and 2050 (Wood/Optimat, 2022).
Hydrogen infrastructure	Hydrogen storage - medium salt cavern	Average	Such applications of storage would only be implemented for particular uses, such as high orders of magnitude in energy storage and/or for very long times (seasonal) (IEA, 2023). Electrification and other sources, such as pumped hydro-storage, are more economical and efficient than hydrogen for fulfilling an application (Liebreich Associates, 2021). This also must consider that most of the hydrogen produced is used onsite, where it is produced (IEA, 2023). Therefore, storing and transporting will only be needed for a small fraction of all hydrogen produced globally. In that sense, even though it is not a new technology, underground hydrogen storage will have to compete with other energy storage and use technologies. Based on the announced projects, both salt caverns and depleted gas fields will account for 45% each (90% in total) of the hydrogen storage capacity in 2050 (30TWh) (IEA, 2023). IEA (2023) forecasts a needed hydrogen storage capacity of 1,200 TWh under the Net Zero scenario in 2050. Even though a small proportion of overall hydrogen demand will require storage, and salt caverns will compete with other storage technologies, the UK will maintain a market share in line with the sector average because salt cavern storage is a mature technology in the UK. The same is not valid for depleted gas fields because of the high risk of fugitive emissions of gases that could undermine their deployment.
	Depleted gas field storage	Lower than average	See above.
	Hydrogen transmission/transport	Average	Transmission/transport is a whole suite of technologies; a national pipeline is required for large-scale uptake in hydrogen, and more hydrogen needs to be moved by trailer to more remote applications, particularly in the short to medium term (Source: Ricardo's experts' judgement). For local (read as regional or national consumption) consumption, pipelines and trailer trucks (tube trailers) will be dominant. While for international trade, liquid organic hydrogen carriers (LOHC) will dominate in the form of ammonia, methanol, and dibenzyl toluene, among others (Source: Ricardo's expert's judgement). However, 90% of hydrogen is expected to be consumed on-site in the Net Zero scenario in 2030 (IEA, 2023), leaving a low fraction needing transmission or transport infrastructures.

Tech family	Technology	Rating	Justification/rationale and key sources
Bioenergy	Pyrolysis	Lower than average	Pyrolysis is gaining a competitive advantage in different sectors, especially in the waste management industry (e.g. plastic recycling) rather than the energy industry. This is mainly because pyrolysis oil is generally considered a low-efficiency energy vector compared to other technologies (e.g. gasification, biomass boilers). In addition, biochar - potentially generated by pyrolysis processes - still presents an unclear legal status, and its carbon sequestration potential still needs to be fully understood and investigated. Therefore, without regulation around the production and use of biochar in the UK, the benefits of biomass pyrolysis for energy purposes are limited.
	Gasification	Higher than average	Despite the numerous past failures associated with implementing gasification in the country, mainly related to municipal solid waste disposal, gasification still presents a wide range of applications, according to Ricardo's expert judgement. In particular, its feedstock acceptance flexibility and capacity to generate sustainable aviation fuel (SAF) and hydrogen drive current investors' interest in the market.

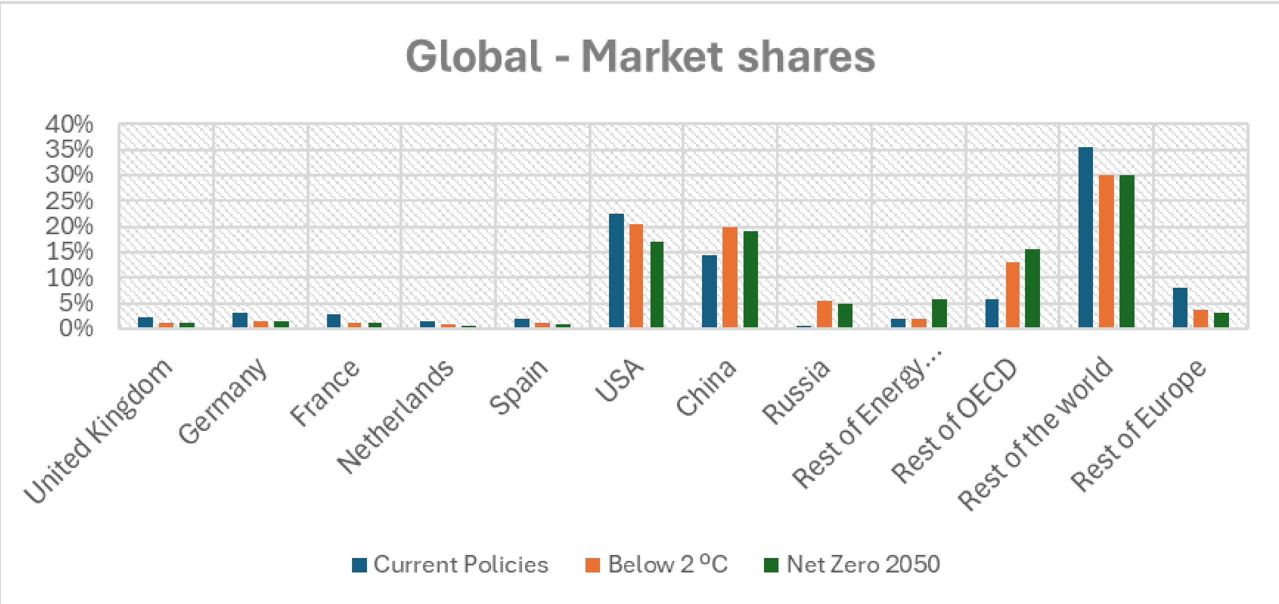
6.3 RQ2: UK COMPETITIVE ADVANTAGE

6.3.1 Quantitative analysis at the sector level

The primary producers of hydrogen and alternative fuels are the Rest of the World (mostly Brazil and Saudi Arabia), commanding a market share of approximately 30%—36%. This is followed by the USA, with a market share ranging from 17% to 23%, and China, with a market share of around 15% to 20% across scenarios in 2050. The UK holds a comparatively small market share in the global market for hydrogen and alternative fuels.

The scenarios in the GEM-E3 model assume that the domestic market entirely meets the demand for hydrogen in all countries. This assumption significantly determines the magnitude of market shares projected for 2050.

Figure 6-4: Market shares in 2050



Source: Ricardo analysis based on GEM-E3 outputs

6.3.2 Key drivers of competitive advantage

The previous section refers to hydrogen production, while this part concerns technology manufacturing. Two primary drivers affect the manufacturing of hydrogen and bioenergy technologies: the increasing demand for hydrogen and bioenergy, and the re-shoring trend. The former is led by several policy initiatives aimed at fostering the market for hydrogen and bioenergy. Supporting the construction of powerplants and consuming these products implies increased demand for production, storage and transport technologies. Instead, re-shoring refers to the increasing reliance on domestic production and plants rather than imports and can have two opposite effects. On the one side, governments can re-shore hydrogen and bioenergy production, hampering economies of scale. This choice can be due to the will to have a national production capacity. In this case, demand for hydrogen production technologies increases because more power plants operate. On the other hand, governments re-shore manufacturing capacity for hydrogen production technologies, hampering economies of scale. In this case, international competition increases, reducing market shares for each manufacturing firm.

Beyond these drivers, multiple enablers and barriers can boost or hamper the manufacturing of hydrogen and bioenergy technologies (see the table below for a complete list). Among the barriers, the low level of off-take agreements is worth mentioning. Indeed, an unstable demand for hydrogen can counterbalance the incentives for increasing hydrogen production capacity. Subsequently, a downsize in hydrogen demand would imply a decrease in demand for hydrogen-related technologies. Conversely, policy supporting technology manufacturing – e.g. IRA in the US or the Innovation Fund in the EU – can support the development of technology manufacturing capacity, increasing the possibility of national manufacturers of gaining larger market shares.

Table 6-9: Key drivers of energy policy and market developments globally

Category	Driver	Discussion	RAG
Drivers	Increasing demand for production technologies	IEA (2023) expects 52 Mt H2 and 18 Mt H2 to be produced through electrolysis and fossil combustion combined with CCS, respectively, in the 2050 Net Zero scenario. In particular, international policies have focused on stimulating hydrogen production: • Fiscal stimuli such as the IRA in the US, the Low Carbon Hydrogen Business Model in the UK or the European Hydrogen Bank in the EU (DNV, 2022) • The most relevant incentive for hydrogen production laid out by the IRA is the new Clean Hydrogen Production Tax Credit, granting a tax credit for 10 years for projects placed in service before January 2033 producing “clean hydrogen”. The tax credit amount varies from USD 0.12 to USD 0.6 per kg of hydrogen produced, depending on the emissions intensity of the hydrogen production. The value of these credits is multiplied by five if the facility meets certain labour conditions. (IEA, 2023) • Multilateral development banks increased their financial commitments in the area of hydrogen in 2022 and 2023. Nine-tenths of the funds governments of developing economies received were loans to finance project feasibility studies, capacity building and project developers. Less than 1% has been committed as technical assistance grants or project equity. The main funders are the European Investment Bank and World Bank which directed the most significant commitments to India, Brazil and Chile. In November 2022, the World Bank Group launched a Hydrogen for Development Partnership (H4D) to foster capacity-building and regulatory solutions, business models, and technologies towards adopting low-emission hydrogen in developing countries. (IEA, 2023) Governments interventions are pushing for the creation of a hydrogen market: • A total of 41 governments, accounting for nearly 80% of global energy-related CO_2 emissions, have adopted hydrogen strategies (IEA, 2023). Concerning biofuels, in the EU, under RED III, there is an obligation for the combined share of advanced biofuels and biogas produced from the feedstock listed in Part A of Annex IX and of renewable fuels of non-biological origin in the energy supplied to the transport sector to be at least 1% in 2025 and 5.5% in 2030. According to ReFuelEU Aviation regulation, sustainable aviation fuels (SAF) should account for at least 5% of aviation fuels (of which 4.3% are advanced biofuels) by 2030 and 63% (of which	N/A

Category	Driver	Discussion	RAG
		35% are advanced biofuels) by 2050. Similar targets have been adopted worldwide (Dimitriadou & Lavinsky, 2022). An increase in demand for SAF would lead to a rise in demand for gasification technology. (Source: Ricardo's experts' judgement)	
	Reshoring	Governments are adopting policies to bring back the production of technologies perceived as strategic, hampering economies of scale. This trend can lead to two different scenarios: 1. Demand for hydrogen production technologies increases as more countries require local installations. For example, the EU Carbon Border Adjustment Mechanism (CBAM) makes it considerably more expensive for EU consumers/companies to import hydrogen into the EU. This means that EU companies will have incentives to buy from producers within the European single market, increasing demand for technologies and equipment to produce hydrogen in the EU. Given the regulatory similarities between the UK and the EU and their geographical proximity, British equipment manufacturers could benefit from this increased demand in the EU. 2. As more local producers of hydrogen production equipment are created, international competition increases, reducing market shares for each manufacturing firm.	N/A
Enablers	Decreasing costs and competitiveness	Currently, a kilogram of green hydrogen can have a levelised cost between 4 and 8 euros per kg, but final users may end up paying up to 9 to 12 euros per kg of hydrogen at the pump (Zhou & Searle, 2022). LOCH (Levelised cost of hydrogen) is expected to decline in the following years thanks to economies of scale, technological efficiencies and policy incentives (DNV, 2022; Hydrogen Council, 2020). Decreasing costs for hydrogen could lead to an increase in hydrogen demand, implying an increase in demand for hydrogen production technologies, too. However, an increase in hydrogen production technologies can increase price competitiveness, reduce profitability, and lead to market saturation.	
	Policy supporting technology manufacturing	Governments can target not only hydrogen production, leading to an increase in hydrogen technologies, but also manufacturing capacity itself. These policies can support the creation of manufacturing sites or the expansion of manufacturing capacity. Examples are the following: • In the US, the Advanced Energy Project Credit extends the 30% investment tax credit and creates funding for manufacturing projects producing fuel cell electric vehicles, hydrogen infrastructure, and electrolysers. (Hydrogen and Fuel Cell Technologies Office, n.d.) • In the EU, the Net Zero Industry Act proposal addresses technologies significantly contributing to decarbonisation, including electrolysers and fuel cells, biogas/biomethane, and CCS. The Strategic Net Zero technologies identified in the Annex to the Regulation will receive particular support and are subject to the 40% domestic production benchmark. In addition, the Innovation Fund (EUR 40 billion) supports the development, manufacturing and deployment of CCS and hydrogen technology, while a funding line of HorizonEurope supports R&D related to hydrogen and decarbonisation technologies.	
Barriers	Few offtake agreements	Unstable demand for hydrogen could hinder the demand for hydrogen technologies. Few contracts between producers and buyers relate to hydrogen (Polly, 2023). Despite high demand forecasts, production capacity unmatched by concrete demand would affect the hydrogen production level, reducing the demand for hydrogen technologies (Polly, 2024). This reduction would impact technology manufacturers.	
	Manufacturing Capacity Bottlenecks in Electrolyser Technology	The expansion of electrolyser technology faces barriers due to the need for parallel scale-up in manufacturing capacity for essential components such as membranes, cathodes, anodes, bi-polar plates, and power electronics. Current assembly facilities may encounter bottlenecks if the production of these components does not match the envisaged capacity expansion of electrolyser projects (IEA, 2023).	

Category	Driver	Discussion	RAG
	Worldwide rising costs and gas prices	A decline in natural gas prices and a rise in the relative costs of electrolysis hydrogen have intensified competition in the value chain. The struggle to maintain profit margins has resulted in a need for large-scale system installations to accumulate operating hours for industry-standard performance guarantees. The lack of such opportunities increases risks and inflates costs, particularly for the most efficient design (IEA, World Energy Outlook 2023, 2023).	

6.3.3 Geographical benchmarking

Besides the US, EU, and China, which account for 65% of the total electrolyser manufacturing capacity in 2030, India and Japan are the other key market players. However, they position themselves differently in the supply chain of hydrogen- and bioenergy-related technologies. India focuses more on manufacturing itself. According to the IEA (2023), India will account for 6% of the global electrolyser manufacturing capacity in 2030. Instead, Japan can be framed as an 'inventor' country. Indeed, between 2010 and 2020, 36% of total patents globally came from Japan (IRENA, 2022). In addition, Japan is one of the three countries where shipbuilders build liquefied gas tankers (IEA, 2023).

Except for Japan, the other four countries foster manufacturing capacity thanks to a combination of supply incentives and policies stimulating demand for hydrogen and bioenergy-related technologies. Governments have adopted financing schemes to boost domestic manufacturing capacity and support demand with regulatory and economic interventions.

Table 6-10: Major UK competitors globally

Country	Description
US	Based on companies' announcements, US electrolyser manufacturing capacity could reach 31 GW/yr (20% of the global manufacturing capacity) by 2030 (IEA, 2023). This capacity is boosted thanks to multiple economic incentives. For instance, the Advanced Energy Project Credit extends the 30% investment tax credit and creates funding for manufacturing projects producing fuel cell electric vehicles, hydrogen infrastructure, and electrolysers. It can also be applied to retrofitting facilities for low-carbon industrial heat, carbon capture, transport, utilisation, and storage systems. The US government not only support US manufacturers directly but also stimulates domestic hydrogen production and domestic hydrogen demand thanks to the Inflation Reduction Act, coupled with the Hydrogen Hubs initiative launched in 2021 and an expansion of the budget of the Loans Programme Office (IEA, 2023). According to Ricardo's expert judgement, the status of pyrolysis in the US is complex and multifaceted, with promising developments and hurdles to overcome. Pyrolysis is gaining traction as a potential solution for waste management, plastic recycling, and renewable energy production. Companies like Agilyx, RES Polyflow, and Blue Marble Renewable Energy are investing in commercial-scale pyrolysis facilities. In addition, regarding biomass gasification, there are four plants in development by SGH2, Mote (US-based company) and Yosemite Clean Energy (US-based company) in the US, while Kore Infrastructure has had a pilot pyrolysis plant operating in Los Angeles since 2021 (IEA, 2023). The US government supports pyrolysis technologies: in 2022, the Department of Energy awarded USD 15 million for research on 'advanced conversion technologies' like pyrolysis.
EU	Regarding electrolysers, the EU is expected to reach a manufacturing capacity of 31 GW by 2030 (20% of the global manufacturing capacity) (IEA, 2023). In addition, the EU stimulates domestic demand for hydrogen, driving demand for hydrogen-related technologies. Based on the announced projects, Europe accounts for almost 30% of all announced electrolytic hydrogen projects in 2030. The front runners are Spain, Denmark, Germany and the Netherlands, accounting for nearly 55% of total electrolytic hydrogen production in Europe in 2030 (IEA, 2023). This manufacturing capacity has been supported by a layered regulatory framework (EU Alternative Fuels Infrastructure Regulation and Hydrogen and Decarbonised Gas markets package, TEN-E regulation, European Hydrogen Backbone). In particular, the Net Zero Industry Act regulation under discussion would set targets and economic incentives for technology manufacturing. Indeed, the EU has recently started strengthening its economic incentives. For instance, the Innovation Fund (EUR 40 billion) supports the development, manufacturing, and deployment of CCS and hydrogen technology. Moreover, the State aid framework allows for a matching principle if an EU country aims to attract or keep a manufacturing site of innovative technologies.
China	Regarding electrolysers, China is expected to reach a manufacturing capacity of 38.75 GW/yr (25% of the global manufacturing capacity) by 2030 (IEA, 2023). This increase in manufacturing capacity matches ambitious targets in hydrogen production. China's Hydrogen Development Roadmap sets

Country	Description
	several objective targets: 10 GW installed electrolyser capacity by 2025, at least 35 GW by 2030, and more than 500 GW by 2050 (DNV, 2022). Based on projects, the installed electrolyser capacity in China is expected to reach 3.3 GW by 2024 and reach almost 5.4 GW by 2025. Furthermore, the average project size is growing fast: the number of projects with a capacity in the 100-500 MW range is increasing in China (IEA, 2023). Regarding hydrogen transport, China is one of three countries (the others are Japan and South Korea) where shipbuilding yards build liquefied gas tankers (IEA, 2023).
India	Regarding electrolysers, India is expected to reach a manufacturing capacity of 9.3 GW/yr (6% of the global manufacturing capacity) by 2030 (IEA, 2023). In addition, through the National Hydrogen Mission, India has identified several hydrogen activities for investment with a proposed financial outlay of EUR 95 million towards 2025 for R&D, pilot projects, infrastructure, and supply chain (DNV, 2022). Private and public investments are occurring in bioenergy. Reliance successfully tested in August 2023 the gasification of torrefied biomass for hydrogen production and plans to develop a pre-commercial demonstrator to produce 18 kt H2/y using catalytic gasification (IEA, 2023). Moreover, the Indian Oil Corporation and the Indian Institute of Science are developing a small plant (88 t H2/yr) to demonstrate biomass gasification for hydrogen production, aiming to start operation in December 2023. Finally, the Indian government is also promoting biomass-based routes and has earmarked funds to specifically support 40 kt H2/y of capacity production from biomass (IEA, 2023).
Japan	Concerning hydrogen technologies, Japan has developed the most significant number of inventions between 2010 and 2020 (36% of the total). In particular, in the same period, Japan has developed 25% and 30% of patents regarding hydrogen production and storage (IRENA, 2022). A small fraction of patents is protected in Japan from abroad, indicating high technology capability but fewer market opportunities. The growing number of international technology partnerships could see Japan emerge as a technology leader, even as a net importer of hydrogen (IRENA, 2022; IEA, 2023). Regarding hydrogen transport, Japan is one of three countries (the others are China and South Korea) where shipbuilding yards build liquefied gas tankers (IEA, 2023).

6.3.4 UK competitive advantage: qualitative analysis

Even though the UK has potential competitive advantages in manufacturing hydrogen- and bioenergy-related technologies, the main ones captured in the table below, the gap with competitors has been closing in the last few years. For instance, given the policy, regulatory framework, and technology development, the UK had an initial competitive advantage for certain electrolyser technologies. However, it is likely to be rapidly overtaken by other countries. China is producing more electrolysers than any other country. If they can design reliable products that comply with UK, EU, and US safety standards, the market will be in price competition. The same phenomenon happened in R&D, according to the judgment of Ricardo's experts. The UK was leading on several hydrogen R&D initiatives, though it has recently fallen behind following the advancement of EU measures encouraging R&D investments in decarbonisation technologies.

The UK has a regulatory and policy framework that could support an industrial landscape with the technology and expertise needed to manufacture hydrogen- and bioenergy-related technologies (see the tables below). Nevertheless, it is falling behind due to a surge of competition from other countries. Protectionist economic and regulatory measures fuel this competition. In this scenario, the UK can reap some benefits, attracting market shares in specific niches. Anyway, these shares will be smaller than the shares of the other players.

Table 6-11: UK competitive advantages

Advantage	Description
Regulatory framework supporting hydrogen production	The UK has adopted a set of regulations and strategies aimed to favour hydrogen production. These interventions could foster technology manufacturing, too. In 2022, the UK launched its Energy Security Strategy, which targets low-emission hydrogen production of 10 GW by 2030, with at least half being electrolytic hydrogen (IEA, 2023). Furthermore, the Low Carbon Hydrogen Standard (LCHS) and the Road Transport Fuels Obligation regulate the carbon intensity of low-carbon hydrogen. The UK LCHS defines what constitutes 'low carbon hydrogen' at the point of production. The standard details the methodology for calculating the emissions associated with hydrogen production and the requirements producers are expected to meet to prove that the hydrogen they produce is compliant. A clear regulatory framework can support businesses and investments.
Technology Development	With the Future Fuels for Flight and Freight Competition (F4C), the Green Gas Support Scheme and the Advanced Fuels Fund competition, the UK government has acquired

Advantage	Description
	extensive knowledge regarding the technology development and the potential risks associated with pyrolysis and gasification. At the moment, the government has supported, via these competitions, nine gasification and pyrolysis developers (Fulcrum; Lanzatech; Velocys Altalto; Abudia; Alfanar; ESSO; Nova Pangea; ABSL; Kew Technologies). This has provided a remarkable amount of insight in terms of technical know-how, which can be translated into valuable intellectual property if patented locally. These projects have also contributed considerably to the country's progression of R&D. The knowledge gathered could be translated into effective policy measures to consolidate the commercial and technical advantage the UK now retains.
Government economic incentives	The UK government has implemented policies and incentives to support the development of renewable energy technologies, including gasification. These include the Renewable Heat Incentive (RHI) and the Feed-in Tariffs (FITs) schemes, according to the judgement of Ricardo's experts. The schemes have been proven successful in supporting the country's energy transition. Several fundings were adopted to foster hydrogen technology production, such as the Hydrogen Supply Competition, Net Zero Hydrogen Fund, Hydrogen Allocation Rounds and Industrial Hydrogen Accelerator competition (DESNZ, 2023). The level of funding is greater than GBP 600 million (Albrecht, et al., 2020).
Developed Oil&Gas Industry	Both gasification and pyrolysis technologies, if deployed for the production of fuels, are closely linked to the Oil&Gas sector. The UK presents a long history of technical development of O&G technologies (e.g. BP, Shell, Exxon) and a fully developed O&G infrastructure. The technical know-how and skill required to develop these new processes correctly may rely on the existing O&G industry. In addition, gasification and pyrolysis technologies, especially pyrolysis plants, are now designed to be incorporated into conventional refinery processes (e.g. Steam Crackers) for polymer production. The UK is one of the major polymer producers in the region, with a total production of 1.7 MT of raw materials[30], easing the introduction of this new technology in the hydrocarbon value chain.

Table 6-12: UK competitive disadvantages

Disadvantage	Description
Negative stigma	Several gasification projects have ended in the UK due to technical and management issues (Perchard, 2016). This has generated poor confidence for investors and local authorities, who often prefer alternative energy solutions during the procurement stage. These projects have failed in different contexts. They were all focused on waste to syngas power generation rather than waste to fuels, which, despite the increased capex needed, still presents a considerable financial advantage. Considering the new environmental policy landscape and the likely additional support that public authorities could provide, technology developers face lower uncertainty and potentially higher profit margins than before.

6.3.4.1 UK Competitive advantage: key conclusions per technology

In the following table, we classify each technology as being either:

- A "**primary focus area**", highlighted in green, i.e. an area where the UK is expected to have consolidated advantage;
- A "**further opportunity**", in yellow, i.e. an area where the UK could gain a competitive advantage from positioning itself as a potential early mover; or
- A "**lower potential"** area, in red, i.e. an area on which the UK does not appear to have potential.

Table 6-13: Technologies classification based on UK competitive advantage

Tech family	Technology	Classification	Answer & justification/rationale
Hydrogen production	Electrolysis	Further opportunity	The electrolyser market has already been advancing with alkaline and PEM electrolysers as established technologies. China has a competitive advantage in production costs compared to Europe (Parkes, 2024) and has the largest market share for the mentioned technologies. Nonetheless, SOEC electrolysers are promising because they can operate efficiently at the

[30] https://www.bpf.co.uk/industry/Default.aspx

Tech family	Technology	Classification	Answer & justification/rationale
			range cost of alkaline electrolysers but with the load flexibility of PEM electrolysers. This technology has a great outlook for disrupting the market and could win market share from the already established technologies (i.e., Alkaline and PEM). From this perspective, UK manufacturers might gain a competitive advantage as early movers if they focus on delivering SOEC electrolysers to the market before the Chinese or other competitors.
	Autothermal reforming (ATR)	Further opportunity	The UK has little potential in ATR technology manufacturing. However, the UK is home to companies within the CCS sector, including those developing CCS-enabled hydrogen production technologies, such as Johnson Matthey's LCHTM technology, which is already licensed internationally. There is potential for the UK to export CCS technologies and technical expertise, especially to neighbouring European nations (CCUS-Enabled Production Working Group, 2023). Despite all of this, the market size potential for ATR appears to be limited, and the UK industry would focus on the CCS of blue hydrogen production.
Hydrogen infrastructure	Hydrogen storage - medium salt cavern	Primary Focus	The UK may have a competitive advantage in this technological area, even though this technology is implemented locally, meaning that export opportunities may be limited. The UK's opportunities lie in the engineering and implementation services sector since the UK has almost two decades of experience developing gas and hydrogen storage in salt caverns (Jahanbakhsh, Potapov-Crighton, Mosallanezhad, Tohidi Kaloorazi, & Maro, 2024). Such experience gives the UK a competitive advantage because this knowledge and expertise can be exported in the forms of services in other geographies when salt carven hydrogen storage is planned to be implemented. Teesside in the UK is the first hydrogen storage in salt caverns outside the US from the existing salt caverns used for hydrogen storage. This confirms the UK's early mover position regarding this technology. (Geostock, 2023)
	Depleted gas field storage	Further opportunities	Considering that depleted gas field storage is also performed locally and cannot be exported as a manufactured technology, the UK has opportunities to export services to implement this solution. However, the difference in storage capacity magnitude between depleted gas fields and salt caverns makes this a further opportunity rather than a primary focus area. Depleted gas field storage is set to be used to store larger quantities of hydrogen when the hydrogen market reaches higher demand levels for seasonal storage in high orders of volume.
	Hydrogen transmission/transport	Lower Potential	Regarding hydrogen transport, this technological area must be analysed domestically and internationally. Currently, the UK is developing important hydrogen pipeline projects, either repurposing gas pipelines or building dedicated hydrogen pipelines (SGN, 2023). According to Ricardo experts, if the UK focuses on developing and delivering these local projects successfully, it could prove that the UK engineering sector is ready to transfer such knowledge and expertise to provide project development and engineering services worldwide. Nonetheless, the US already has 1,600 km of hydrogen lines worldwide, and other countries such as Italy (Snam hydrogen route) and China (currently building all of Asia's hydrogen pipelines) seem to have the early mover advantage. (WEF, 2023).

Tech family	Technology	Classification	Answer & justification/rationale
			Conversely, regarding the use of LOHCs for hydrogen transport globally, due to the high levelised costs of hydrogen when compared to countries like Chile, Colombia, or even Spain within Europe, the UK faces a challenge in competing in the production of such LOHCs (Biogradlija, 2022). Regarding manufacturing ships or vessels that can transport hydrogen, other more mature ship-building industries, such as South Korea, have leadership over the UK.
Bioenergy	Pyrolysis	Lower potential	Currently, the UK lacks dedicated technology or process license suppliers to gain a competitive edge compared to other geographical regions (e.g., EU, USA) (Source: Ricardo's experts' judgement).
	Gasification	Primary focus areas	The UK's strength in gasification-based routes lies in the related processes, such as in the syngas cleaning process and the conversion to gaseous (e.g. bio-H_2, biomethane) or liquid (e.g. Fischer-Tropsch, methanol) fuels, rather than gasification technology itself. In addition, given the recent development related to the SAF mandate and the Biomass Strategy, the UK has a considerable advantage in the gasification field (Department for Transport, 2023). The use of R&D supporting funds like the AFF program or the Green Sky Program has boosted technology development and attracted foreign investment. The UK could gain a competitive advantage from these technology development programs, especially if part of the intellectual property developed is patented in the region (Source: Ricardo's experts' judgement). Currently, the UK is the single country with the most planned projects related to SAF production, most of which adopt gasification technologies.

7. NUCLEAR

7.1 INTRODUCTION

This section focuses on the potential market size, UK market share, and UK competitive advantage of three technologies from two nuclear tech families. These technologies have been chosen for analysis because they are all up-and-coming nuclear technologies currently in early development. The following concisely summarises each tech family and technology and their scope for this analysis.

Nuclear Gen IV is a set of reactors considered the next generation of nuclear reactor designs. These generators' targeted benefits are increased safety, economic efficiency, and reduced radioactive waste. They are being developed by 14 countries in international cooperation with the aim of launching them for commercial use in the 2030s.

- **High Temperature Gas Reactor (HTGR)**, otherwise known as a very high-temperature reactor, is a Gen IV nuclear reactor that operates at temperatures of up to 1000°C (Konno et al., 2017). For the Gen IV reactors, the HTGR is recognised for its high efficiency, security, environmental applicability, and industrial application in hydrogen production (Yang, et al., 2014). In the context of this analysis, only the HTGR among the Gen IV reactors is in scope. This analysis will not encompass the other five Gen IV technologies proposed by the Generation IV International Forum: gas-cooled fast reactor, lead-cooled fast reactor, molten salt reactor, sodium-cooled fast reactor, and the supercritical water-cooled reactor (World Nuclear Association, 2020).

This analysis will focus on two **Advanced Nuclear Technologies** not considered nuclear Gen IV: Small Modular Reactors (SMRs) and Floating Nuclear Power Stations.

- **Small Modular Reactors (SMR)** are reactors smaller than conventional nuclear power reactors, designed with modular technology. Their modularity enables them to be constructed in a factory and transported to a separate location for installation. The size and modularity of SMRs will allow them to be installed in locations that conventional nuclear power reactors cannot; additionally, they can be deployed incrementally to meet increasing energy demands (Liou, 2023).
- **Floating Nuclear Power stations** are offshore barges equipped with small nuclear reactors. The main benefit of these power stations is their mobility, as they do not occupy land resources and can be moved to deliver energy to different locations (Zou, Liu, & Huang, 2020). The scope of floating nuclear Power stations for this analysis includes small reactors on offshore barges that can supply facilities or other locations with energy. However, marine vessels that utilise nuclear reactors to only power the vessel itself are not in scope.

This analysis will focus on these three nuclear technologies but also include a high-level analysis of the nuclear market in general.

Table 7-1: In-scope technologies

Sector	Tech families	Technologies
Nuclear	Nuclear Gen IV	High Temperature Gas Reactor
	Advanced Nuclear Technologies	Nuclear (SMR)
		Floating Nuclear Power stations

7.1.1 Key takeaways

- The UK is actively involved in nuclear technology across two research areas: High Temperature Gas Reactors (HTGRs) and Small Modular Reactors (SMRs). In HTGRs, the UK benefits from historical expertise and ongoing investments. Similarly, the country is actively attracting investment in SMRs.
- Domestic development and continued support for these technologies will be crucial to export opportunities. Our expert judgment is conservative, as the UK has, in recent history, used its industry to supply its internal demand and has exported more services than goods. We assess HALEU export opportunities in terms of IP and technologies to be most promising internationally.
- HTGRs have reached a more advanced stage of technical maturity, and the skills and capabilities to deploy them already exist in the supply chain, making them more attractive for investment globally (NEA,

2022). Their role in the electricity mix would be akin to that played by existing reactor technologies, with an increased focus on counterbalancing the shutting down of fossil fuel-fired power stations.

- SMRs, according to our expert opinion, will be a promising technology if they manage to bring down construction costs, which remain high in the nuclear industry. However, their commercial viability and technological benefits will depend heavily on the specific type of reactor employed. From a strategic point of view, both interviewees noted how all other things
- Being equal, this technology would be more suited to large countries with substantial off-grid populations and more niche applications, including military or complex industrial complexes.
- None of the interviewed experts expressed optimism regarding the potential of floating nuclear power plants to capture a substantial share of the global market. Russia appears to hold the primary interest in their development, while other regions show limited interest. Efforts by specific organisations to target other areas should not be construed as indicative of genuine interest from those countries.

7.2 RQ1: POTENTIAL MARKET SIZE AND UK MARKET SHARES

7.2.1 Quantitative analysis at the sector level

According to the GEM-E3 results, the UK does not feature any nuclear equipment industries, and its market size is relatively modest compared to that of the broader international market.

Table 7-2: Market size (demand in billion USD)

NGFS Scenario	Geography	2020	2025	2030	2035	2050
Current policies	Global market	213.2	183.5	169.5	167.9	166.7
	Domestic market	5.1	4.1	4.5	4.7	8.0
	Export market	208.1	179.4	165.0	163.2	158.7
Below 2 ºC	Global market	213.2	183.5	169.5	199.2	189.4
	Domestic market	5.1	4.1	4.5	3.9	4.4
	Export market	208.1	179.4	165.0	195.2	185.0
Net Zero 2050	Global market	213.2	219.6	208.3	203.5	192.4
	Domestic market	5.1	6.6	4.9	3.8	3.8
	Export market	208.1	212.9	203.3	199.7	188.6

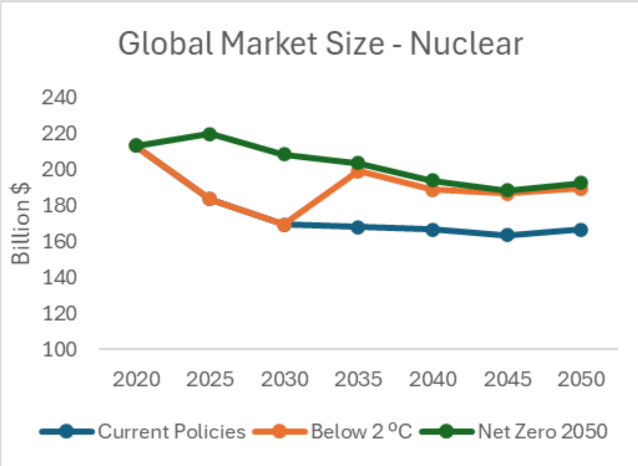
Table 7-3: UK share of each market [31]

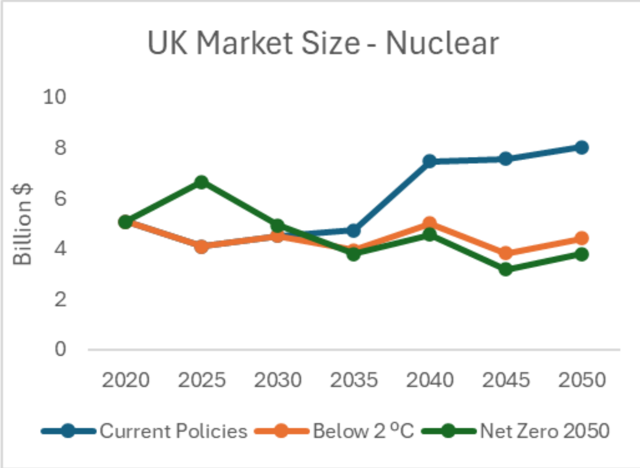
NGFS Scenario	Geography	2020	2025	2030	2035	2050
Current policies	Global market	0%	0%	0%	0%	0%
	Domestic market	0%	0%	0%	0%	0%
	Export market	0%	0%	0%	0%	0%
Below 2 ºC	Global market	0%	0%	0%	0%	0%
	Domestic market	0%	0%	0%	0%	0%
	Export market	0%	0%	0%	0%	0%
Net Zero 2050	Global market	0%	0%	0%	0%	0%
	Domestic market	0%	0%	0%	0%	0%
	Export market	0%	0%	0%	0%	0%

Figure 7-1 shows the Global and UK market sizes for the year 2050. When comparing the net-zero scenario to the current policies, the penetration of renewables in power generation production increases, whereas the role of nuclear power diminishes over time. This leads to a lower market size for the UK in 2050 in the net-zero scenario compared to the current policy scenario.

[31] In the GEM-E3 results UK does not have production of nuclear equipment.

Figure 7-1: Global and UK market size - Demand





7.2.2 Qualitative analysis: market size

To overcome the relative lack of publicly available data and information regarding market size and trends affecting nuclear technologies, we conducted two interviews in February 2024 with two representatives of the Nuclear Industry Association. The material gathered during these sessions was used to complement our research and provide insights on the current direction of travel within the industry at the UK and global scales, as well as on the likelihood that some technologies may have greater growth potential.

7.2.2.1 Nuclear Global Market Size

Global-investment in nuclear generation is projected to have been just over USD 60 billion in 2023 (IEA, 2022). The global tradeable market related to nuclear energy is expected to grow to GBP 100 billion in 2030, then decrease to GBP 37 billion by 2050 (Vivid Economics, 2019) as new build and decommissioning rates decrease. The average annual investment in USD billion is expected to be 114 from 2023-30, 121 from 2031-35, and then decrease to 93 from 2036-50 (IEA, 2023).

In addition, nuclear power capacity in 2022 was assessed at 413 GW and is estimated to grow to 812 GW by 2050 (IEA, 2022). An annual investment of over USD 100 billion will be required to achieve this growth from 2023 to 2050. Despite installed capacity doubling by 2050 compared to the 2022 baseline, the share of nuclear power is expected to remain stable at around 8% (IEA, 2023).

These estimates were confirmed during the interviews held with NIA representatives.

7.2.2.2 Nuclear Gen IV – High Temperature Gas Reactor

Although HTGR technology is technically available, at the time *High-temperature Gas-cooled Reactors and Industrial Heat Applications* was written in 2022 by the Nuclear Energy Agency, the technology had not been applied to an industrial process and thus had not demonstrated its practicality yet. Nuclear power stations of previous generations share the main challenges of HTGR in that they will be subjected to the negative public perception of nuclear projects in general. For the successful future completion of HTGR projects, long-term efforts and significant investment appear to be required, as well as the development of high-assay, low-enriched uranium supply chains for fuel availability and close engagement with national nuclear regulators and interested industrial players early on is required (NEA, 2022).

Based on opinions received during our consultations with experts, HTGRs are perceived as a more advanced technology than SMRs or floating nuclear power stations. The latter refers to ways to deploy a reactor rather than a technology family. The HTGR family is also a gateway to more advanced generation IV reactors. However, their energy efficiency and effectiveness in achieving commercial viability will depend on the chosen reactor technology.

7.2.2.3 Advanced Nuclear Technology – Small Modular Reactors

Research indicates an uncertain market size for Small Modular Reactors (SMRs). In a high-case scenario, global production of 105-425 SMR units is projected between 2020-2035 (NEA, 2022). The estimated development cost for a first-of-a-kind SMR in the UK by 2035 is estimated to be less than GBP 2.5 billion (EFWG on SMRs, 2018). Assuming an overnight cost of GBP 2.5 billion per unit, the estimated global production cost for SMRs during 2020-2035 ranges from GBP 250 billion to GBP 1 trillion. However, this estimate should be used as an indication only since it uses data from 2018 and lacks consideration for accrued interest during production or other influencing factors.

Industry expert interviews suggest SMRs could have a market mainly in countries lacking grid capacity or financial resources for large-scale nuclear reactors. However, the cost efficiency of SMRs remains uncertain, raising questions about whether they can surpass larger reactors in unit cost.

7.2.2.4 Advanced Nuclear Technology – Floating Nuclear Power Stations

Existing literature sources lack precise estimations regarding the market size at the technology level within the nuclear sector. The market for floating nuclear power stations remains small; therefore, a sizing and trend assessment exercise is challenging. Only one such plant, the Akademik Lomonosov in Russia, generating 70 MWe, has been successfully developed (World Nuclear News, 2023). Russia intends to develop and install more floating nuclear power stations, with plans for the second generation RITM-200M reactors announced by Rosatom in July 2017. These reactors, more powerful than those used in the Akademik Lomonosov, are scheduled for installation from 2028 (World Nuclear Association, 2021).

While additional vessels fitted with RITM-200M reactors are under construction in China, these are intended for Russia, with Russia remaining the primary funder for floating nuclear power plant development. An agreement between China and key markets in the Middle East, Southeast Asia, and Africa has been signed; however, these are aspirational markets and do not necessarily reflect actual market trends in those regions. Furthermore, operations in these regions are anticipated to occur between 2029 and 2036 (World Nuclear News, 2023).

7.2.2.5 Summary: global market size trends

The following table summarises global market size trends at the technology level.

Table 7-4: Global market size growth potential: RAG rating by technology

Tech family	Technology	RAG Rating	Justification/rationale
Nuclear Gen IV	High Temperature Gas Reactor	High	HTGRs have reached a more advanced stage of technical maturity, and the skills and capabilities to deploy them already exist in the supply chain, making them more attractive for investment globally (NEA, 2022). Based on the opinions of interviewed experts, HTGRs' role in the electricity mix would be similar to that of existing reactor technologies, with an increased focus on counterbalancing the shutting down of fossil fuel-fired power stations. Although there may be co-location benefits to HTGR for heat generation, as written above, their applicability to industrial processes has not yet been demonstrated.
Advanced Nuclear Technologies	Nuclear (SMR)	High	According to our expert opinion, SMRs will be a promising technology if they can reduce construction costs, which remain high in the nuclear industry. However, their commercial viability and technological benefits will depend heavily on the specific type of reactor employed. From a strategic point of view, both interviewees noted that all other things being equal, this technology would be more suited to large countries with substantial off-grid populations and more niche applications, including military or complex industrial complexes.
	Floating nuclear power stations	Low	None of the interviewed experts expressed optimism regarding the potential of floating nuclear power plants to capture a substantial share of the global market. Russia appears to hold the primary interest in their development, while other regions show limited interest. Efforts by specific organisations to target other areas should not be construed as indicative of genuine interest from those countries. (World Nuclear News, 2023).

In summary, the global nuclear market appears to be growing, and several sources, including statements from the interviewed nuclear industry experts, point to an estimated nuclear capacity of 800—916 GW by 2050 (IEA, 2023). Although publicly available information online is limited, we have assessed that HTGRs and SMRs show global growth potential. However, floating nuclear power stations, as a concept rather than a proper reactor technology type, demonstrate less flexibility to be deployed outside niche applications to plug off-grid demand and have received considerably less investment so far.

7.2.3 Qualitative analysis: market shares

7.2.3.1 Trade flows analysis

The table below shows the annual average of UK exports (2017-2021) for some selected HS subheading codes (provided by DESNZ) relating to components used in the manufacture of nuclear power equipment and parts. These numbers can be interpreted as proxies of the UK's share of tradable export markets. The total average for this sector stands at 0.9% of the global tradable market.

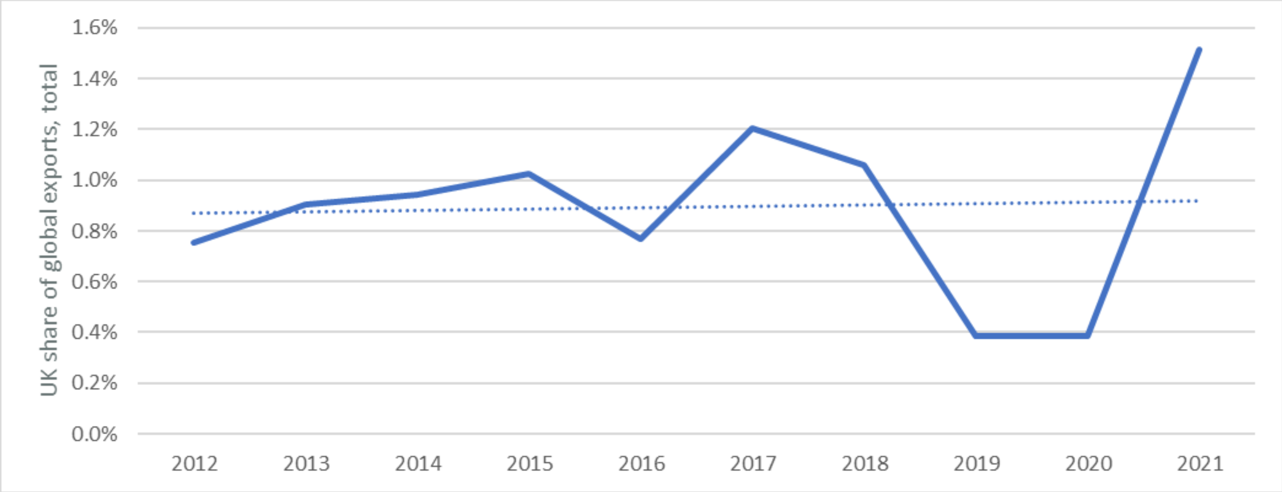
Table 7-5: UK share of global exports, selected HS subheadings, 2017-2021

Group	Subheading included in group	Annual UK exports, average 2017-2021 (nominal)	UK share of global exports
28 Inorganic chemicals; organic or inorganic compounds of precious metals, of rare-earth metals, of radioactive elements or of isotopes	– 284410 Natural uranium and its compounds – 284420 Uranium enriched in u 235 and its compounds; plutonium and its compounds – 284430 Uranium depleted in u 235 and its compounds; thorium and its compounds – 284441 Tritium and its compounds – 284442 Tritium and its compounds – 284443 Actinium-225, actinium-227, californium-253, curium-240, curium-241, curium-242, curium-243, curium-244, einsteinium-253, einsteinium-254, gadolinium-148, polonium-208, polonium-209, polonium-210, radium-223, uranium-230 or uranium-232, and their compounds – 284444 Other radioactive elements and isotopes and compounds – 284450 Spent (irradiated) fuel elements (cartridges) of nuclear reactors	USD 60.2M	0.9%
84 Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof	– 840110 Nuclear reactors – 840120 Machinery and apparatus for isotopic separation, and parts thereof – 840130 Fuel elements (cartridges), non-irradiated – 840140 Parts of nuclear reactors – 840211 Steam or other vapour generating boilers – 840212 Watertube boilers with a steam production not exceeding 45 tonnes per hour – 840219 Other vapour generating boilers, including hybrid boilers	USD 47.2M	1.0%
Total		**USD 107.4M**	**0.9%**

Source: Ricardo elaboration on UN Comtrade data

The figure below shows a downward trend in the UK's share of global exports (for the total HS codes analysed) between 2012 (0.8%) and 2020 (0.4%) before increasing to 1.5% in 2021.[32]

Figure 7-2: UK share of global exports, 2012-2021



Source: Ricardo elaboration on UN Comtrade data

Figure 7-2 above demonstrates non-zero estimations of the export market for the UK in nuclear energy, which differs from the estimations of 0% in Table 7-3 The difference in these estimations is due to their scope. Figure 7-2 above is based on data for exports from the nuclear industry in its entirety, whereas the estimations in Table focuses only on the three technologies in scope (HTGR, SRM, and floating nuclear power stations).

7.2.3.2 UK Market Share: Qualitative analysis

Assuming that the UK can capture a more significant share of the tradeable market in the future, nuclear exports could be at their largest at GBP 1.3 billion a year by 2030 and GBP 0.7 billion a year by 2050 of export gross added value. Furthermore, nuclear exports would support an estimated 20,000 jobs in 2030 and 8,300 jobs by 2050. UK nuclear exports and the number of supporting jobs are estimated to be the greatest in the 2030s and consequently higher than estimations by 2050. This is due to the replacement of existing nuclear stock and the expansion of nuclear capacity (Vivid Economics, 2019). Similarly, for estimates of the global nuclear market, the market will grow to its largest in 2030-2035 and then decrease towards 2050.

The Climate Change Committee's Energy System Modelling Environment model estimates a nuclear capacity of 58GW by 2050 in the UK (Vivid Economics, 2019). However, reaching such capacity by 2050 in the UK is rather unlikely, considering coherence with the 2022 Energy Security Strategy and its ambition to achieve 24GW by 2050 using eight new large reactors and SMRs (IEA, 2022). Based on reports from the All-Party Parliamentary Group on Nuclear Energy and the Nuclear Skills Strategy Group, we can expect a workforce for the scenario of achieving 24GW by 2050; the estimated civil and defence workforce is 180,000 – 250,000. (APPG on NE, 2023), (NSSG, 2023).

From the interviews with nuclear industry experts, fuel enrichment undertaken by Urenco is currently among the UK's strongest competitive advantages, and the UK should have an opportunity to export nuclear fuel enrichment technologies, and potentially the fuel itself, if these mature to include production of HALEU. However, the UK does not yet possess such an advantage, and enriched fuel is not typically exported from the UK as of 2024 but only serves its domestic market. Urenco operates enrichment plants closer to demand.

Table 7-6: Market Estimations of the Nuclear Market in the UK

Nuclear Market Category	Estimations
Nuclear domestic market	Estimated to contribute GBP 9.6 billion per annum in gross added value, supporting 130,000 jobs by 2050.

[32] This increase is due to a growth in UK exports of code 840130 "Fuel elements (cartridges), non-irradiated" from an average of USD 1.3 million in 2012-2020 to USD 101.7 million in 2021.

Nuclear Market Category	Estimations
Construction	65% of the construction of Hinkley Point C is estimated to go to domestic firms If the new nuclear reactor fleet does not materialise, the UK's captured market will likely be the front and back end of the fuel cycle rather than construction. It is the primary opportunity for the UK in nuclear energy, with construction in new deployment estimated to be GBP 6.5 billion per annum, supporting 88,000 jobs per annum.
Front end of the fuel cycle	UK share of the front end of the fuel cycle market in the UK is estimated to be 57% by 2050.
Back end of the fuel cycle	Estimates to contribute GBP 3.1 billion in gross added value to the UK's economy by 2050, supporting 43,000 jobs.
Decommissioning	Estimated to contribute GBP 1.8 billion gross added value with a UK market share of 80%, supporting 20,000 jobs by 2050.
Waste management	Estimated to contribute GBP 1.3 billion gross added value with a UK market share of 80%, supporting 23,000 jobs by 2050.
Capex components	If the UK develops its intellectual property, such as SMRs, its domestic market share is expected to be 88% by 2050.
Capex construction	If the UK develops its intellectual property and substantially increases construction supplies and ownership, its domestic market share is expected to be 88% by 2050.
Domestic market	Could contribute to GBP 9.6 billion per annum in gross value added in the UK, supporting 130,000 jobs by 2050.
Export market	Could contribute to GBP 1 billion per annum of gross value added, supporting 8,300 jobs by 2050 (Vivid Economics, 2019).

Table 7-7: UK Market Share Quantitative Analysis

Tech family	Technology	UK Market Share – Qualitative Analysis
Nuclear Gen IV	High Temperature Gas Reactor	As per interviews with nuclear industry experts, the UK has a unique advantage that can enable market capture of exports for HTGRs. The UK has considerable expertise in gas-cooled reactors due to its century-old activity in the sector. An example is the Dragon Reactor Experiment, built in the 1960s, using helium gas coolant and graphite as the neutron moderator (NAE, nd). Additionally, as of July 2023, the National Nuclear Laboratory, in partnership with the Japan Atomic Energy Agency, secured funding for the UK's first modular HTGR, demonstrating promise for the UK's ability to capture a share of the global HTGR market (National Nuclear Laboratory, 2023).
Advanced Nuclear Technologies	Nuclear (SMR)	On the 8th of February 2024, it was announced that Community Nuclear Power, the UK's only independent SMR development company, will deploy four SMRs in North Teesside. This development will be the first privately funded SMR deployed in the UK by the 2030s (Smart B., 2024). The announcement shows promise in the UK's ability to capture a share of the global market for SMRs, thus increasing the growth potential for a private SMR market in the UK. Especially with the formation of Great British Nuclear, assigned to select the best SMR technologies for investment (APPG on NE, 2023). According to industry sources, the UK market share of small modular reactors depends on home market deployment. The link between state support and the size of the civil nuclear power industry is deep. Therefore, an opinion was expressed that if the UK does not choose the SMR being developed by Rolls-Royce (Rolls-Royce, n.d.) , there will be limited export components. About this, a contract has already been signed between Rolls-Royce and Sheffield Forgemasters (Rolls-Royce, 2023) . Three main obstacles related to the UK capturing a share of the global SMR market were highlighted. Firstly, an immature technology would require a large order to justify investment in the manufacturing equipment. Secondly, these investments entail a significant risk, which could impact the ability to obtain a loan to enable development without government guarantees.

Tech family	Technology	UK Market Share – Qualitative Analysis
		Thirdly, the UK does not produce and export steam turbines at a scale comparable to other countries, further raising costs and reducing its competitiveness.
	Floating Nuclear Power stations	There is a general reluctance to invest in floating nuclear power stations, and limited capital is being directed globally towards this concept. A key barrier is the poor public perception and perceived risk associated with nuclear power stations in general. However, all experts pointed out that similar technologies are employed in military vessels, which spend less time in port and may routinely be located further away from inhabited centres. The successful development of floating nuclear power stations in the UK would depend on changes to UK regulations.

7.2.3.3 *UK market shares – summary of qualitative analysis*

In the table below, we assess whether there is potential for the UK to capture a market share higher than, in line with, or below the sector average indicated in the qualitative analysis above.

Table 7-8: Technologies that have the potential to attract significantly higher/lower market shares compared to the sector average

Tech family	Technology	Rating	Justification/rationale
Nuclear Gen IV	High Temperature Gas Reactor	Higher than average	The UK has an advantage in capturing a market share of HTGRs over other countries because it has acquired experience and expertise over a long period of time. Additionally, funding has been secured for the UK's first modular HTGR, demonstrating promise for the UK to capture a share in global investment in HTGRs (National Nuclear Laboratory, 2023). Finally, the announced Green Industries Growth Accelerator (GIGA) could strengthen the future UK market share. Indeed, GIGA will invest GBP 300 million "in the production of the fuel (HALEU) to power high-tech new nuclear reactors" (Davies, 2024). An increase in the availability of HALEU might support the deployment of HTGRs and the demand for this technology (NEA, 2022). However, despite being positive, the effect of GIGA on HTGRs is not straightforward: the increase in demand could be satisfied by other competitors. In this sense, GIGA could support UK manufacturing, but the magnitude of its effect is not clear.
Advanced Nuclear Technologies	Nuclear (SMR)	Higher than average	The 2022 Energy Security Strategy includes funding for SMRs in its ambition of achieving 24GW by 2050 (IEA, 2022), demonstrating the UK Government's commitment to investment in SMRs. Additionally, several private contracts have been signed for SMR development, making SMRs more likely to attract UK market shares. These developments and the skills present in the UK reflect early investment and government support for the SMR concept. Success, as with other technologies in the nuclear field, will depend on stable energy and industrial policies.
	Floating Nuclear Power stations	Lower than average	In addition to the public perception of safety, unlike the other two technologies, the lack of private or public investment in their development indicates a low promise of the UK capturing a portion of the global market. Especially considering that only one country is investing significantly in developing floating nuclear power. (World Nuclear News, 2023)

Given the UK's rich historical knowledge of HTGRs and the existing investment allocated towards advancing HTGR and SMR technologies, the UK has considerable potential to secure a share of the international nuclear energy market in these domains. However, the absence of investment in floating nuclear power stations, public safety concerns, and limited interest from stakeholders beyond Russia indicate a diminished potential for the UK in this particular technology sector.

7.3 RQ2: UK COMPETITIVE ADVANTAGE

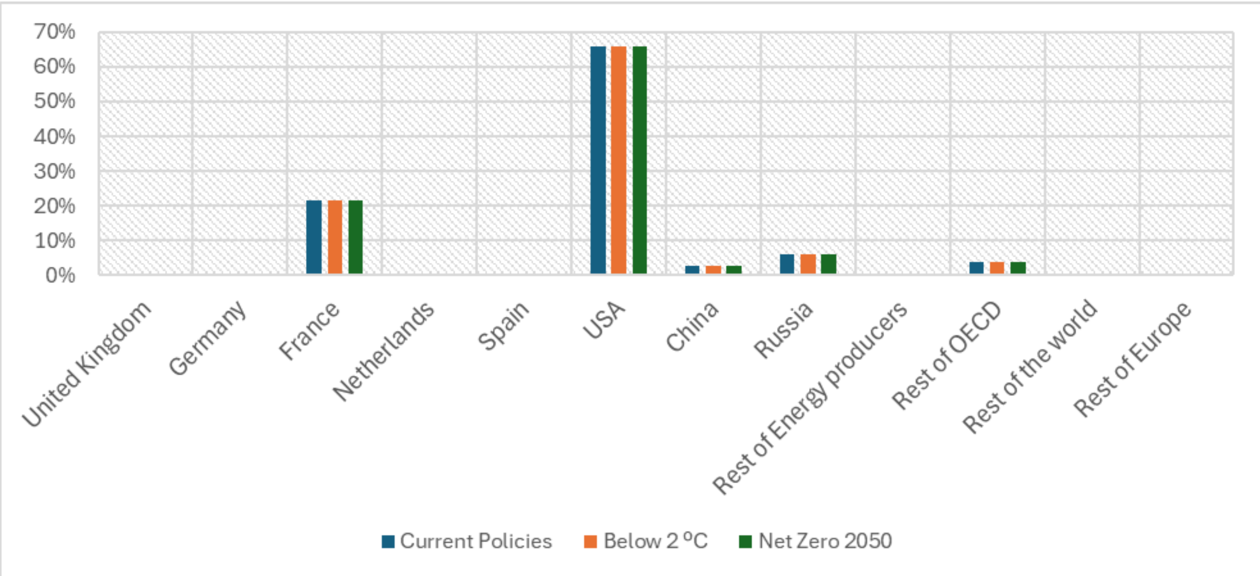
The UK is actively involved in nuclear technology across two research areas: high temperature gas reactors (HTGRs) and small modular reactors (SMRs). In HTGRs, the UK benefits from historical expertise and ongoing investments. Similarly, the country is actively attracting investment in SMRs. However, the UK is not actively exploring floating nuclear power stations.

Domestic development and continued support for these technologies will be crucial to export opportunities. Our expert judgment is conservative, as the UK has, in recent history, used its industry to supply its internal demand and has exported more services than goods. We assess HALEU export opportunities in terms of IP and technologies that are most promising internationally.

7.3.1 Quantitative analysis at the sector level

The manufacturing of nuclear equipment is predominantly concentrated in the USA, which holds a market share of approximately 66%. Following closely is France, which accounts for a share of around 21%. Additional contributors to the nuclear equipment industry include Russia, China, Canada, and South Korea.

Figure 7-3: Market shares in 2050



7.3.2 Key drivers of competitive advantage

Nuclear power production is highly complex and dependent on stable and consistent industrial policy. However, even when these conditions exist, various factors may influence the successful development of nuclear technologies. Historically, increased safety and efficiency have been the main drivers of nuclear reactor design advancements. Synergies with a military nuclear weapons programme have made it easier for nuclear powers to develop a domestic civil programme.

More recently, the desire for increased energy security, reducing dependence on imports often from hostile countries, and the need to decarbonise electricity grids while expanding capacity have all rekindled interest in nuclear technology.

Several blockers exist, not just in the UK but at a global level. While reactors have undergone a degree of modularisation and off-site production, shortening construction times, the buildings that host them and their associated facilities have not and are subject to the frequent cost overruns and delays all megaprojects are subject to. Additionally, several components in the lifecycle of a nuclear power station, whether modular or not, drive the LCOE for all these technologies much above their renewable counterparts. Among these are the need to extensively engage with a public opposed to nuclear, increased attention to safety leading to expensive insurance and expensive cleanup costs associated with incidents, and rising costs to manage spent radioactive fuel and decommission existing power stations.

Several factors drive the discussion of the role and strategy of nuclear power. Nuclear power is a low-carbon, low-emission energy source, and it can address the need to support the production of clean energy during the energy transition and beyond. According to the judgment of Ricardo's nuclear industry experts, tackling climate change is the main driver for investing in nuclear power. A second significant driver is defence, namely the opportunity to draw from established expertise for nuclear weapons or nuclear marine propulsion programs, which increases the demand to enrich uranium.

Energy security is a primary concern worldwide, stemming from disruption of supplies, geopolitical instability, and increasing energy prices. Nuclear energy would provide stability, also through domestic electricity production. Moreover, adding nuclear power to a country's energy mix can prevent significant setbacks caused by supply shocks and market fluctuations. Countries can be driven towards nuclear energy if they have limited access to other energy resources or have guarantees against changes in the supply of existing energy sources.

Economic factors also drive investment in nuclear energy. Developing countries producing nuclear energy can export energy to developed countries, which tend to have a higher energy per capita demand. Similarly, the global increase in the demand for electricity drives investment in nuclear energy.

The public perception of the safety of nuclear plants represents the most relevant barrier to investments in nuclear energy. The public opinion is strongly influenced by the nuclear disasters of the past decades, and this has, in turn, influenced decision-making on nuclear strategy in several countries.

Finally, the significant initial investment required to develop nuclear reactors is a major barrier. However, advancements in nuclear reactor technology have led to promising results in reducing the cost of development, electricity costs, and natural resource optimisation. Nuclear energy relies on significant initial investment costs; however, this can be reduced by advancements in reactor technology, for example, by utilising SMRs with lower initial investment costs per unit.

Table 7-9: Key drivers of energy policy and market developments globally

Category	Driver	Answer	RAG
Drivers	Combatting climate change	To decrease (or mitigate the increase of) greenhouse gas emissions and air pollution, countries may increase their reliance on renewable or low-emission energy sources. Since nuclear power is a low-carbon, low-emission energy source, the ambition to increase the proportion of clean energy could drive the investment in nuclear power . Additionally, the nuclear industry experts expressed their opinion that combatting climate change was the main driver for investing in nuclear energy and developing nuclear policy.	N/A
	Energy security	Energy security is a major driver for nuclear energy policy due to the stability provided by nuclear energy. Factors influencing the drive for energy security via nuclear energy could include disruption of supplies, geopolitical instability, and increasing energy prices (Review of drivers and barriers for nuclear power in the UK, 2009). An effective method of ensuring energy security is to produce electricity domestically, which is an essential condition for the deployment of SMRs (NEA, 2016).	N/A
	Energy diversification	Increasing the diversity of a country's energy source improves the country's ability to absorb shocks in one energy input by increasing the use of another (Debrah et al., 2020). Each source of energy has its pros and cons. For example, nuclear energy has the benefit of being relatively stable in terms of market fluctuations; however, nuclear power plants require a significant investment to develop. There is not one energy technology that is the cheapest under every circumstance; it depends on different factors such as availability and the type of market. If a country diversifies its energy supply, it can utilise the benefits of each energy type to its advantage.	N/A
Enablers	Economic	Some nations may increase their energy supply using nuclear power to boost their economies. Since wealthy countries use more energy per capita than developing nations, developing nations could invest in and establish nuclear programs to export energy to wealthier nations.	
	Nuclear defence programs	Domestic nuclear energy programs may be supported or sustained to maintain a pool of personnel and expertise to draw on for nuclear weapons	

Category	Driver	Answer	RAG
		or defence programs. After combatting climate change, nuclear industry experts expressed their opinion that defence was the second most significant driver of investing in nuclear energy and developing nuclear policy.	
	Increasing electricity demand	Increasing electricity demand drives new investment and developments in nuclear energy (Review of drivers and barriers for nuclear power in the UK, 2009). For example, increasing electricity demand is significant in Ghana's drive for nuclear energy inclusion (Debrah et al, 2020).	
	Limited access to alternatives	Limited access to alternative energy sources could motivate investing in and developing nuclear power sources. For example, restricted access to hydro resources drives Ghana's nuclear power developments (Debrah et al., 2020). Additionally, changes to the supply of existing energy sources, such as natural gas (Debrah et al., 2020), can also be a driving factor in looking for more consistent energy supplies, such as nuclear power.	
	Prices of natural gas	Natural gas price volatility in some countries, such as Nigeria and neighbouring countries, has led to natural gas and power shortages. Nuclear energy prices are much less volatile than natural gas and responsive to price fluctuations, providing a much more stable energy market (Debrah et al, 2020). The need for a source of energy with a stable price could be a driving factor of nuclear energy policy.	
	Technological development	With the current multilateral effort to develop the next generation of nuclear reactors, the ambition to develop nuclear technology that reduces electricity costs and optimises natural resource utilisation could influence nuclear policy positions for nations.	
Barriers	Public perception of safety	The public perception of nuclear energy has historically been mixed, with Austria, Sweden, Italy, and Ireland either voting to phase out nuclear power or protesting against new reactors being built. After the Fukushima Daiichi nuclear accident, some countries changed their nuclear policy position. For example, Germany decided to close its nuclear reactors early, and Switzerland decided not to continue its plants beyond their lifetime. In addition, China, which has the most expected installed nuclear energy capacity by 2050, has reduced those expectations by half (VCDNP, 2018).	
	Economic	The LCOE for nuclear power is high and rising, which disadvantages it compared to other cheaper technologies with lower capital cost uncertainty.	

7.3.3 Geographical benchmarking

The US, China, and Russia are all key market players in the global nuclear market, both in terms of nuclear power generated and to the extent the key players are involved in the technologies in scope. China's involvement in SMRs and Russia's involvement with floating nuclear power stations are particularly notable. Table 7-10 below outlines how each key market player positions themselves in the global nuclear market.

Table 7-10: Major UK competitors globally

Country	Description
US	In 2017, the USA was the world's largest nuclear power producer, providing 56% of the country's carbon-free electricity. The USA relies heavily on nuclear power, which provides around 20% of the country's electricity each year (Office of Nuclear Energy, 2019). While the USA has lost its competitive global position in nuclear energy to Russia and China, the USA is aiming to increase its competitive advantage. National security is a major factor in the USA's desire to expand its position as a key global player in nuclear energy. As a part of the 2020 'strategy to assure U.S. National Security', the U.S. government aims, among other actions, to revive and strengthen the uranium mining industry, remove strategic vulnerabilities across the nuclear fuel cycle, accelerate technical advances, and move into markets currently dominated by Russian and Chinese State-Owned Enterprises. The USA's nuclear policy is to reclaim its position as a world leader in nuclear power (U.S. Department of Energy, 2020). Additionally, in 2022, the U.S. Department of Energy announced the USD 6 billion Civil Nuclear Credit Program, which will support the continued operations of nuclear energy facilities. This program aims to support 100% clean electricity goals by 2035 and net-zero emissions by 2050 (Department of Energy, 2022). Although the USA has lost its position as the dominant player in

Country	Description
	nuclear power, for national security to achieve net-zero emissions, the USA is implementing initiatives to increase its position as a global player. One such initiative is an investment of USD700 million through the Inflation Reduction Act to support the development of a HALEU national supply chain (Office of Nuclear Energy, n.d.).
China	China's strategic energy policy is to develop energy in an "economical, clean, and safe" way. With this position, China aims to significantly increase its consumption proportions of renewable energy (IAEA, 2020). China views nuclear energy as a key power source to meet its increasing power consumption. Moreover, China views nuclear power as an available, economical, and reliable renewable energy source (Hibbs, 2018). China's plans to increase its proportion of nuclear power build upon an already established system where China is a global leader in advanced nuclear technology development (IEA, 2022) and has the largest share of the nuclear market of any other country. In the NZE scenario, it is estimated that China will account for one-third of all nuclear capacity by 2050 (IEA, 2023). In addition to increasing its nuclear capacity to meet growing power consumption, China's policy position includes a focus on exporting nuclear technology, such as nuclear reactors and recycling and disposal (Smith & Gieré, 2017), or supplying Russian-designed floating nuclear reactors to Russia.
Russia	The Russian Federation (Russia) has taken a strong position towards nuclear power. There are 38 nuclear power reactors in operation, and 20.7% of the Russian national electricity is produced by nuclear power. Russia plans to expand the role of nuclear energy within Russia, including expanding existing programmes and developing reactor technologies such as floating nuclear Power stations. Moreover, Russia is moving to close the nuclear fuel cycle (IAEA, 2021). As a part of this expansion, a Federal Target Programme estimates a nuclear share in electricity supply of 25-30% by 2030 and 45-50% by 2050. Additionally, the Federal Target Programme envisages a share of 70-80% by the end of the century, demonstrating an aggressive expansion in the role of nuclear power in Russia and a heavy reliance on the sector for its electricity supply. However, it must be noted that the IAEA report does not specify which Federal Target Programme reports the data above, and this information cannot be found in publicly available Federal Target Programmes (IAEA, 2021). Based on secondary sources (since the only publicly available report is in Russian) (Government of the Russian Federation, 2021), Russia's Energy Strategy 2035 contains estimates that the production of nuclear electric power in 2035 will be 111.1 – 119.9% of the 2018 value of 204.3 kWh. The estimates are lower than those reported in the Federal Target Programme (Mitrova & Yermakov, 2019). Nuclear Power in Russia is regulated by the Law on Utilisation of Atomic Energy and the Law on State Policy in the Field of Radioactive Waste Management. These laws and regulations, along with other rules and regulations from the regulating authorities, address safety in the construction, operation, and decommissioning of nuclear site installations (IAEA, 2021).

7.3.4 UK Competitive advantage: qualitative analysis

Irrespective of the technologies in this analysis, based on the Vivid Economics report, the main strengths for the UK to capture some of the nuclear energy power shares are the nuclear fuel cycle, decommissioning, and the manufacture of pumps and valves. However, the report notes that the UK's main weakness is the lack of a UK reactor design, which limits business opportunities to access high-value CapEx trade (Vivid Economics, 2019). This weakness could impact the UK's ability to capture some of the global share of the SMR, HTGR or floating nuclear powerplant markets.

Concerning decommissioning, it is worth noting that the UK has previously won contracts in Europe and that, as the global nuclear fleet ages, the UK has a significant opportunity to win further decommissioning contracts. The tradeable decommissioning market accessible to the UK is estimated at GBP 21 billion by the 2030s. Additionally, it is plausible that the UK could capture 5% of the global market for decommissioning by 2050 (Vivid Economics, 2019).

The following table summarises the UK's competitive advantage for each nuclear technology reported in this analysis.

Table 7-11: UK competitive advantage

Advantage	Description
High Temperature Gas Reactors	Based on expertise obtained from interviews with nuclear industry experts, the UK has a competitive advantage in developing HTGR due to its experience and knowledge over a

Advantage	Description
	long period of developing gas-cooled reactors. Additionally, funding has been acquired for the UK's first modular HTGR, demonstrating the UK's commitment to cultivating a national market (National Nuclear Laboratory, 2023). However, experts noted that the UK's advantage due to its experience and expertise will not make it as competitive as China in capturing the global HTGR market.
Small Modular Reactors	The UK has a competitive advantage in capturing some of the global SMR market. The experts interviewed stated that this competitive advantage could only be achieved if the UK commits to the significant investment required and utilises the SMRs being developed by Rolls-Royce. In the formation of Great British Nuclear, which has been instructed to "select the best SMR technologies, assign sites to those technologies, form project development companies for those sites, and potentially invest in projects through commercial operation", the Goal is to deliver 24 GW of new nuclear power in the UK by 2050 (APPG on NE, 2023). Additionally, on the 8th of February, it was announced that Community Nuclear Power will deploy four SMRs in North Teesside, the first privately funded SMR to be deployed in the UK by 2030s (Smart B, 2024). Demonstrating a commitment to investing and developing SMR technologies to increase the UK's nuclear capacity. In terms of the expert's views that utilisation of Rolls-Royce's SMRs is required for the UK to have a competitive advantage, a contract has already been signed between Rolls-Royce and Sheffield Forgemasters (Rolls-Royce, 2023). However, one drawback to the UK's competitive advantage in capturing some of the global SMR market is that the UK has lost its ability to develop steam turbines and, in this aspect, has been overtaken by other countries such as Korea.
Floating Nuclear Power stations	For three reasons, the UK has no competitive advantage in capturing some of the global market for floating nuclear Power stations. Firstly, based on experts' opinions, the UK is unlikely to invest in floating nuclear Power stations due to the perceived risk of a mobile nuclear powerplant and due to public perception. Secondly, unlike SMRs or HTGRs, the UK has committed to private or public investment in developing floating nuclear Power stations. Thirdly, Russia is the only country investing significantly in floating nuclear power plants (World Nuclear News, 2023). If the UK were to start investing in the development of floating nuclear Power stations now, they would not have a competitive advantage against countries like Russia or China.
Green Industries Growth Accelerator (GIGA)	As announced, GIGA would invest GBP 300 million in fuel production to power high-tech new nuclear reactors (HALEU) (Davies, 2024). An increase in the availability of HALEU might support the deployment of HTGRs and the demand for this technology (NEA, 2022) . However, it is not clear the magnitude of this positive effect because the increase in demand could be satisfied by other competitors along with the UK.

Table 7-12: UK competitive disadvantage

Disadvantage	Description
Lack of UK reactor design	The UK's main weakness is the lack of a UK reactor design. The main consequence is that it limits business opportunities to access high-value CapEx trade, thus affecting the UK's ability to capture some of the global share in the markets of the SMR, HTGR, or floating nuclear power plants.
Low comparative production and export of steam turbines	The UK does not export steam turbines on a comparable scale to other countries, particularly key players in nuclear energy such as China and the USA (OEC, 2022). Additionally, regarding the production of steam turbines, China has 3 of the global top 10 steam turbine manufacturers, and the USA has 1. Meanwhile, the UK is not on this list (Blackridge, 2024). Comparative to other countries, for geothermal steam turbine manufacturing, Japan accounts for 82% of the market; and for geothermal binary cycle turboexpander manufacturing, Israel accounts for 74% of the market (NREL, 2017). Comparative to key players in the nuclear market and other countries, the UK does not have a foothold in producing or exporting steam turbines, increasing costs to capture parts of the global nuclear energy market, thereby reducing the UK's competitiveness.

7.3.4.1 UK Competitive advantage: key conclusions per technology

In the following table, we classify each technology using an RAG rating methodology as being either:

- A "**primary focus area**", highlighted in green, i.e. an area where the UK is expected to have consolidated advantage;

- A "**further opportunity**", in yellow, i.e. an area where the UK could gain a competitive advantage from positioning itself as a potential early mover; or
- A "**lower potential**" area, i.e. a technology on which the UK does not appear to have potential, in red.

Table 7-13: Technologies classifications

Tech family	Technology	Rating	Answer & justification/rationale
Nuclear Gen IV	High Temperature Gas Reactor	Primary focus area	The UK has a competitive skills advantage due to its historical expertise, experience in gas-cooled reactors, and commitment to securing funding for HTGRs (National Nuclear Laboratory, 2023). However, unlike China, the UK is not perceived as competitive in the global market as a key player.
Advanced Nuclear Technologies	Nuclear (SMR)	Primary focus area	The UK may have a competitive advantage for SMRs due to commitment to public funding (APPG on NE, 2023) and due to the private contracts that have already been signed in the development of SMRs in the UK (Smart B., 2024) (Rolls-Royce, 2023). However, a drawback to the UK's competitive advantage is its ability to develop steam turbines relative to strong manufacturing countries.
	Floating Nuclear Power stations	Lower potential	Not many countries have committed to the development of floating nuclear power stations. While this could mean that the UK could technically become an early mover in the development of floating nuclear power stations relative to global commitment, any commitment would likely not make the UK competitive with Russia, which already has a significant competitive advantage due to existing investments, developments, and commercial ties to potential buyers (or manufacturers, such as China). Additionally, based on experts' opinions, the UK will unlikely have a competitive advantage due to the perceived risk of the mobile nature of floating nuclear power stations.

8. SMART SYSTEMS

8.1 INTRODUCTION

This chapter covers an analysis of the smart systems market and its associated technologies[33]. The term 'smart systems' refers to everything related to the electric system between any point of generation and any point of consumption that, through the addition of technologies, becomes more flexible and interactive and can provide real-time feedback (IEC, 2018). The analysis focuses on three technological families:

1. **Storage** refers to the means of deferring the final use of energy to a moment later than when it was generated (EASE, 2023). The technology assessed is thermal energy storage. Currently, the technologies most widely used worldwide are molten salt, electric thermal storage heaters, solar energy storage, and ice-based systems.
    - **Thermal energy storage** 'refers to storage of energy in thermal form and the subsequent release or reconversion of such energy into electrical energy' (EASE, 2023). It consists of three sub-technologies:
        - Sensible heat storage raises or lowers the temperature of a liquid or solid storage medium to store and release thermal energy for applications of low to very high temperatures (EASE, 2023). This most common form of thermal energy storage has found commercial success on residential and industrial scales. The storage duration can range from minutes up to months.
        - Latent heat storage uses a phase change material to absorb and store thermal energy at a constant temperature during the off-peak via melting. Then, it releases the stored thermal energy during peak-demand time as it solidifies (EASE, 2023). The storage duration can last hours to days.
        - Thermochemical heat storage operates in two ways: chemical reactions and sorption processes. In the former, energy is stored as the heat of reaction of reversible reactions (EASE, 2023). The latter stores thermal energy either through adsorption or absorption. The storage duration can last hours to days or potentially even up to months.
2. **Demand side response (DSR)** involves services, businesses and consumers increasing, decreasing or shifting their electricity use to help balance electricity grids, reacting to a signal (ESO, n.d.).
    - **Vehicle-to-grid (V2G)** is the process of returning the energy stored in an electric vehicle's (EV) battery back into the electricity network (Topping, 2023). The related technologies are the EV battery, the charger, the app, and the underlying optimisation software. The assessment focuses on the hardware infrastructure (EV charging points, fleets, hubs) and DSR management software.
3. **Transmission** concerns the electricity conveyed across long distances at high voltage levels, while distribution refers to the electricity conveyed to consumers at lower voltage levels for safety and accessibility reasons (Eurelectric, n.d.). The technologies analysed are critical in the transition between transmission and distribution due to their role in regulating voltage and converting the current.
    - **Power electronics** concerns the control and conversion of electrical power using solid-state electronics (Pollar, 2024). Control involves voltage regulation or power delivery smoothing, while conversion implies changing AC into DC or vice versa.
    - **HVDC (High Voltage Direct Current) converters** are installation transforming DC into alternate current or vice versa (De Paola, Andreadou, & Kotsakis, 2023).

Table 8-1: In-scope technologies

Sector	Tech families	Technologies
Smart systems	Storage	Thermal energy storage
	DSR	V2G (vehicle-to-grid)
	Transmission	Power electronics

[33] The selection of the analysed technologies is the result of an iterative process between DESNZ and Ricardo.

Sector	Tech families	Technologies
		HDVC converters

8.1.1 Key takeaways

- The market size for smart systems technology will experience an increase in the next 6 years. The overall market size is expected to be between USD 130.2 billion and USD 214 billion in 2030. In particular, thermal energy storage and power electronics will account for 70%-77% of the market value of smart systems technologies analysed.
- In the Net Zero scenario, the market expands by 4.6 times in 2050 compared to 2020. This growth surpasses the rates observed in the Current policy scenario (~3.6 times) and Below 2 ºC (~4.4 times).
- The UK has the potential to attract an average market share compared to other competitors in manufacturing two technologies: V2G and power electronics. Concerning the current situation where small UK manufacturers have to compete with large established companies, the UK has the potential to develop a global presence in the smart systems landscape, ultimately leading to an increased share of UK manufacturers in the global V2G market. Instead, regarding power electronics, even though the UK has several companies specialising in design, manufacturing, and deployment, it will face fierce competition from other countries, restricting its market share.
- As projected in the GEM-E3 model, the UK market slightly increases its market share in the Net Zero scenario compared to the other scenarios considered.
- The demand for smart systems technologies is mainly driven by the increasing penetration of renewable energy and the growing demand for electricity. Indeed, the increased reliance on intermittent energy sources and the increase in electricity consumption will require the deployment of technological solutions, i.e. smart system technologies, to improve the flexibility and resilience of the electricity network.
- In addition to the US and the EU, market competitors are China, India, and Japan. Despite adopting funding mechanisms to boost their manufacturing capacity, these countries host the leading companies responsible for producing and innovating smart systems technologies.
- The UK has a regulatory and policy framework that could support the industrial landscape needed to manufacture smart systems technologies. Nevertheless, it suffers from the lack of large UK manufacturing companies and the competition of established companies with a high market power.
    - The UK enjoys some competitive advantages. The regulatory framework of the electricity market and the announced Green Industries Growth Accelerator might increase the demand for smart systems technologies produced in the UK, supporting UK manufacturers. In addition, the UK has funding mechanisms such as the Driving the Electric Revolution challenge and projects to develop its manufacturing capacity.
    - The UK has to deal with competitive disadvantages, too. The UK lacks industrial expertise in power electronics because of its weak historical presence in heavy industry and power equipment manufacturing compared to other leading countries. In addition, the UK suffers from a low investment level in the sector in previous years.

8.2 RQ1: POTENTIAL MARKET SIZE AND UK MARKET SHARES

8.2.1 Quantitative analysis at the sector level

8.2.1.1 Market size

This section discusses market size projections and the UK's market share in the battery industry. As of 2020, the global market size stands at approximately USD 63 billion, and the current policy scenario projections indicate an increase over the coming years, reaching around USD 227 billion by 2050, as projected in the GEM-E3 model.

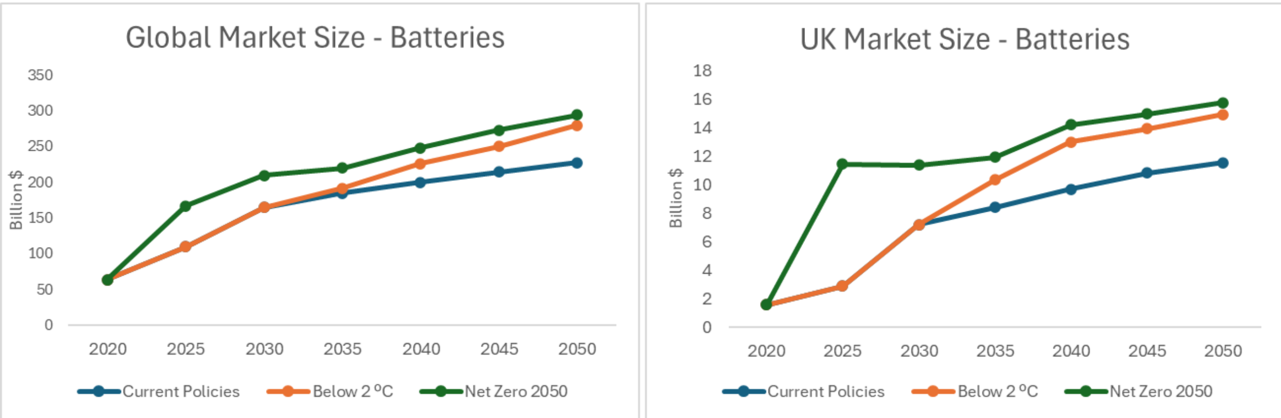
The Net Zero scenario implies a significant transformation of the energy system and sees the highest deployment of battery technologies compared to any other simulated scenarios globally. In the Net Zero scenario, the market will increase by 4.6 times in 2050 compared to 2020 (compared to ~3.6 times in the Current Policies scenario and ~4.4 times in the Below 2 ºC scenario).

Higher adoption of electric vehicles due to the decarbonisation mitigation efforts in GHG emissions increases the demand for batteries.

Table 8-2: Market size (demand in billion USD)

NGFS Scenario	Geography	2020	2025	2030	2035	2050
Current policies	Global market	63.3	109.4	164.8	184.4	227.3
	Domestic market	1.6	2.9	7.2	8.4	11.6
	Export market	61.7	106.5	157.6	176.0	215.7
Below 2 ºC	Global market	63.3	109.4	164.8	191.7	280.0
	Domestic market	1.6	2.9	7.2	10.3	14.9
	Export market	61.7	106.5	157.6	181.3	265.1
Net Zero 2050	Global market	63.3	167.0	209.6	219.9	294.3
	Domestic market	1.6	11.4	11.4	11.9	15.8
	Export market	61.7	155.5	198.2	208.0	278.5

Figure 8-1: Global vs UK Market for EV Batteries



8.2.1.2 UK Market share

UK market share in the global market is small, ranging from 0.2% to 0.4% across scenarios and over time. It is projected to increase its market share slightly in the Net Zero scenario compared to the other scenarios. The UK's contribution to the export market is projected to be minor, around 0.1%.

Table 8-3: UK market shares

NGFS Scenario	Geography	2020	2025	2030	2035	2050
Current policies	Global market	0.2%	0.2%	0.3%	0.3%	0.3%
	Domestic market	3.8%	3.7%	3.8%	3.8%	3.6%
	Export market	0.1%	0.1%	0.1%	0.1%	0.1%
Below 2 ºC	Global market	0.2%	0.2%	0.3%	0.3%	0.3%
	Domestic market	3.8%	3.7%	3.8%	3.9%	3.6%
	Export market	0.1%	0.1%	0.1%	0.1%	0.1%
Net Zero 2050	Global market	0.2%	0.4%	0.3%	0.3%	0.3%
	Domestic market	3.8%	3.8%	3.9%	4.0%	3.7%
	Export market	0.1%	0.1%	0.1%	0.1%	0.1%

8.2.2 Qualitative analysis: market size

Based on recent literature findings, the technologies analysed will likely experience positive market size growth in the future. Given the several estimations and annual growth rates available for each technology, we have adopted the most recent market size estimation before 2024 and then selected two annual growth rates to provide a range by excluding outliers in the distribution of growth rates.

- **Thermal energy storage**: Several estimations and annual growth rates are available (Global Market Insights, 2023; Mordor Intelligence, 2023; Allied Market Research, 2022; Grand View Research, 2019). Nevertheless, to assess the market size in 2030, the market size estimation for 2022 was chosen: USD 36.4 billion (Global Market Insights, 2023). As for annual growth rate, the two rates adopted were 9.45% and 6.25%[34] (Mordor Intelligence, 2023; Grand View Research, 2019). In the best-case scenario, the market size will be USD 74.9 billion in 2030. In the worst-case scenario, the market size will be USD 59 billion in 2030.
- **V2G:** Several estimations and annual growth rates are available (Transparency Market Research, 2022; IMARC Group, 2023; Fortune Business Insights, 2023; Allied Market Research, 2022). Nevertheless, to assess the market size in 2030, the market size estimation for 2023 was chosen: USD 3.4 billion (IMARC Group, 2023). As for annual growth rates, the two rates adopted were 34.8% and 21.4% (IMARC Group, 2023; Transparency Market Research, 2022). In the best-case scenario, the market size will be USD 27.4 billion in 2030. In the worst-case scenario, the market size will be USD 13.2 billion in 2030.
- **Power electronics**: Several estimations and annual growth rates are available (Precedence Research, 2023; Fortune Business Insights, 2023; Future Market Insights, 2022). Nevertheless, to assess the market size in 2030, the market size estimation for 2022 was chosen: USD 28 billion (Future Market Insights, 2022). The two adopted annual growth rates were 13.8% and 5% (Fortune Business Insights, 2023; Future Market Insights, 2022). In the best-case scenario, the market size will be USD 78.7 billion in 2030. In the worst-case scenario, the market size will be USD 41.3 billion in 2030. According to the judgement of Ricardo's experts, annual demand could grow by 5% even after 2030 for two reasons: First, the increasing maturity of power electronics technologies could lead to a decrease in cost, favouring deployment. Second, the growing penetration of low-carbon technologies on the producer's and consumers' sides will increase the role of power electronics. For this set of reasons, the market size in 2050 was estimated at USD 109.7 billion.
- **HVDC Converters**: Several estimations and annual growth rates are available (Global Market Insights, 2023; The Insight Partners, 2024; Market Research Future, 2024; The Business Research Company, 2024). Nevertheless, to assess the market size in 2030, the market size estimation for 2023 was chosen: USD 12.28 billion (The Business Research Company, 2024). The two adopted annual growth rates were 15.5% and 4.5% (Global Market Insights, 2023; Market Research Future, 2024). In the best-case scenario, the market size will be USD 33.6 billion in 2030. In the worst-case scenario, the market size will be USD 16.7 billion in 2030. According to the judgement of Ricardo's experts, annual demand could grow by 4.5% even after 2030 for two reasons: First, the increasing installation of offshore wind turbines fosters the deployment of HVDC connections because HVDC provides a stable connection to the grid. Second, HDVC is more suitable for long-distance power transfer. Indeed, power generation and consumption will occur in different geographical locations due to the penetration of renewable energy sources in the power system. For this set of reasons, the market size in 2050 was estimated at USD 40.3 billion.

Given the estimates presented above, the overall market size of smart systems is expected to be between USD 130.2 billion and USD 214 billion in 2030. The market size in 2050 is not estimated for each technology because sources do not provide plausible annual growth rates until 2050. Only the market size for transmission technologies in 2050 was estimated based on the judgement of Ricardo's experts, who foresee that the increasing penetration of low-carbon technologies and renewable energy sources will continue to drive market growth after 2030. Conversely, in the case of the other technologies, the lack of information makes difficult to understand which trends will affect the market. For instance, the market could become saturated between 2030 and 2050, slowing its growth.

[34] As for the following technologies, the growth rates were selected after discarding outliers and choosing the lowest and the highest values around the median value.

Table 8-4: Global market size growth potential: RAG rating by technology

Tech family	Technology	Ranking	Justification/rationale and key sources
Storage	Thermal energy storage	Medium	The market size was USD 36.4 billion in 2022 (Global Market Insights, 2023). Given the estimates presented for 2030, the growth potential can range between USD 22.6 billion and USD 38.5 billion. According to ENTSO-E technopedia, thermal energy storage technologies have different maturity levels. Large-scale volcanic rock is in the demonstration stage (TRL 7). Instead, heated fluid in insulated containers is the market uptake stage (TRL 9). For instance, EnergyNest and Eco-stock are already commercial (ENTSO-E, n.d.). EASE (2023) confirms this diversity among categories. For sensible heat, most technologies are already commercially available, and there is a track record of pilots and use cases. For latent heat, a large range of technologies is in the technical maturity stage, with some already commercially available and others in the R&D phase. Finally, thermochemical heat technologies are nascent and in the R&D or pilot phase.
DSR	V2G (vehicle-to-grid)	High	In 2023, the market size was USD 3.4 billion (IMARC Group, 2023). Given the estimates presented for 2030, the growth potential can range between USD 9.8 billion and USD 24 billion. According to ENTSO-E technopedia, V2G technologies are under development. Statnett pilot validated the ability of a fleet of EVs to provide FFR within 2 seconds (TRL 6), while INVADE preliminarily tests DC V2G technology to provide congestion management and voltage control services to the DSO (TRL 5).
Transmission	Power electronics	High	In 2022, the market size was USD 28 billion (Future Market Insights, 2022). Given the estimates presented for 2030, the growth potential can range between USD 13.3 billion and USD 50.7 billion. Flexible AC transmission system (FACTS) devices are relevant power electronics technologies. Indeed, FACTS includes all of the power electronics-based systems used in AC power transmission. Most of these technologies are almost mature or ready for market uptake. For instance, phase shifting transformers are ready for full-scale deployment (TRL 9), while static synchronous series compensator is in the demonstration stage (TRL 7) (ENTSO-E, n.d.). Within FACTS devices, there is also STATCOM (STATic synchronous COMpensator): a fast-acting device capable of providing or absorbing reactive current, thereby regulating the voltage at the connection point to a power grid. According to ENTSO-E technopedia, it is a system ready for full-scale deployment (TRL 8). In addition, according to the judgement of Ricardo's expert, due to the increasing penetration of low-carbon technology devices and renewable energy sources and the challenges that they will introduce to the power networks, there is a very high potential for implementation of power electronic devices in the modern future power systems in medium voltage and distribution power networks.
	HVDC Converters	Medium	The market size was USD 12.28 billion in 2023 (The Business Research Company, 2024). Given the estimates presented for 2030, the growth potential can range between USD 4.4 billion and USD 21.3 billion. HVDC converters are ready for market uptake. They include AC/DC and DC/AC converters and equipment for

Tech family	Technology	Ranking	Justification/rationale and key sources
			reactive power support and filtering. The AC/DC and DC/AC converters can generally use two technologies: Line Commutated Converters (LCC), a well-established technology, and Voltage Source Converters (VSC), which are more recent and provide greater controllability. VSC is TRL 8, and LCC is TRL 9 (De Paola, Andreadou, & Kotsakis, 2023).

8.2.3 Qualitative analysis: UK market shares

8.2.3.1 Trade flows analysis

The table below shows the annual average of UK exports (2021-2022) for some selected Harmonised System (HS) subheading codes (provided by DESNZ) relating to components used in the manufacture of equipment and parts relevant to the Smarty Systems sector. These numbers can be interpreted as proxies of the UK's share of tradable export markets. The total average for this sector stands at 1.3% of the global tradable market.

Table 8-5: UK share of global exports, selected HS subheadings, 2021-2022

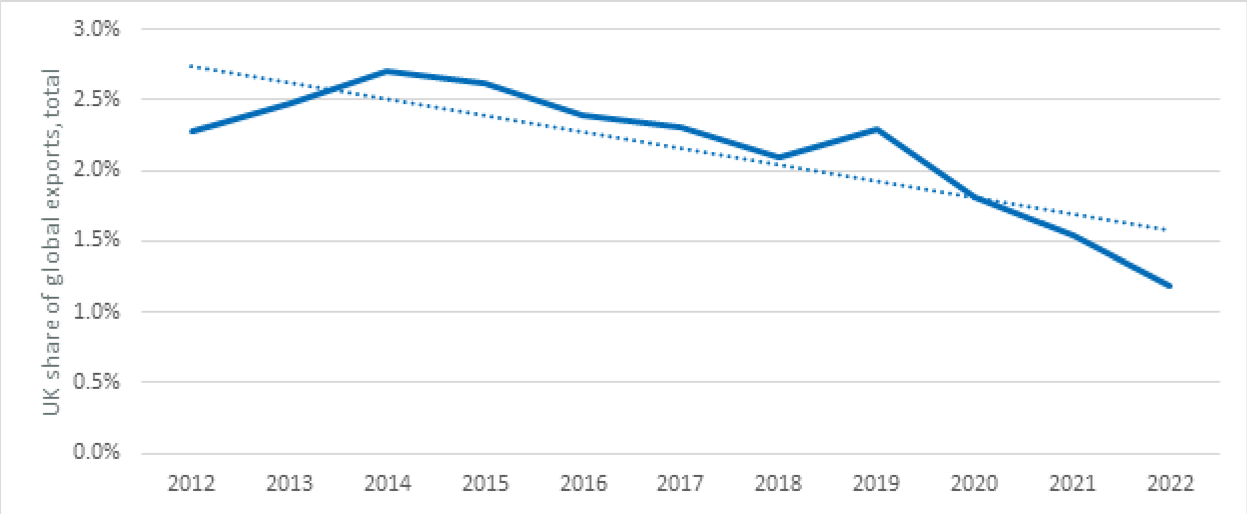
Group	Subheading included in group	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
75 Nickel and articles thereof	– 750890 Other articles of nickel > Other	USD 331M	13.9%
85 Electrical machinery and equipment and parts thereof; sound recorders and reproducers, television image and sound recorders and reproducers, and parts and accessories of such articles	– 850131 Other dc motors; dc generators, other than photovoltaic generators – 850650 Primary cells and primary batteries > Lithium – 850680 Other primary cells and primary batteries – 850720 Other lead-acid accumulators – 850730 Electric accumulators, including separators therefor > Nickel-cadmium – 850750 Electric accumulators, including separators therefor > Nickel-metal hydride – 850760 Electric accumulators, including separators therefor > Lithium-ion – 850780 Electric accumulators, including separators therefor > Other accumulators – 850790 Electric accumulators, including separators therefor > Parts – 853650 Electrical apparatus for switching or protecting electrical circuits, or for making connections to or in electrical circuits > Other switches	USD 1,097M	0.8%
90 Optical, photographic, cinematographic, measuring, checking, precision, medical or surgical instruments and apparatus; parts and accessories thereof	– 902830 Electricity meters – 903031 Other instruments and apparatus, for measuring or checking voltage, current, resistance or power (other than those for measuring or checking semiconductor wafers or devices) – 903032 Multimeters, with a recording device – 903039 Other instruments and apparatus, for measuring or checking voltage, current, resistance or power > Other, with a recording device	USD 922M	3.0%

Group	Subheading included in group	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
	– 903281 Automatic regulating or controlling instruments and apparatus > Other instruments and apparatus – 903289 Automatic regulating or controlling instruments and apparatus > Other instruments and apparatus > Other		
Total		**USD 2,350M**	**1.3%**

Source: Ricardo elaboration on UN Comtrade data

The figure below shows a downward trend in the UK's share of global exports for the total HS codes analysed, from a max of 2.7% in 2014 to 1.2% in 2022.

Figure 8-2: UK share of global exports, 2012-2022



Source: Ricardo elaboration on UN Comtrade data

8.2.3.2 Qualitative analysis: UK market shares

In line with other technologies, most manufacturers of smart system devices are situated outside of the UK, resulting in a limited global market share for the UK, according to the judgement of Ricardo's experts. Given the prevailing policies, investments, international competition, and the current trajectory of UK manufacturers in this sector, it seems improbable that the UK market share will experience significant global growth in the field of smart power systems even though little positive trends will affect UK manufacturers due to the increasing demand for smart system technologies at the global level.

- **Thermal energy storage**: Fuelled by technologies like molten salt, electric thermal storage heaters, solar energy storage, and ice-based systems, the thermal energy storage market is primarily driven by North America, Europe, Asia Pacific, Latin America, and the Middle East and Africa. According to the judgement of Ricardo's expert, despite not being prominently featured, the UK is emerging in this sector, with notable players such as Caledonian MacBrayne and Calmac indicating a growing market presence. With the UK's commitment to achieving Net Zero 2050 and a focus on the electrification of heating, there is potential for growth by 2030. However, it remains uncertain how this will translate into increased market share for UK manufacturers on a global scale.
- **V2G**: With a focus on decarbonising transportation and government incentives in the UK, leading to increased application of EV charge points and EVs, there is a growth potential for the UK in the global market share in the future. However, considering the competition and the rapid share growth of

competitors in the US and Europe, it is uncertain whether the UK's global share will increase significantly in this market, according to the judgement of Ricardo's experts.

- **Power electronics**: Given that many key players in the power electronics market are concentrated in the US, Europe, and South Asia, and considering the UK's relatively small geographic footprint, it is plausible that the UK market share of power electronic devices in power transmission systems may remain relatively stable through 2030 according to the judgement of Ricardo's experts.
- **HVDC converters**: While HVDC technology has a lengthy utilisation history, its current market growth and technological advancements stem from new applications. Despite this background, according to the judgement of Ricardo's experts, UK manufacturers currently play a limited role in both the global and domestic HVDC market, suggesting it is improbable for their global market share to increase significantly by 2030.

From the evidence presented, it is possible to draw some conclusions on the future UK market share in manufacturing specific technologies and its potential in attracting higher shares (see the table below for further information). For all the technologies analysed, it appears that the UK will not be able to attract higher shares than the average due to the lack of established UK-based manufacturers and high competition within the sector. Even considering the announced Green Industries Growth Accelerator (GIGA), the conclusions would not change. Indeed, as announced, GIGA would invest GBP 390 million in electricity networks and offshore wind (Davies, 2024). An increase in demand for network technologies would affect smart systems manufacturing positively. However, it is not clear how this policy will affect the UK market share because the UK government has started to discuss policy design with stakeholders at the moment when this report is published. Hence, it is unclear which technologies GIGA will target and what funding it will invest in.

Table 8-6: Technologies that have the potential to attract significantly higher/lower market shares compared to the sector average

Tech family	Technology	Answer	Justification/rationale and key sources
Storage	Thermal energy storage	Lower than average	While the UK has been active in research, development, and deployment of thermal energy storage technologies, including innovations in areas like concentrated solar power (CSP) and renewable energy integration, its market share in the global thermal energy storage market may not be as significant as that of some other countries such as the United States, China, or Germany. The key players in this area are companies such as BrightSource Energy Inc., SolarReserve LLC, Abengoa SA, Terrafore Technologies LLC, Baltimore Aircoil Company, Ice Energy, Caldwell Energy, Cryogel, and Steffes Corporation, which are primarily based in the United States and Europe. The UK does not seem to have a notable share in this market.
DSR	V2G (vehicle-to-grid)	Average	While it may be challenging to determine the precise market share of UK manufacturers in the global vehicle-to-grid (V2G) technology market, the presence of only one prominent V2G company in the UK (Moixa), alongside several key players worldwide suggests that the UK's current market share may be relatively smaller compared to leading countries like the US and Germany according to the judgement of Ricardo's expert. However, with the emergence of new technology and the UK Government's initiatives, such as Driving the Electric Revolution and Net Zero 2050 plans, coupled with the involvement of various manufacturing sectors and regulatory bodies, the UK is poised to tap into a significant domestic market. By capitalising on this opportunity through strategic investments, UK manufacturers have the potential to dominate domestically and establish a strong global presence in the smart systems landscape, ultimately leading to an increased share of UK manufacturers in the global V2G market.

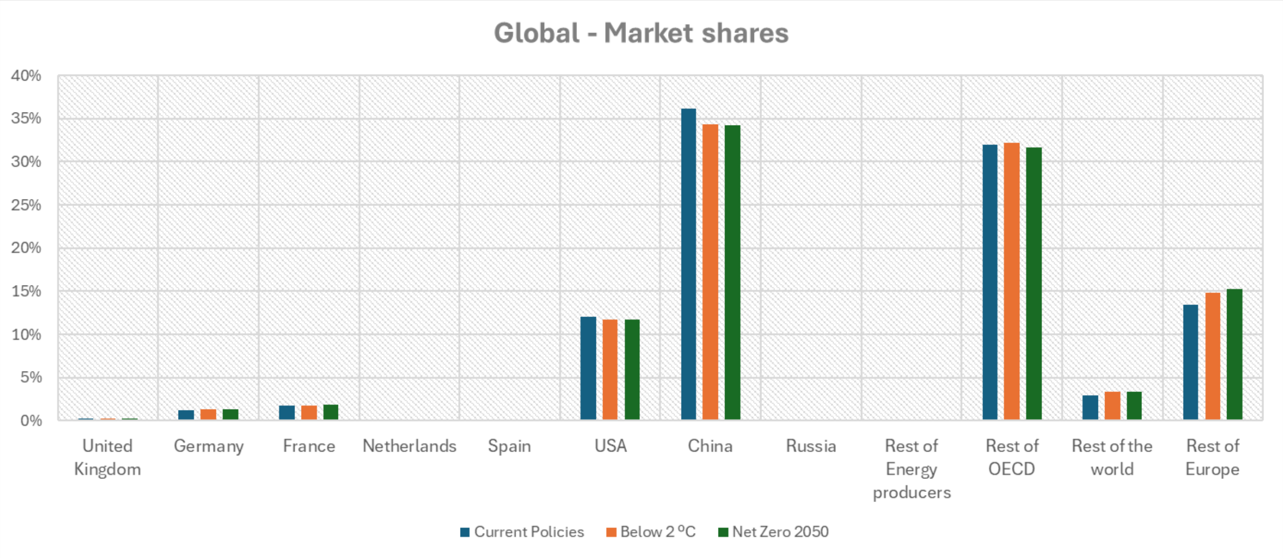
Tech family	Technology	Answer	Justification/rationale and key sources
Transmission	Power electronics	Average	The UK has made significant contributions to the field of power electronics. It has several companies specialising in the design, manufacturing, and deployment of power electronic devices. Still, its global market share in this sector may likely be smaller than that of leading countries such as the United States, Germany, Japan, and China. Most key power electronic manufacturers are based in the USA and Germany, and recently, growing numbers are in China. Nevertheless, the presence of manufacturers and innovative projects at the UK level has the potential to keep the global share of UK manufacturers in the global market according to the judgement of Ricardo’s expert. However, since the large-scale manufacturers have not been established yet, the investments will be directed at improving the infrastructure in the first stage. Only later investments will focus on enhancing manufacturing capacity. This delay could affect the UK market share negatively.
	HVDC Converters	Lower than average	The global market for HVDC converters is populated by several key players, including ABB (a multinational corporation headquartered in Switzerland), Siemens Energy, General Electric (GE) Renewable Energy, Mitsubishi Electric Corporation (a Japanese multinational electronics and electrical equipment manufacturer), Hitachi ABB Power Grids, Toshiba Corporation (based in Japan), C-EPRI Electric Power Engineering Co., Ltd (a Chinese company specialising in HVDC converter), NR Electric Co., Ltd (headquartered in China), which are primarily based in Europe, Japan, China and USA. UK-based manufacturers do not seem to have a significant share of this market. This might have been initiated by some geographical specifications for the pioneer countries, which has made them accelerate their progress in this area.

8.3 RQ2: UK COMPETITIVE ADVANTAGE

8.3.1 Quantitative analysis at the sector level

According to the projection from the GEM-E3 model, China leads the market, commanding a high share of around 35%. Following China, other key players include the USA, Korea, Japan and India that are covered under the Rest of the OECD region and the Rest of the World region. The UK's contribution to the global market is small, around 0.3% across scenarios. Asian countries dominating the production landscape, including China, Japan and Korea, have made considerable investments in battery research and development, resulting in significant expertise and knowledge within the battery industry. The battery industry expansion is mainly driven by the growing demand for batteries from adopting electric vehicles.

Figure 8-3: Market shares in 2050



8.3.2 Key drivers of competitive advantage

Several drivers affect the manufacturing of smart systems technologies (see the table below for a complete list). However, the most relevant enablers are the ongoing electrification of power consumption and the increasing penetration of renewable energy sources into the grid. Indeed, electricity consumption will increase due to the changes in energy demand (IEA, 2024). At the same time, renewable energy sources will cover two-thirds of the energy generated (IEA, 2021). This high reliance on these intermittent energy sources will require technological solutions to address potential issues related to energy security. In this sense, DSR, storage and transmission technologies will be critical to ensure a continuous matching between the supply and demand of electricity in the grid.

Table 8-7: Key drivers of energy policy and market developments globally

Category	Driver	Discussion	RAG
Enablers	Increasing penetration of renewable energy sources into the grid	Risks to meeting electricity security of supply have been at times of high demand, particularly peak demand. In the future, storage, demand side response (DSR) and other forms of flexibility will play a key role in managing the system (ESO, 2023). In the future, high demand will not be the only risk to the security of supply as increased renewable generation will result in supply determining periods of risk. For example, low demand during periods of high renewable supply will pose an equal risk to periods of higher demand but with much lower levels of renewable generation (Brown & Jones, 2024). These periods of undersupply are typically short (hours or a few days) and can be managed by options including several flexible technologies: interconnectors, DSR and vehicle-to-grid (V2G) (ESO, 2023).	
	Increasing electricity demand	Global electricity demand grew by 2.5% in 2022, similar to the average growth of 2.6% in the previous decade (Wiatros-Motyka, 2023). Despite the growth rate of 2.2% in 2023, IEA forecasted an accelerated rate of 3.4% in the period 2024-2026 (IEA, 2024). The increasing electricity demand, particularly peak demand, coupled with the ongoing penetration of renewable energy sources into the grid, will require a stable supply of electricity that matches the demand. From this perspective, the need for thermal energy storage and V2G technologies will increase.	
	High offtake of EVs	According to the IEA (2023), the total fleet of EVs (excluding two/three-wheelers) will grow from almost 30	

Category	Driver	Discussion	RAG
		million in 2022 to about 240 million in 2030 in the current policies scenario, achieving an average annual growth rate of about 30%. Instead, in the Net zero scenario, in which the fleet of EVs grows at an average yearly rate of around 40%, the total fleet of EVs will reach 380 million in 2030 (IEA, 2023). This increase could pave the way for selling V2G and storage technologies.	
	Cost-effectiveness of HVDC	AC and DC high-voltage lines achieve cost-parity at 483 km. Over longer distances, the additional costs of the transformer substations required for the HVDC connections are compensated by the increased efficiency and lower losses provided by the direct current link (De Paola, Andreadou, & Kotsakis, 2023). In addition, HVDC transmission losses are significantly lower than HVAC due to the absence of transmission line capacitive/reactive charging effects (Alassi, Bañales, Ellabban, Adam, & MacIver, 2019).	
Barriers	Distribution power network opacity	There are not enough metering devices installed in the UK distribution network. This low deployment can hamper the diffusion of smart systems technologies because metering devices are a key element of smart energy systems and a necessary step in adopting other smart system technologies.	
	High investment costs	Securing sufficient funding and investment for large-scale deployment of smart grid technologies can be a significant barrier. For example, to improve modern power systems (Infrastructure update), there is always an element of power electronic devices involved, and these devices are usually expensive, especially in higher power ranges.	
	Integration of smart system devices with communications and control systems	Lack of standardised protocols and compatibility issues between different vendors' technologies can hinder progress.	
	Customer Awareness on Demand Side Programs	Lack of consumer awareness and acceptance will be a barrier to further implementation of smart metering devices and the operation of Demand Response Programs.	
	Data management and cybersecurity concerns	The proliferation of data generated by smart grid devices requires robust data management systems to process, analyse, and utilise this information effectively. At the same time, the increased connectivity and reliance on digital technologies introduce new cybersecurity risks.	

8.3.3 Geographical benchmarking

Regarding the manufacturing of smart systems technologies, most of the capacity is in the US, the EU and China. For instance, the leading global HDVC converter suppliers were Siemens, Alstom, and ABB in 2019, all based in the EU. At the same time, most companies manufacturing thermal energy storage technologies are in the US. A similar distribution also applies to patenting: State Grid Corporation of China and China Southern Power Grid in China, and ABB and Alstom in the EU are the prominent active firms regarding HVDC technologies.

Table 8-8: Major UK competitors globally

Country	Description
US	Most thermal energy storage manufacturers are based in the US: BrightSource Energy Inc., SolarReserve LLC, Terrafore Technologies LLC, Baltimore Aircoil Company, Ice Energy, Caldwell Energy and Steffes Corporation. Regarding HVDC converter manufacturing, General Electric is one of the leading producers worldwide (IEA, 2023).

Country	Description
EU	The EU has adopted coordination and funding mechanisms to foster the manufacturing of smart systems technologies. As a coordination platform, the European Battery Alliance (EBA) was launched in 2017 by the European Commission, EU countries, industry, and the scientific community (European Commission, 2023). Supported by the Commission and the European Investment Bank, the EBA brings together EU national authorities, regions, industry research institutes and other stakeholders to develop a competitive battery value chain. Instead, the EU provides two examples of fiscal tools. On the one hand, the Innovation Fund (EUR 40 billion) supports the development, manufacturing and deploying of energy storage technologies. On the other hand, the actual State aid framework allows for a matching principle if an EU country aims to attract/keep a manufacturing site of innovative technologies. Two of the leading manufacturers of thermal energy storage technologies are based in the EU: Abengoa SA and Cryogel. Regarding HVDC converter manufacturing, the leading global HDVC suppliers were Siemens, Alstom and ABB in 2019, all based in the EU (Alassi, Bañales, Ellabban, Adam, & MacIver, 2019). Nevertheless, only Hitachi Energy in Switzerland has its factory for making power semiconductors, whereas the other suppliers have to source these key components externally from semiconductor manufacturers (IEA, 2023). ABB and Alstom are two of the most relevant companies in patenting despite their smaller volumes than other competitors (De Paola, Andreadou, & Kotsakis, 2023).
China	Concerning HVDC patenting, the most active companies in this field are the State Grid Corporation of China and the China Southern Power Grid (De Paola, Andreadou, & Kotsakis, 2023). NR Electric is also relevant but with smaller patenting volumes. Regarding HVDC converter manufacturing, NR Electric and C-EPRI Electric Power Engineering are two of the primary producers worldwide (IEA, 2023).
Japan	Regarding HVDC converter manufacturing, Mitsubishi Electric is one of the main producers worldwide (IEA, 2023).
India	Regarding HVDC converter manufacturing, Bharat Heavy Electricals Limited is one of the main producers worldwide (IEA, 2023).

8.3.4 UK competitive advantage: qualitative analysis

Even though the UK has potential competitive advantages in manufacturing the main smart systems technologies listed in the table below, the gap with competitors has been growing in the last few years due to the lack of large manufacturers and the high level of competition in the sector. Indeed, the small size of UK manufacturers hampers their innovation capacity because they lack internal economic and human resources to invest in R&D activities, according to the judgement of Ricardo's experts. In addition, according to Ricardo's expert judgement, most UK innovation funding is targeted more at deploying these technologies than at their production. Due to this small share of funding assigned to developing manufacturing capacity compared to other sectors, such as aviation, UK firms cannot challenge foreign competitors. Finally, according to Ricardo's expert, public funding mechanisms need to reform their monitoring, reporting, and verification requirements to improve their effectiveness.

The UK has a regulatory and policy framework that could support its industrial landscape for manufacturing smart systems technologies (see the tables below). Nevertheless, it suffers from the lack of previous expertise of UK companies in the sector and the surge of competition from other countries. Economic measures and industrial expertise fuel this competition. In this scenario, the UK cannot reap some benefits, attracting market shares in specific niches, unless it adopts an enabling economic and regulatory framework. In any case, these shares will be smaller than the shares of the other players.

Table 8-9: UK competitive advantages

Advantage	Description
Regulatory framework of the electricity market	The UK has adopted a cost-pass-through method to foster innovation in networks. The positive effects from cost-pass-through seem to be related to a high degree of flexibility, long-term consistency and amount of regulation in supporting R&D investments (Couto Ribeiro & Jamasb, 2024). Furthermore, the cooperation between utilities, suppliers and services (ICT and telecommunications firms) has supported the higher patent application level.
Experimentation for V2G	The UK has favoured a series of projects to foster the development and deployment of V2G. For instance. a vehicle-to-grid (V2G) programme began in April 2018 through a collaboration

Advantage	Description
	between OVO Energy, Kaluza, Nissan Motor Company, research consultancy Cenex, and Indra Renewable Technology, and supported by funding from the Office for Low Emission Vehicles and the Department for Business Energy and Industrial Strategy (Ofgem, 2021). The project sought to roll out V2G across UK homes, showcasing the technology's significant economic, environmental and societal value. Since the beginning of the project, 330 V2G devices have been installed across the UK, and over three million 'free' miles were made available to customers who exported energy back to the grid during peak times (Ofgem, 2021) . An additional example is the Electric Nation V2G project. Western Power Distribution delivered it in partnership with CrowdCharge (Electric Nation, 2020). The project recruited 100 Electric Vehicle drivers who drove a Nissan EV with a battery capacity of 30kWh or more and lived in the Midlands, South West or South Wales. Those eligible trialled a domestic vehicle-to-grid (V2G) smart EV charger worth GBP 5,500. Participants were rewarded by plugging in at specified times, and the charger could be kept at the end of the trial for just GBP 250 (Electric Nation, 2020). Furthermore, the UK government's V2X (vehicle-to-everything) innovation programme aims to address barriers to enabling energy flexibility from bi-directional electric vehicle charging. This programme is part of the Flexibility Innovation Programme, which aims to support innovative solutions to enable large-scale widespread electricity system flexibility and ensure that the UK remains competitive in global markets (UK Government, 2024).
Funding mechanisms	Regarding V2G, Innovate UK has supported V2G projects totalling GBP 46 million, with partners including Octopus, OVO, and Nissan (Electric Nation, 2020). In addition, the Driving the Electric Revolution challenge under Innovate UK aims to invest in electrification technologies, including power electronics, machines, and drives. The investment supports the UK's push towards a net zero carbon economy and contributes to developing clean technology supply chains. The budget accounts for GBP 80 million from 2019 to 2024 (UK Research and Innovation, 2023).
Green Industries Growth Accelerator (GIGA)	As announced, GIGA will invest GBP 390 million in electricity networks and offshore wind (Davies, 2024). An increase in demand for network technologies would positively affect smart systems manufacturing. However, the magnitude of this positive effect is unclear because the UK government has started to discuss policy design with stakeholders when this report is published.

Table 8-10: UK competitive disadvantages

Disadvantage	Description
Industrial path-dependence	According to Ricardo's expert, the relatively smaller market share of UK manufacturers in global markets for technologies like V2G, thermal energy storage, and HVDC converters can be attributed to several factors. Historically, the UK has not had a strong presence in heavy industry and power equipment manufacturing compared to other leading countries. Additionally, lower levels of investment, intense global competition, regulatory differences, and the need for international collaboration pose challenges for UK manufacturers.

8.3.4.1 UK Competitive advantage: key conclusions per technology

In the following table, we classify each technology as being either:

- A "**primary focus area**", highlighted in green, i.e. an area where the UK is expected to have a consolidated advantage;
- A "**further opportunity**", in yellow, i.e. an area where the UK could gain a competitive advantage from positioning itself as a potential early mover; or
- "**Lower potential**" in red, an area where the UK does not appear to have potential.

Table 8-11: Technologies classification based on UK competitive advantage

Tech family	Technology	Classification	Answer & justification/rationale
Storage	Thermal energy storage	Further opportunities	According to Ricardo's expert, with continued advancements in heating electrification and the involvement of domestic manufacturers, there are growth opportunities, albeit to a lesser extent compared to other sectors, considering the competition level globally and the well-established key players in North America and Asia.

Tech family	Technology	Classification	Answer & justification/rationale
DSR	V2G (vehicle-to-grid)	Further opportunities	With the emergence of relatively new technology and the UK Government's initiatives, such as Driving the Electric Revolution and Net Zero 2050 plans, coupled with the necessity of the involvement of various manufacturing sectors and regulatory bodies, the UK appears poised to tap into a significant domestic market. By leveraging this opportunity and making strategic and timely investments in this sector, UK manufacturers have the potential to dominate domestically and establish a strong global presence in the evolving landscape of smart systems according to the judgement of Ricardo's expert.
Transmission	Power electronics	Further opportunities	There are still ample opportunities in this growing market, with no dominant key players established yet. While UK manufacturers have not traditionally focused on this area, they can expand their global market share through strategic and timely investments in this sector (Source: Ricardo's expert's judgement).
	HVDC Converters	Lower potential	According to Ricardo's expert, UK manufacturers are falling behind their international counterparts. Therefore, exploring alternative opportunities and shifting focus towards new development areas may be more advantageous than entering this highly competitive market.

9. HEATING & COOLING

9.1 INTRODUCTION

This section explores possible future trends in the use of heat pumps in industry, residential, and commercial heating and cooling, which consist of air-to-air, air-to-water, and ground-source variants. The decision to exclusively focus on heat pumps is grounded in the findings of a preliminary assessment and the judgment of Ricardo's experts, who identified this technology as having the highest potential for the UK.

In general, heat pumps operate based on their ability to move heat from one source and transfer it to another using the refrigeration cycle. They may, in specific applications, reverse this cycle to provide cooling. They are categorised by the origin of their heat source: air, ground, or water, and by how they distribute the heat, either through air or liquid.

In specific terms:

- Air source heat pumps (ASHPS) harness heat from the surrounding air.
- Ground source heat pumps (GSHPS) extract heat from the ground.
- Water source heat pumps (WSHPS) draw heat from water sources.

How the heat is distributed further defines the heat pump system. This encompasses air-to-air (ATA), air-to-water (ATW), ground-to-water (GTW), ground-to-air (GTA), water-to-water (WTW), and water-to-air (WTA) systems. Each of these systems is capable of both heating and cooling.

Heat pumps are deployed across multiple static applications in the domestic market, the commercial/non-domestic market, and the industrial sector. The markets are substantially different, particularly in the industrial sector. The technology, applications, and operational ranges tend to be different. Much of the supply chain focuses on one or other of the areas, and the end drivers for heat pump adoption can vary.

However, most global and UK-wide data treats heat pumps as one market. The sector-specific data was sparse and could not be reliably compared with other data sets. The market size is dominated by domestic (83%, followed by 14% commercial and 3% industrial) and light commercial mass-produced equipment (Eunomia Research & Consulting Ltd , 2020), which perhaps explains this finding. This analysis, therefore, considers the market data as one common market and uses these sub-set markets to assess specific risks and opportunities.

This section presents the main global and UK market developments, encompassing current levels and future forecasts. The key players are introduced in terms of their market share and sector specialisation. Furthermore, the UK's main opportunities and focus areas are discussed, considering primary supply chain hurdles and manufacturing bottlenecks. This analysis relies on an extensive literature review and input from Ricardo's experts.

Table 9-1: In-scope technologies

Sector	Tech families	Technologies
Heating and cooling	Heat pumps	Heat pumps

9.1.1 Key takeaways

- Globally, the heat pump market is expected to reach nearly USD 350 billion by 2030, while the UK market is projected to amount to USD 3 billion.
- The worldwide growth in heat pump manufacturing is driven by financial incentives, policy support, and the push to transition away from fossil fuels, particularly in Europe, to reduce dependence on Russian gas.
- Most countries with manufacturing capacity prioritise satisfying domestic demand over exports, with China being the only exception, exporting a minor share mainly to Europe. This is influenced by logistical constraints related to heat pump dimensions and varying regulatory requirements for heat pumps across different countries and regions.
- The UK currently faces challenges in the global heat pump manufacturing sector due to intense competition from China, the US, and the EU, limiting its export potential. Technical obstacles, such as

high costs and logistical difficulties, further hinder international exports. Despite the unfavourable market conditions, the UK aims to meet domestic demand, focusing on mid-range commercial and non-domestic sectors for potential growth, aligning with sustainability goals.

- For the UK, becoming a global competitor in the heat pump market remains a significant challenge. Future success depends on increased manufacturing capacity, strategic investments, and technological advancements beyond 2030.

9.2 RQ1: POTENTIAL MARKET SIZE AND UK MARKET SHARES

9.2.1 Quantitative analysis at the sector level

9.2.1.1 Market size

This section presents the anticipated market size and the UK's market share within the advanced heating and cooking[35] industry. As of 2020, the global market size for advanced heating and cooking equipment reached an approximate valuation of USD 202 billion, with the United Kingdom contributing with a market size of around USD 2.1 billion.

Projections from the GEM-E3 model indicate an upward trajectory globally and within the UK across all scenarios. In the current policy scenario, the global market size is anticipated to reach USD 471 billion. In more ambitious scenarios aligning with stringent decarbonisation targets, the global market is projected to soar even higher, reaching USD 557 billion in the Below 2 ºC scenario and USD 565 billion in the Net Zero scenario.

Concerning the UK, the projections show a progression in market size across the scenarios. In the current policy scenario, the market size is projected to reach USD 7.9 billion, indicating an average annual growth of 4.5% over 2020-2050. In the Below 2 ºC scenario, aligning with higher decarbonisation efforts, the market size is expected to increase further to USD 10.2 billion. In the ambitious decarbonisation goals of the net-zero scenario, the UK's market size is anticipated to reach a commendable USD 10.5 billion in the Net Zero scenario.

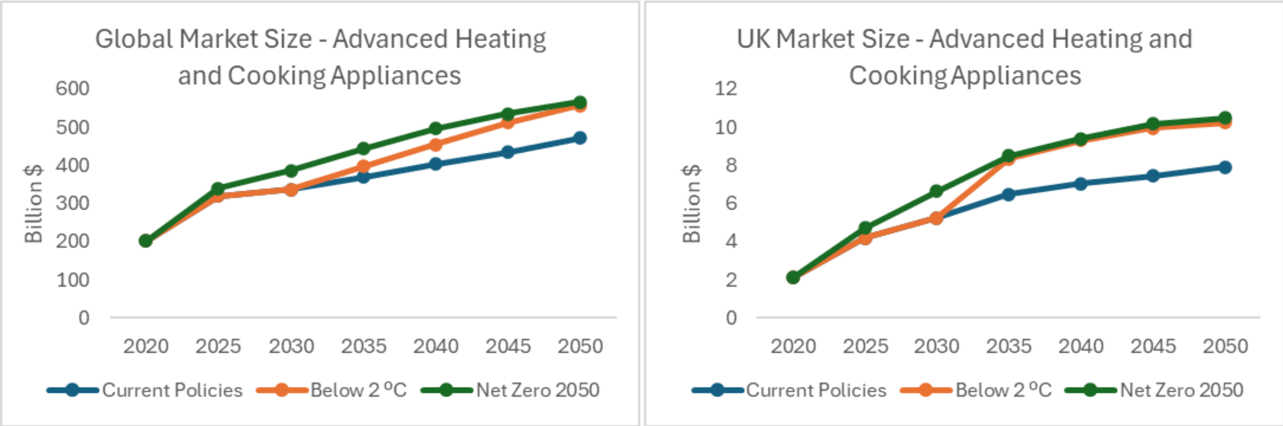
Table 9-2: Market size (demand in billion USD)

NGFS Scenario	Geography	2020	2025	2030	2035	2050
Current policies	Global market	202.0	319.3	337.4	368.9	471.0
	Domestic market	2.1	4.2	5.2	6.5	7.9
	Export market	199.9	315.1	332.2	362.4	463.1
Below 2 ºC	Global market	202.0	319.3	337.4	396.9	557.4
	Domestic market	2.1	4.2	5.2	8.3	10.2
	Export market	199.9	315.1	332.2	388.6	547.2
Net Zero 2050	Global market	202.0	340.1	386.8	443.9	565.8
	Domestic market	2.1	4.7	6.6	8.5	10.5
	Export market	199.9	335.3	380.2	435.4	555.3

Source: Ricardo analysis based on GEM-E3 outputs

[35] The GEM-E3 model sector which could better resemble “heating and cooling” is defined within the model as “advanced heating and cooking appliances” therefore, the terminology used in the quantitative assessment is “heating and cooking” when referring to this sector.

Figure 9-1: Global and UK market size – Demand



Source: Ricardo analysis based on GEM-E3 outputs

9.2.1.2 Market share

The UK's global market share stood at 1% in 2020, and nearly half of the domestic demand is covered by UK production. Over time, the UK's market share is projected to slightly increase by 0.6% in the current policy scenario to reach 1.6%. In the Below 2 ºC scenario and Net Zero scenario, the UK market share reaches 1.7%.

Table 9-3: UK share of each market

NGFS Scenario	Geography	2020	2025	2030	2035	2050
Current policies	Global market	1.0%	1.4%	1.5%	1.6%	1.6%
	Domestic market	44.9%	67.6%	60.1%	62.2%	61.6%
	Export market	0.5%	0.5%	0.5%	0.5%	0.5%
Below 2 ºC	Global market	1.0%	1.4%	1.5%	1.9%	1.7%
	Domestic market	44.9%	67.6%	60.1%	67.9%	65.3%
	Export market	0.5%	0.5%	0.5%	0.5%	0.5%
Net Zero 2050	Global market	1.0%	1.5%	1.6%	1.8%	1.7%
	Domestic market	44.9%	68.8%	64.8%	66.0%	65.6%
	Export market	0.5%	0.5%	0.5%	0.5%	0.5%

Source: Ricardo analysis based on GEM-E3 outputs

9.2.2 Qualitative analysis: market size

Globally, the global investment is anticipated to triple by 2030, reaching USD 350 billion (in real 2021 dollars), a figure comparable to the combined investment in global solar photovoltaic (PV) and wind power in 2021 (IEA, 2022c).

In the UK:

- Market size GBP 3 billion[36] by 2030 (PWC, 2021).
- GBP 38 million of planned investment from the industry sectors: GBP 15 million from Mitsubishi, GBP 3 million from Vaillant, GBP 20 million from Ideal Heating (IEA, 2023f).
- GBP 450 million public BUS launched in May 2022, offering grants of GBP 5,000 towards the cost of a heat pump (Guardian, 2023).
- GBP 30 million funding channelled through the Heat Pumps Investment Accelerator Competition from DESNZ (DESNZ, 2023).

[36] If the UK reaches 600k heat pump installations per year in 2030, PWC forecasts the market size will already have reached approximately 3 billion in Capex.

- GBP 192 million from the Defense Production Act funds, earmarked to support the manufacturing and deployment of electric heat pumps (Green Match, 2024).

In the current global landscape, heat pumps constitute approximately 10% of total sales in the residential heating equipment sector (IEA, 2023o). Notably, there is a surge in sales, particularly for air-to-water heat pumps in Europe, where they commonly substitute gas-fired boilers. Looking ahead to 2030, the proportion of heat pumps in heating equipment sales is expected to more than double in the Stated Policies Scenario and reach approximately one-third in the Additional Policies Scenario (IEA, 2023o). According to the IEA, the global installed capacity of heat pumps is expected to more than double by 2030 under the stated policies scenario, starting from approximately 1,000 gigawatts thermal (GWth) in 2022 (IEA, 2023o). In the additional pledges scenario, deployment levels are even more ambitious, targeting nearly 2,500 GWth by 2030 (IEA, 2023o). Despite this growth, challenges persist, particularly regarding high upfront costs. Additionally, the existing design of electricity tariffs and energy taxation in some countries continues to disadvantage heat pumps compared to fossil fuel boilers.

Success in increasing heat pump manufacturing will significantly rely on public support and business investments, as well as a higher number of installers and accelerated progress. To align with the Net Zero Emissions scenario, the global heat pump stock must expand to nearly 3,000 GWh by 2030, with over two-thirds of this capacity installed in advanced economies (IEA, 2023o).

Cost emerges as the primary determinant in the adoption of heat pumps, where the prevalence of air-to-air and air-to-water variants is primarily attributed to their lower upfront cost as compared to ground source variants (IEA, 2022c). Indeed, while air-to-air and air-to-water models have upfront cost ranges between USD 2,000-15,000 depending on the country, ground-source models can cost up to USD 38,000 and are rarely less expensive than USD 15,000 (IEA, 2022c) with similar ranges also reported in IRENA's report (2022).

It is anticipated that a third of the UK government's 2028 heat pump targets will be met from newly built properties (HM Government, 2021), supported by the proposed Future Homes Standard, with the remainder predominantly consisting of air source heat pumps retrofitted to existing stock. However, the adoption of heat pumps in the future will also be driven by factors such as the suitability of shared ground loops for challenging to decarbonise low-rise flats and the evolution of 5th-generation heat networks in cities, leading to a growing demand for small water-to-water heat pumps in the domestic market (Source: Ricardo's expert's judgement).

A crucial short- and mid-term indicator is the disclosure of manufacturing projects related to heat pumps to anticipate the expansion of manufacturing capacities. In 2023, such announcements have decelerated worldwide compared to 2022, with only a limited number reported since the year's commencement. The IEA attributes this slowdown to manufacturers' uncertainty about short-term demand, exacerbated by the reduction of installation incentives in key markets, leading to a decline in manufacturing project announcements (IEA, 2023l). The manufacturing projects revealed for heat pumps fulfil approximately 35% of the deployment requirements outlined in the Net Zero Emissions (NZE) Scenario for 2030 (IEA, 2023l). Despite this, expansion in heat pump manufacturing capacity typically aligns with near-term demand trends, allowing for rapid scaling when needed. Moreover, heat pumps are often part of a broader manufacturing portfolio, making their announcements less conspicuous, particularly outside of Europe, compared to other technologies. Like heat pump producers, component manufacturers also rarely publicise their expansion plans. Nonetheless, there is a prevailing confidence within the heat pump industry that it can scale up production rapidly enough to meet the anticipated 15-20% annual increase in demand (IEA, 2023f).

Regarding the geographical distribution of projected growth in heat pump manufacturing, the current scenario indicates less concentration than other net-zero technologies. However, announced additions to manufacturing capacity and dedicated investments suggest an impending shift, with a greater share anticipated for EU manufacturers and a slight decrease in the proportions held by China and the United States (IEA, 2023l). Europe leads in the number of announced heat pump projects, with 13 manufacturers in countries such as Germany, Poland, Belgium, Turkey, the United Kingdom, France, Sweden, Slovakia, and the Czech Republic revealing their concrete expansion plans (IEA, 2023f). Japanese companies contribute to approximately 25% of these announcements; Midea, a Chinese manufacturer, accounts for 2%, and the rest originate from European companies (IEA, 2023f). Nearly half of the total investments are directed towards expanding existing factories. The European Union is well-positioned to fulfil the rising demand for heat pumps due to its existing capacity, which can cater to 35-40% of the targeted heat pump sales by 2030, as previously mentioned.

Furthermore, a substantial pipeline of additional projects aligns aggregate EU production capacity with the anticipated demand in the additional policies scenario (IEA, 2023o). The disclosed projects also indicate a marginal broadening of the manufacturing base for heat pumps in building applications, where no single country or region is expected to contribute to more than 50% of the capacity (IEA, 2023l). Beyond these regions, notable changes are not anticipated.

Table 9-4: Global market size growth potential: RAG rating by technology

Technology	Application	Classification	Justification/rationale and key sources
Heat Pumps	General domestic and light commercial heat pumps; mass-market products	Medium	The largest share of the building heating market will subsequently carry the largest share of the electrification of heat policies.
	Larger scale heat pumps for commercial/industrial	Low	It has a much smaller share of the built environment but will also include energy centres of district heat networks. Industrial users have heat pumps of one of a larger array of decarbonisation of heat technologies.
	Water-to-water domestic heat pumps	Low	While the market is potentially large, it requires the uptake of not yet commonly used heat distribution methods: 5th-generation heat networks and shared ground loop arrays for the domestic market.

9.2.3 Qualitative analysis: UK market shares

9.2.3.1 Trade flows analysis

The table below shows the annual average of UK exports (2021-2022) for some selected Harmonised System (HS) subheading codes (provided by DESNZ) relating to components used in the manufacture of heating & cooling equipment and parts. These numbers can be interpreted as proxies of the UK's share of tradable export markets. The total average for this sector stands at 2.4% of the global tradable market.

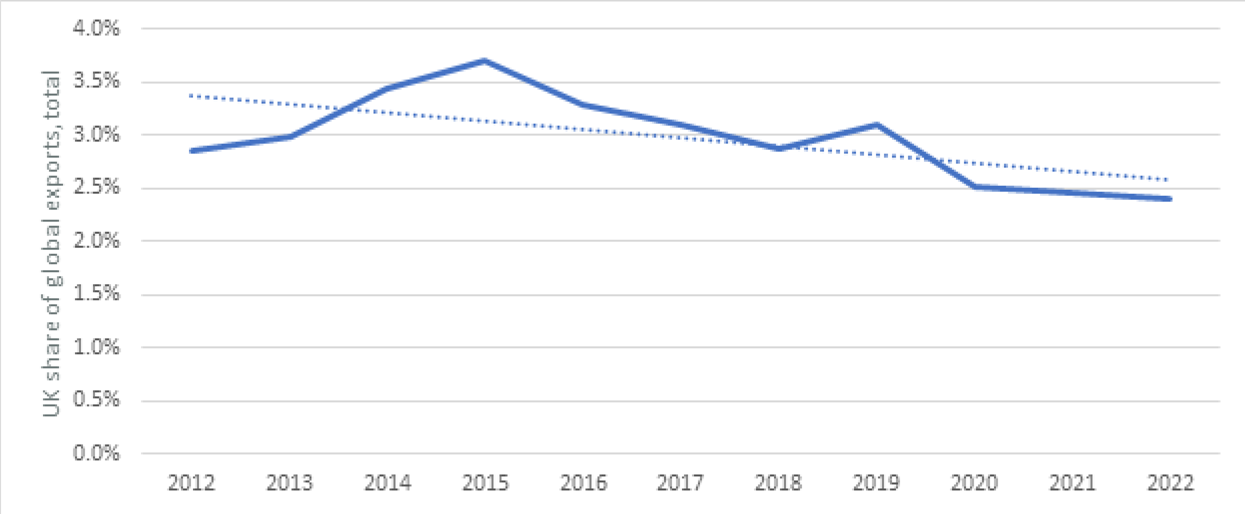
Table 9-5: UK share of global exports, selected HS subheadings, 2021-2022

Group	Subheading included in group	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
84 Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof	– 841581 Incorporating a refrigerating unit and a valve for reversal of the cooling/heat cycle (reversible heat pumps) – 841861 Other refrigerating or freezing equipment; heat pumps – 841869 Refrigerators, freezers and other refrigerating or freezing equipment, electric or other; heat pumps - others – 841899 Refrigerators, freezers and other refrigerating or freezing equipment, electric or other; heat pumps - parts – 841919 Instantaneous or storage water heaters, non-electric – 841950 Heat-exchange units	USD 796M	2.0%
90 Optical, photographic, cinematographic, measuring, checking, precision, medical or surgical instruments and apparatus; parts and accessories thereof	– 902810 Gas meters – 902820 Liquid meters – 902830 Electricity meters – 902890 Gas, liquid or electricity supply or production meters, including calibrating meters therefor - Parts and accessories – 903190 Measuring or checking instruments, appliances and machines, not specified or included elsewhere - Parts and accessories – 903210 Thermostats – 903289 Other instruments and apparatus	USD 1,275M	2.9%
Total		**USD 2,071M**	**2.4%**

Source: Ricardo elaboration on UN Comtrade data

The figure below shows a downward trend in the UK's share of global exports for the total HS codes analysed, from a max of 3.7% in 2015 to 2.4% in 2022.

Figure 9-2: UK share of global exports, 2012-2022



Source: Ricardo elaboration on UN Comtrade data

9.2.3.2 Qualitative analysis: market shares (discussion at worldwide level)

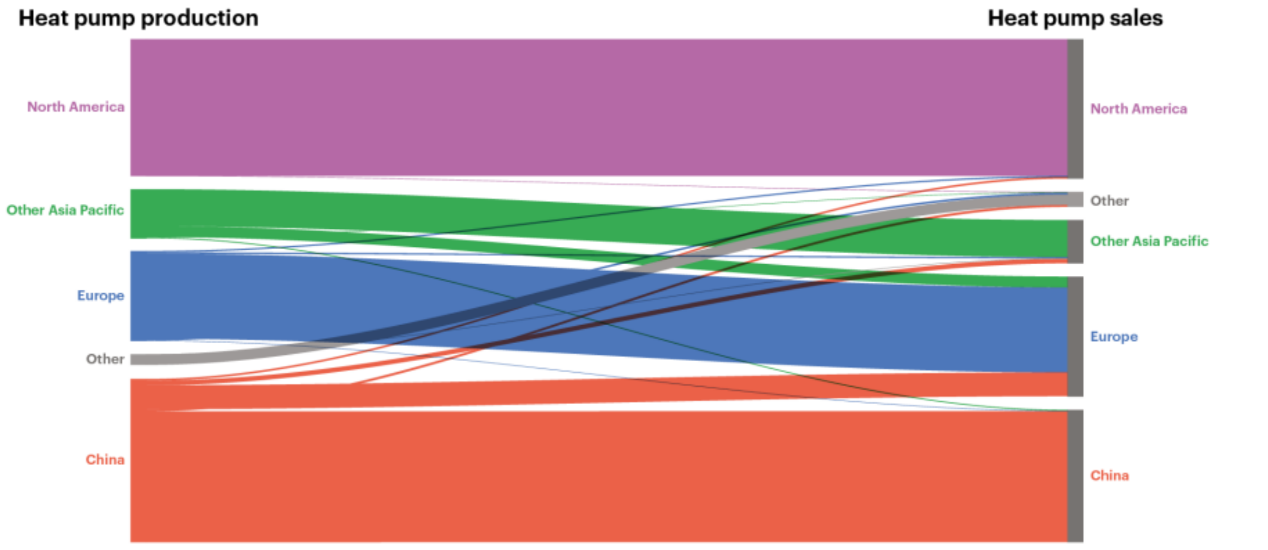
The global market for heat pumps is rapidly increasing. Sales rose 11% globally in 2022 and heat pumps are expected to significantly increase their market share in heating equipment sales by 2030 (IEA, 2023o). The initial popularity of heat pumps, especially in North America, was driven by their reversible nature for heating and cooling; however, the current momentum is fuelled by the growing demand for transition heating methods (source: Ricardo's expert's judgement). Global heat pump manufacturing capacity (excluding air conditioners) amounted to around 120 GWth at the end of 2021 (IEA, 2023f). As of the same year, Europe and North America primarily imported heat pumps for heating and heating/cooling, whereas China, Japan, and Korea served as net exporters (IEA, 2023f).

In 2022, the market had already considerably expanded compared to 2021. Approximately 3 million heat pumps were installed in European buildings, marking a nearly 40% rise from the preceding year and an assessed value of the European heat pump market of approximately USD 14 billion (IEA, 2023n). In November of that year, many manufacturers had already committed to increasing their heat pump production capacity, with investments exceeding EUR 4 billion (IEA, 2023n). According to the announced policy scenario, more than 330 GW of heat pumps will be deployed by 2030 (IEA, 2023o).

However, while the manufacturing base for heat pumps for building applications will broaden slightly, no country or region will account for more than 50% of capacity (IEA, 2023l). These expected increases are evident in the two figures below.

However, contrary to other net-zero technologies (e.g., solar panels), heat pumps are not widely traded except for some specific components. This is mainly due to their big dimensions and weight, which makes them very costly to transport and keeps exports at very low levels. Indeed, the share of inter-regional trade in global manufacturing is less than 10% for heat pumps, compared with nearly 60% for solar PV (IEA, 2023f). Heat pumps must also be adapted to regional contexts and national regulations concerning recyclability, efficiency, voltage, safety and refrigerants, which can vary widely between different countries or even within a country (IRENA, 2022). Therefore, they are usually only suitable for the market where they are produced (IEA, 2023f). This emerges clearly from Figure 9-3, which shows the international trade flows of heat pumps. Most heat pumps are sold in the same region where they are produced, except for minor exceptions in the European market with imports from China and the Asia Pacific region.

Figure 9-3: Global inter-regional trade flows of heat pumps, 2021



Notes: HP = heat pumps. Normalised values based on gigawatts of thermal output. heat pump sales and production are based on market data and IEA modelling estimates. trade flows are based on the UN Comtrade database (harmonised system product code: 841861). Code 841861 refers to "heat pumps other than air conditioning machines of heading no. 8415" (i.e. it exclusively refers to heating equipment), and it is therefore used as a proxy for "mainly heating heat pumps". Several additional UN Comtrade codes are associated with heat pump technology: code 8415 for air conditioners, code 841581 for reversible air-to-air heat pumps, and code 841869 for "refrigerating or freezing equipment, heat pumps other than compression type units whose condensers are heat exchangers". However, those groupings include both cooling and heating-oriented equipment.

Sources: IEA analysis based on UN (2022a) and company announcements.

The heat pump market is regionally compartmentalised. China and North America import very few units, while Chinese imports account for around 20% of European sales.

(IEA, 2023).

Currently, heat pumps contribute to over 1,000 gigawatts (GW) of capacity in residential and non-residential buildings, with nearly half of this capacity installed in North America (IEA, 2022c). Despite this, the highest penetration of heat pumps is currently observed in the coldest regions of Europe. In Norway, they fulfil 60% of the total heating needs in buildings, while in Sweden and Finland, the figure exceeds 40%, primarily due to enduring policy support (IEA, 2022c). As reported by the IEA, most of the worldwide heat pump market is controlled by companies headquartered in Japan and China, collectively constituting almost 70% of the market share (IEA, 2023n). Although the top five global manufacturers are in the Asia Pacific region, only around half of their production capacity is based there (IEA, 2023n).

Currently, supply chains are facing challenges, especially in procuring vital components such as chips. It is also worth noting that over 90% of compressors, a crucial component, are currently imported from the Asian market (IEA, 2023f). Future bottlenecks in components, notably semiconductors and compressors, could emerge, especially if rapid changes to heat pump and refrigerant standards disrupt supply chains. While compressors are needed in many industries, some heat pump compressors require specific designs for certain temperature ranges and refrigerants. This is why some manufacturers responsible for producing over 30% of heat pumps worldwide in 2021 already produce their own compressors (IEA, 2023f). Thus, harmonisation of relevant international standards will be essential in avoiding bottlenecks and slowdowns in heat pump production chains. Conversely, policies to support domestic manufacturing of such components could lower transportation costs, which currently constitute 6-14% of total heat pump costs, and faster heat pump production (IEA, 2023f).

In terms of sectors, the residential one dominates the heat pump market, accounting for a significant share of the total market size (Green Match, 2024). This is primarily due to rapid urbanisation, increasing demand for energy-efficient products, policy support, and public financial incentives. In terms of technology, the air-to-air reversible heat pump market exhibits greater dynamism and is predominantly driven by Asian countries engaged in global exports (IEA, 2023f).

9.2.3.3 Qualitative analysis: UK market shares

The heat pump market in the UK is undergoing significant developments, driven by the government's ambitious targets and financial incentives. The UK government aims to have 600,000 heat pumps installed annually by 2028, aligning with its commitment to transition away from traditional gas boilers (HM Government, 2021). However, in 2021, only 55,000 heat pumps were fitted, showcasing a substantial gap between current installations and the government's target. In contrast, 1.5 million gas boilers were installed in the same year (Guardian, 2023).

To encourage the adoption of heat pumps, the GBP 450 million Boiler Upgrade Scheme (BUS) was launched in May 2022, offering grants of GBP 5,000 towards the cost of a domestic heat pump (Guardian, 2023). Despite the initiative, the response was initially tepid, with only 11,996 vouchers issued out of the 30,000 available. Of these, 9,981 vouchers were redeemed, amounting to GBP 50.16 million of the GBP 150 million in grants annually for the next three years (Guardian, 2023). As of December 2023, the number of vouchers issued through the BUS increased to 27.041, with 19.064 redeemed (DESNZ, 2024). Non-domestic heat pumps have been indirectly incentivised through schemes such as the Public Sector Decarbonisation Fund and the Green Heat Network Fund, although the split of such funding packages spent on heat pumps cannot be abstracted.

Moreover, in April 2023, UK DESNZ opened a call for grant application funding of up to GBP 15 million dedicated to investments in the manufacture of heat pumps and strategically important components (DESNZ, 2023). Named the Heat Pumps Investment Accelerator Competition (HPIAC), the available fund amounts to GBP 30 million and is intended to accelerate the production of heat pumps and make the technology widely available across the UK. This initiative further confirms the commitment to overcoming market challenges and promoting sustainable heating solutions.

Another government effort to boost the heat pump market in the UK is the allocation of GBP 192 million from the Defense Production Act funds, earmarked to support the manufacturing and deployment of electric heat pumps (Green Match, 2024).

Finally, as announced in March 2024, the Green Industries Growth Accelerator (GIGA) could positively affect industrial heat pump manufacturing. Indeed, among the technologies the fund targets, there should be compressor packages (DESNZ, 2024), a component that can be used in industrial heat pumps. While commercial ones require lower-pressure hermetically sealed compressors, industrial heat pumps deal with higher-pressure operations. In this sense, according to the judgement of Ricardo’s expert, supporting the manufacturing of compressors for hydrogen production could generate cross-sectoral benefits for manufacturing industrial heat pumps. However, despite this positive effect, its expected impact on the market is not straightforward. Hence, a satisfying assessment of GIGA's impact on heat pump manufacturing is difficult to deliver at the time of publication of this report.

At the industry level, many international companies have decided to enhance their manufacturing capabilities in the UK, constituting excellent opportunities for market expansion. Some examples provided by the UK Department for Energy Security and Net Zero and the Department for Business and Trade (DESNZ & DBT, 2023) are:

- Mitsubishi Electric has invested GBP 15.3 million in its Livingston facility to increase productivity, efficiency, and research and development (R&D) capabilities.
- Ideal Heating, which focuses on low-carbon heating, has invested GBP 16 million in its Hull factory to support production and storage capacity expansion.
- Octopus Energy has also invested strategically, injecting GBP 10 million into the UK's first heat pump R&D and training centre in Slough. Additionally, Octopus Energy has invested in Renewable Energy Devices, a Northern Irish heat pump manufacturer, with plans to scale production capacity to over 12,000 heat pumps annually, creating 100 new green jobs in Northern Ireland.

According to the judgement of Ricardo’s expert, among the companies in the UK's heat pump market, Star Refrigeration Kensa and Clade emerge as the only significant players with UK manufacturing bases. Star Refrigeration manufactures many net-zero technologies; hence, its turnover does not indicate the size of the heat pump market. On the other hand, Clade and Kensa exclusively focused on heat pumps. Clade has an estimated annual turnover of GBP 22.5 million in 2022 (Global Database, 2022), while Kensa has GBP 7 million (Cooling Poste, 2021), which are the main indicators of the UK’s current heat pump market size.

9.2.3.4 UK market shares: summary of qualitative analysis

External considerations: Considering the IEA’s projections for 2030 (IEA, 2023o), it becomes evident that China, the United States, and the European Union will collectively control nearly three-quarters of the heat pump supply chain, boasting robust manufacturing capabilities. Exporting heat pumps proves inconvenient due to size, regulatory frameworks, and varied contextual requirements. Furthermore, as discussed earlier, most countries produce their own heat pumps.

Internal considerations: In the United Kingdom, the Boiler Upgrade Scheme underwent revisions in October 2023, augmenting the grants to GBP 7,500, aiming to subsidise a portion of the expenses associated with transitioning from fossil fuel heating systems to air-source or ground source heat pumps (IEA, 2023l). Despite this, criticism has arisen from manufacturers due to concerns that easing the terms of a fossil fuel boiler phase-out might undermine confidence in heat pumps, creating heightened uncertainty for investors and consumers. These developments suggest that potential future trends in the UK market share for heat pumps may be influenced by the evolving policy landscape and industry sentiments.

Considering both external and internal factors and acknowledging the UK's strengths in alternative renewable energy sources such as Wind and Tidal, it is improbable that the UK will surpass a few percentage points of the global manufacturing capacity for heat pumps by 2030. The dominance of established players in the industry, logistical challenges, and the UK's focus on other renewable energy sectors indicate a limited share in the manufacturing landscape for heat pumps.

However, mass-market standardised products can be easily exported, with size not being a significant constraint. This aligns with the high penetration of existing European air conditioning markets in Asian regions, showcasing the adaptability of standardised products. Therefore, according to the judgement of Ricardo's expert, these products, with a certain amount of market-specific refinement, could find a global market, satisfying the needs of domestic and small commercial sectors. On the other hand, the water-to-water heat pump segment, especially those designed for ground source and 5th gen heat networks, presents a more specialised challenge. Their integration into dwellings depends on country-specific space planning, a consideration that adds complexity and uniqueness to each market. While this specialised segment may not achieve the scale of mass-market products, its characteristics make it an interesting area to study and adapt to in certain regions.

In the table below, we assess whether there is potential for the UK to capture a market share higher than, in line with, or below the sector average indicated in the qualitative analysis above.

Table 9-6: Technologies that have the potential to attract significantly higher/lower market shares compared to the sector average

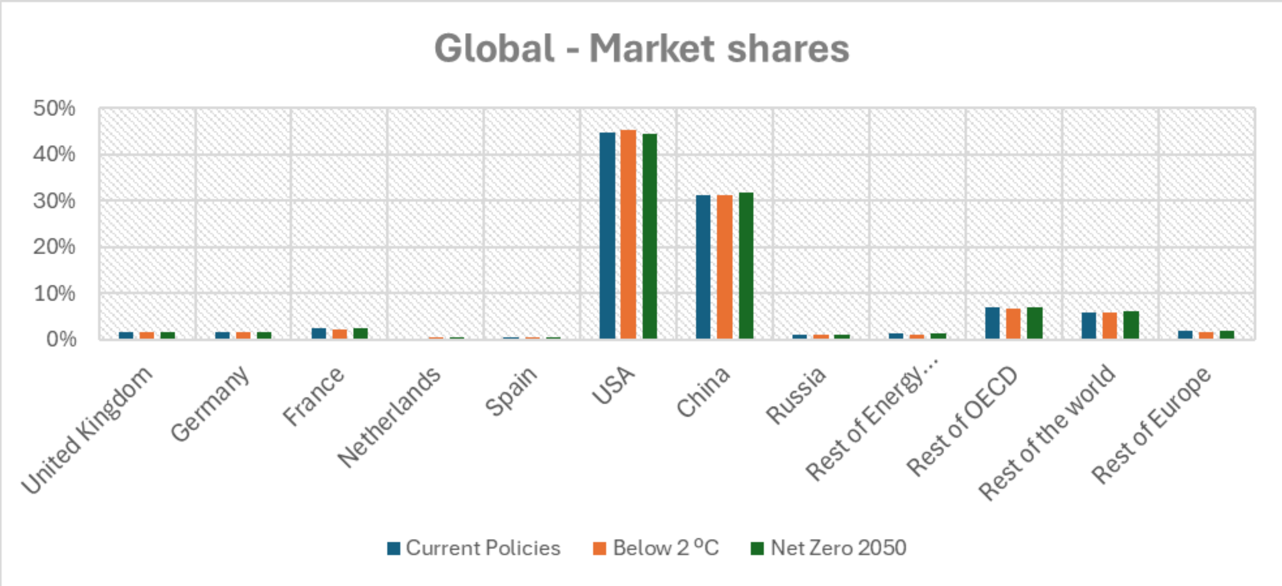
Tech family	Technology	Rating	Justification/rationale and key sources
Heat Pumps	Heat Pumps	Average	Areas of the UK domestic market where mass-market products are not appropriate to facilitate UK manufacturers with sufficient technological advancement in more niche areas (e.g. natural refrigerant) heat pumps for non-domestic and industrial (Clade and Star) or Kensa Shoebox product that capitalises on the lower space availability of UK dwellings which used combi boilers (Source: Ricardo's expert's judgement). Speculatively, the UK achieves a faster roll-out of heat pumps than other localised markets, providing export opportunities where their heating system design and regulations are similar. Conversely, the mass-market heat pump market is dominated by global-sized multinationals with years of experience typically developed in the air conditioning side of the market. Thus, the UK market share is likely to be minimal.

9.3 RQ2: UK COMPETITIVE ADVANTAGE

9.3.1 Quantitative analysis at the sector level

The global production of heating and cooking equipment is widespread, with numerous countries contributing to this market. China and the USA have emerged as the major global producers for both domestic and international markets. Japan, South Korea, and Turkey manufacturers also contribute to producing advanced heating and cooking appliances. The United Kingdom has a significant number of companies that produce or contribute (intermediate inputs) to the production of heating and cooking appliances but are not comparable with those in China and the USA (in terms of sales).

Figure 9-4: Market shares in 2050



Source: Ricardo analysis based on GEM-E3 outputs

9.3.2 Key drivers of competitive advantage

Among the key drivers affecting the potential expansion of the heat pump manufacturing market in the UK are geopolitical considerations, technical and cost constraints on exports, policy and financial support and intense competition worldwide. Indeed, while the geopolitical context might be favourable due to an increased need to reduce reliance on Russian gas supplies and accelerate the green transition – supported by extensive financial incentives – heat pumps face logistical hurdles – as explained above – that significantly restrict their export potential. Moreover, high upfront costs and a lack of skilled labour further restrict future market development possibilities.

For barriers and enablers, a red/amber/green (RAG) rating is provided to reflect their importance according to the process and guiding matrix outlined in Sections 3.2 and 3.3.

Table 9-7: Key drivers of competitive advantage - Enablers

Category	Driver	Discussion	RAG
Enablers	Decreasing dependency on Russian gas (Europe)	In Europe, a significant catalyst for the escalating manufacturing capacity of heat pumps stems from the imperative to eliminate reliance on Russian gas for heating. The urgency is underscored by the projection that annual heat pump installations in the European Union will surge to nearly 7 million by 2030, a considerable rise from the 2 million recorded in 2021 (IEA, 2022c). This swift expansion in heat pump adoption translates into a substantial reduction in gas consumption, amounting to 7 billion cubic meters (bcm) in 2025 and 21 bcm in 2030. This reduction roughly equals 15% of the European Union's gas imports from Russia in 2021.	
	Increasing investments globally	Internationally, there is extensive backing for the augmentation of investments in heat pump production. The global investment is anticipated to triple by 2030, reaching USD 350 billion in real 2021 dollars (IEA, 2022c). Further confirming this trend, the global investment in start-ups and scale-ups focused on heat pumps experienced a nearly sixfold surge between 2016 and 2021. Regarding technological innovation, as measured by patent counts for heat pumps, there has been a more than twofold increase from 2005-09 to 2015-19 (IEA, 2022c). Notably, China and Japan contribute half of all patented inventions in this domain.	

Category	Driver	Discussion	RAG
	Expanding policy and financial support to phase out fossil fuels.	UK Heat and Buildings Strategy sets a relatively rapid pace for uptake in the UK domestic market, which provides impetus and a likely market for UK innovators in this market sector. In over 30 countries, financial support is available for installing heat pumps, with some nations, such as Poland, extending additional assistance for low-income households (IEA, 2022c) and the UK's BUS scheme. Similarly, certain countries, like Canada, incentivise high-efficiency models. The attractiveness of heat pumps is further enhanced by energy tax reforms and the equitable application of CO2 penalties across household heating fuels and electricity, resulting in reduced running costs and increased financial appeal.	
	Relative levels of regulatory alignment with likely export markets	Areas with similar climates and closer geographic reach, i.e. Northern / Central Europe, are primarily governed by harmonised EU standards for heat pump manufacture (does not necessarily apply to installation or the downstream hydraulic systems, which will have wider country-by-country variations)	
	Existing boiler supply chain have the ability to re-focus	Existing UK boiler manufacturers understand the UK heating market well and achieve some export markets (mostly Ireland). Transition to heat pump manufacture is being actively encouraged. (Relevant to the domestic market only)	
Barriers	High upfront costs	The expansion of global manufacturing capacity faces a significant barrier in the form of high upfront costs. This is particularly evident in low-income households, where heat pump ownership remains lower due to persistent upfront cost barriers, a prevalent issue in various parts of Europe (IEA, 2023o). The higher initial expenses associated with heat pumps, both in terms of purchase and installation, present a considerable challenge to widespread adoption. For instance, the cost of acquiring and installing a domestic air-to-air heat pump typically ranges between USD3,000 and USD 6,000 (IEA, 2022c) , and the mean install cost of a domestic air-to-water heat pump in the UK is GBP 13,000 (DESNZ, 2024). Even the most affordable air-to-water models, when considering modifications to existing radiator systems, are two to four times more expensive than conventional natural gas boilers in most major heating markets (DESNZ, 2024). This disparity in upfront costs and additional retrofit costs compared to traditional boilers impedes the broader expansion of global manufacturing capacity for heat pumps. Additionally, while the UK's average costs for ground-based heat pumps align with global averages, its average prices for air-to-air and air-to-water heat pumps are on the higher end of the spectrum and significantly more expensive than condensing gas boilers compared to other countries (IEA, 2022c) (IRENA, 2022). These high prices do not support the expansion of the UK market.	
	Shortages of qualified installers	The shortage of qualified installers poses a significant barrier to global heat pump manufacturing expansion. The IEA predicts a fourfold increase in demand for full-time installers by 2030 (IEA, 2022c). European companies in the heat pump sector are currently struggling with recruitment challenges, particularly in securing skilled electricians, technicians, engineers, and construction workers (European Heat Pump Association, 2023).	
	Manufacturing constraints and supply chain vulnerabilities	Over the past two years, supply chain constraints have impacted the production of heat pumps and crucial components, particularly semiconductors and chipsets. Furthermore, the escalating prices of essential materials such as copper, steel, aluminium, silver for welding, and specific plastics contribute to increased costs.	
	Lack of public knowledge about heat pumps' benefits	The general public's limited awareness of heat pump benefits presents a significant barrier to the global expansion of manufacturing capacity for this technology (IEA, 2022c). The lack of knowledge about the environmental and economic sustainability advantages associated with heat pumps results in consumers being frequently uninformed and not prioritising these systems.	

Category	Driver	Discussion	RAG
	Heat pumps may not be the best-suited technology for export markets, other than in mass-market standardised applications	Exporting heat pumps has challenges due to their size, differing regulatory frameworks and styles of existing heating systems, and climatic variances. This favours the export of mass-market standardised units. This segment of the heat pump market is relatively mature; innovations continue, but those with existing supply chains at scale are better placed to take advantage.	
	UK Electricity Market has a higher retail power cost than a number of European competitors	Exporting a successful domestic market would be the most likely route to success. The relatively high power price in the UK creates a higher barrier to the UK's home market that other European competitors will not face.	

9.3.3 Geographical benchmarking

Table 9-8: Major UK competitors globally

Country	Answer
US	As in other regions, the market for heat pumps in North America is growing rapidly. In 2021, it accounted for about 30% of global heat pump manufacturing capacity, mainly in the United States, and enough to cover domestic demand (IEA, 2023f). Imports to the United States were limited, and foreign companies accounted for about 70% of domestic production (IEA, 2023f). The United States plays a significant role in international heat pump production, contributing approximately 25% of the world's manufacturing capacity (IEA, 2022c). The U.S. market is primarily influenced by policy incentives, driving growth and development in the sector (Clean Energy Technology Observatory, 2022). Despite a slight decline of around 10% in heat pump shipments by mid-2023 compared to the previous year, the U.S. market remains resilient, outperforming fossil fuel alternatives such as natural gas furnaces, which experienced a more substantial decrease of around 25% (IEA, 2023l). The anticipation of rebates for heat pumps under the Inflation Reduction Act (IRA) might be influencing the current slowdown as manufacturers await the introduction of the scheme before increasing production (IEA, 2023l).
EU	Europe accounts for 15% of global manufacturing capacity, with about 170 heat pump factories, including the UK (IEA, 2023f). European-based companies contribute 10% of global heat pump capacity, leading in manufacturing hydronic systems, air-water, groundwater, and brine-water heat pumps. However, about half of the manufacturing capacity within the region is owned by companies with headquarters elsewhere (IEA, 2023f). It is important to note that heat pump manufacturers primarily assemble components, most of which they purchase from other companies based in Europe or Asia (Clean Energy Technology Observatory, 2022). The EU has witnessed substantial growth in the heat pump market, especially in larger heat pumps for the commercial and district heating and cooling segments, mainly driven by a combination of policy and market drivers (Clean Energy Technology Observatory, 2022), experiencing more than a twofold increase in size since 2019 with record-high annual growth rates surpassing 35% in 2021 and 2022 (IEA, 2023l). The EU-27 has achieved a noteworthy milestone as it currently produces between 60%-73% of its internal heat pump demand (European Commission , 2023). This implies that most of the heat pumps needed within the European Union are manufactured within the region itself, most notably in Germany and Italy (Clean Energy Technology Observatory, 2022). Despite this achievement, early data from 2023 suggests a slowdown, particularly in major markets like Italy, Finland, and Poland, raising concerns about potential overcapacity in the short term (IEA, 2023l). According to the European Heat Pump Association, heat pump sales in 14 European countries fell by around 5% overall in 2023 compared to 2022, from 2.77 million to 2.64 million (EHPA, 2024). The EU faces challenges, notably in Germany, where delayed investment decisions persist as recently introduced increased financial incentives will only be available in 2024, and there is a shortage of skilled installers (EHPA, 2024). Italy, the other major market, is also experiencing a slowdown due to the downgrading of the Superbonus 110 tax credit scheme – from 110% to 90% – and uncertainties surrounding tax credit transfers (EHPA, 2024). Despite intra-regional trade being common, a surge in demand in 2021 led to a significant increase in heat pump imports from outside Europe, primarily from Asian countries. While the current shortages of labour and an increasing share of extra-EU imports pose a potential risk to the sector's resilience

Country	Answer
	(European Commission, 2023), Europe's energy crisis, policy support, and ambitious targets for heat pumps are attracting investments in the order of hundreds of millions of euros in European countries (IEA, 2022c)[37]. Announced expansion plans in the region suggest that manufacturing capacity in Europe will keep pace with the expected medium-term growth in demand (IEA, 2023f). REPowerEU aims to double the current heat pump deployment rate, targeting the installation of 30 million new heat pump units between 2022 and 2030 (IEA, 2023f).
China	Currently, China is the global leading manufacturer and exporter of heat pumps, boasting the largest production capacity and workforce in the sector (IEA, 2023o). Ambitious plans for further scale-up characterise the country's technology manufacturing landscape. China has approximately 55,000 workers in this field and manufactures around 40% of the world's heat pumps (IEA, 2022c). In 2021, China experienced a nearly doubled export volume of heat pumps compared to 2020, with Europe being the primary destination, which makes China a key supplier in this market (IEA, 2023h). However, most heat pump manufacturing by companies based in China is geared toward meeting domestic demand (IEA, 2023f). This production is concentrated in four provinces—Shandong, Anhui, Zhejiang, and Guangdong—where around two-thirds of China's global heat pump manufacturing capacity is located (IEA, 2023f). The country's manufacturing capacity continually expands, fuelled by domestic and international demand. The synergies with the air-conditioner industry contribute to this growth, and each year, new players emerge in the Chinese heat pump manufacturing landscape (IEA, 2023f). China is actively promoting the adoption of more efficient models and facilitating exports by aligning its energy efficiency standards and testing practices with international benchmarks (IEA, 2023f).
Japan	In Japan, the heat pump manufacturing sector faces a notable shift, particularly in the heat pump water heater segment, which has been the fastest-growing market in recent years. Japan's market is focused on reversible units, consisting of around 99% of its residential heat pump production (IRENA, 2022). However, as of September 2023, sales in this segment declined by almost 10% compared to the same period in 2022 (IEA, 2023l). The primary driver behind this recent trend appears to be an increase in material costs, subsequently elevating equipment costs (IEA, 2023l). This downturn is noteworthy, given the segment's seven consecutive years of positive market growth, averaging an 8% year-on-year increase.

In 2021, the global heat pump industry saw a significant presence from the top four manufacturers, contributing around 40% to total capacity (IEA, 2023f). China emerged as the only notable heat pump exporter, albeit on a relatively small scale compared to its internal production, while other manufacturers focused on local markets. Shared components, including fans, pumps, tanks, expansion valves, heat exchangers, and compressors, across various heating equipment and industries increased the demand for refrigeration cycle components. Geographically, China, Japan and Korea served as net heat pump exporters, while North America and Europe acted as net importers (IEA, 2023f). European manufacturers lead in monoblocs within air-water heat pumps, while Asian manufacturers lead in split systems (Clean Energy Technology Observatory, 2022).

Though evenly distributed globally, manufacturing capacity is expected to remain dominated by eastern Asian companies. Despite projected growth in Europe and North America, the market's concentration is unlikely to change significantly before 2030, based on current trends and investment plans (IEA, 2023f). There is a concern that major air-conditioner manufacturers, particularly those based in Asia and North America, may shift their focus towards capturing the EU heat pump market due to their ability to produce equipment at a low cost (Clean Energy Technology Observatory, 2022). This trend appears to be already underway in reversible air-air heat pumps, where the EU relies on imports, and in the growing air conditioner market in Europe (Clean Energy Technology Observatory, 2022). However, other types of heat pumps, which depend more on the

[37] Bosch investing more than a USD 100 million in a heat pump factory in Portugal by 2026, and Groupe Atlantic announcing plans for an investment of more than EUR 150 million in France.
From (Clean Energy Technology Observatory, 2022):
'— Saunier Duval (France) investing EUR 10 million to increase its production capacity from 35 000 heat pumps in 2020 to 130 000 units by 2023;
— Vaillant (Germany and France) doubling its production capacity, including EUR 120 million investment in Slovakia;
— Daikin investing in new lines to produce 20 000 units by 2021, with further expansion planned
– notably in Poland, where a new EUR 300 million factory is to open in 2024, employing 1 000 people by 2025;
— Stiebel Eltron aiming to double its heat pump production capacity by 2026, investing EUR 120 million and creating 400 new jobs;
— Bosch planning to invest EUR 355 million in heat pumps by mid-2025;
— Viessmann announcing investment of EUR 1 billion over the next three years in heat pumps and other solutions, including a EUR 200 million investment in propane-based heat pump manufacturing in Poland;
— Panasonic announcing investment of EUR 145 million at its factory in the Czech Republic to increase capacity to 500 000 air-water units by March 2026;
— Hoval investing EUR 40 million in Slovakia.' (P. 36-37)

expertise and recommendations of local installers, may be less susceptible to this trend. Additionally, competition is expected from other sectors, such as Chinese manufacturers of large solar collectors expanding into heating, with half of them offering stand-alone heat pumps and solar heat pump systems (Clean Energy Technology Observatory, 2022).

9.3.3.1 Considerations regarding potential bottlenecks in key components' supply chain

Key manufacturers like Mitsubishi, Carrier, and Daikin, accounting for over 30% of the 2021 production, actively produce their components, such as heat pump compressors (IEA, 2023f). Accounting for roughly a quarter of a heat pump's total cost, compressors present challenges due to their specialised design and manufacturing requirements. The location of manufacturing sites is primarily influenced by the proximity of chemical feedstock and the availability of an affordable and specialised labour force (IEA, 2023f).

Compressor design and manufacturing represent a specialised activity, with a concentration of global suppliers that includes Mitsubishi Electric (Thailand) and several European entities such as Danfoss (Denmark and France), Bitzer, and GEA (Germany), along with Tecumseh (France) and Emerson Copeland (Belgium and Northern Ireland) (Clean Energy Technology Observatory, 2022). Thus, while Europe imports a substantial portion of compressors for air-air heat pumps, those needed for air-water and ground-source heat pumps are predominantly manufactured within the region (IEA, 2023f). Some prominent Asian electronics manufacturers, like Hitachi and Daikin in Japan, produce their own compressors. Ziehl-Abegg (Germany) and ebm-papst are the primary manufacturers of fans, while the pump market is largely dominated by Wilo (Germany) and Grundfos (Denmark) (Clean Energy Technology Observatory, 2022).

The industry's main challenges include semiconductor shortages affecting control panels, electric pumps, and fans (IEA, 2023f), which are worsened by the industry's intricate value chains (Clean Energy Technology Observatory, 2022). However, some manufacturers expressed confidence in overcoming these shortages within the next 12-18 months, potentially leading to a 20% increase in output if components become available (IEA, 2023f).

Bottlenecks in the global heat pump industry extend to refrigerant manufacturing, which is essential in heat pump production, concentrated in China and North America. Key producers are Honeywell International, DowDuPont and Chemours Company (US), Dongyue Group and Sinochem Group (China), and Daikin (Japan). Other minor but relevant manufacturers include SRF (India) and Koura (Mexico). EU contributors are Arkema (France) and the Linde Group (Germany). Although hydrofluorocarbon refrigerants, particularly R410A, dominate the heat pumps market, a notable shift towards alternatives with lower global warming potentials, such as R32, and natural refrigerants like propane is happening (IEA, 2023f).

Lastly, key raw materials and components suppliers include ABB, ArcelorMittal, Aviva Metals, Fuji Electric Co., General Electric, Hitachi, MetalTek, Mitsubishi, Panasonic, Schneider Electric, and Siemens. Elastomer manufacturers include BASF (Germany), Dow (United States), and JSR (Japan) (Clean Energy Technology Observatory, 2022). CAREL (Italy) is a prominent producer of 34 electronic controllers, including sensors, electronic expansion valves, touchscreen displays, and apps.

9.3.4 UK Competitive advantage – qualitative analysis

As of the present scenario, the UK faces a competitive disadvantage in the heat pump manufacturing sector compared to other key market players. Several factors contribute to this outlook.

Table 9-9: UK competitive disadvantages

Disadvantage	Description
Strong competitors	Firstly, the global heat pump market is dominated by strong competitors, primarily China, the US, and the EU, which already manufacture the majority of heat pumps sold worldwide. This makes it challenging for the UK to establish a significant export market. Moreover, most heat pump-producing countries primarily focus on meeting their internal demand. Even the EU, which is the only importing region, already produces over 60% of its heat pump demand internally, with the rest mainly supplied by China, further limiting the UK's potential market share. Additionally, the EU's investments in heat pump manufacturing, channelled through programmes like REPowerEU and FitFor55, suggest a decreasing reliance on imports in the future, further limiting opportunities for the UK. Another missed opportunity for the UK's heat pump export market is North European countries, which are geographically close and among the primary heat pump users globally. These countries are

Disadvantage	Description
	already well supplied by EU countries or internally. This unfavourable situation makes it unlikely for the UK to enter this market.
Logistical hurdles	The weight and characteristics of heat pumps are obstacles to international exports due to related high costs and logistical difficulties.

Despite these challenges, the UK's ambitious targets and planned investments in the heat pump sector position it well to meet its domestic demand in the future. However, the prospects for becoming a global competitor seem limited, given the unfavourable market conditions, competition from established players, and logistical constraints associated with long-distance exports.

Table 9-10: UK competitive advantages

Advantage	Description
In technologies with high levels of flexibility/customisation	The market outlook suggests that the UK will have a higher chance of success in the mid-range commercial and non-domestic sectors, where design flexibility and customisation levels are higher (source: Ricardo's expert's judgement). These sectors sometimes cross into industrial applications, especially when heat pumps are used at lower temperatures. This indicates a potential avenue for growth and diversification within the heat pump market, aligning with the government's broader sustainability goals.

Looking to the future (2030 and beyond), the UK may develop competitive advantages through increased manufacturing capacity, strategic investments, and technological advancements, but as of now, the immediate export market appears challenging to access.

9.3.4.1 UK Competitive advantage: key conclusions per technology

In the following table, we classify each technology as being either:

- A "**primary focus area**", highlighted in green, i.e. an area where the UK is expected to have a consolidated advantage;
- A "**further opportunity**", in yellow, i.e. an area where the UK could gain a competitive advantage from positioning itself as a potential early mover; or
- "**Lower potential**" in red, i.e. an area in which the UK does not appear to have potential.

Table 9-11: Technologies classification based on UK competitive advantage

Tech family	Technology	Classification	Answer & justification/rationale
Heat Pumps	General domestic and light commercial heat pumps; mass-market products	Further opportunity	Mass market products that already have mature supply chains. There is scope for assembly in the UK for the domestic market, but there is no evidence to support the opportunity for the potential export market (Source: Ricardo's expert's judgement).
	Larger scale heat pumps for commercial/industrial	Further opportunity	Larger-scale heat pumps with more niche applications, particularly industrial ones, remain a developing field. Where climate and regulatory similarities exist, the opportunity for early mover advantage exists if the UK can use its domestic market to develop its position. No existing advantage can be demonstrated (Source: Ricardo's expert's judgement).
	Water-to-water domestic heat pumps	Lower potential	This market potential depends on developing options for heat distribution (e.g., 5th-generation heat networks and shared ground loops). Being an early mover to deploy such systems at scale in the UK could lead to an early mover opportunity. No existing advantage can be demonstrated (Source: Ricardo's expert's judgement).

10. INDUSTRY

10.1 INTRODUCTION

This section covers the following tech families: fuel switching (focusing on hydrogen) and materials (focusing on recycling and recovery and low-carbon substitutes). This section's format differs from the other sectors, as we mainly focus on specific applications rather than the sector as a whole. In the quantitative part, the model covers only the hydrogen demand from industry as a fuel and does not cover the equipment that uses hydrogen.

For hydrogen**,** we focus on machinery and equipment that run on hydrogen in industrial production processes. The table below outlines examples of technology types and applications for hydrogen.

Table 10-1: Equipment types and applications for hydrogen use

Equipment types	Applications
Burners	• Direct firing • Components for retrofit • Radiant tube and indirect firing
Boilers	• Steam • High-pressure hot water (HPHW)
Furnaces	• Links to burners, but also explored in its own right
Gas engines	• Power generation and CHP • Transport and marine
Gas turbines	• Power generation and CHP
Fuel cells	• Power generation and CHP • Transport and marine

Individual sites may have a range of decarbonisation options to choose from, meaning that not all sites will opt to decarbonise through the use of hydrogen. The suitability of decarbonisation options within the industry is mainly dependent on the temperatures and types of heating processes involved. There are likely to be high opportunities for hydrogen in high-temperature direct heat (i.e., glass, ceramics, steel), high/mid opportunities in chemicals and distilleries and some opportunities also in high-temperature indirect heat sectors (e.g. food and drink, paper, textiles) (Source: Ricardo's experts' judgement).

The materials technology family naturally covers a wide range of applications. This technology family impacts many industrial sectors, given its wide range of influence and applicability. Many high energy-intensive industries are undergoing an energy transition and decarbonisation phase, including a strategy to decrease their overall environmental footprint while trying to maintain a competitive commercial advantage in the current worldwide economy. Excluding the actions taken by the industry to decarbonise its energy use, other relevant applications to decrease the environmental footprint are recycling and recovery of waste materials and substitution of conventional raw materials with low-carbon alternatives, which are at the forefront of this novel industrial transition.

Therefore, a scoping exercise was conducted for recycling & recovery and low carbon substitutes to limit the width and complexity of discussing those technologies, which have a wide range of applications across different industries. Specific applications were selected as Ricardo's experts indicated them to be the most promising applications in terms of potential for growth for the UK industry:

- For **recycling and recovery**, we focus on the following application:
  - Packaging for food and drinks applications;
- For **low-carbon substitutes**, we focus on the following applications:
  - Bioplastics;
  - Bio-based chemicals.

The details of the reasoning are included in Appendix 3.

Packaging for food and drinks

This discourse aims to explore the diverse techniques employed in packaging waste recycling, focusing on the most recent technological advancements in the field, specifically those dedicated to plastic packaging. We will elucidate the established processes alongside these emerging technologies, which hold the potential to transform discarded materials and grant them a new lease on life.

Bioplastics

According to European Bioplastics (2023), a plastic material is defined as a **bioplastic** if it is either biobased, biodegradable, or features both properties. Biobased plastics originate from renewable biomass, such as plants (sugarcane, corn, straw, etc.). Chemical modification or fermentation of plant or animal-derived lipids and sugars is also performed for bioplastic production (Sudhakar, 2021). However, the property of biodegradability is decided by the chemical composition of a polymer and not by its source. **Bioplastics can, therefore, be either bio-based or biodegradable, or both.** Bioplastics can be:

- fossil fuels-based plastics but biodegradable, i.e., Polybutylene Adipate Terephthalate (PBAT),
- bio-based but non-biodegradable (drop-ins), i.e., Bio-based Polyethylene, Polypropylene, Polyethylene-terephthalate, or
- bio-based as well as biodegradable plastics, i.e. Polylactic acid (PLA), Polyhydroxyalkanoate (PHA), Polybutylene succinate (PBS) (European Bioplastics, 2020).

The focus of this study is on bioplastics that are biobased and also biodegradable.

Bio-based chemicals

Bio-based chemicals are derived from biological, chemical, or physical transformations of plant or animal-based feedstocks, such as sugar, starch, oils, fats, and lignocellulose sourced from forestry, agricultural crops, and organic waste (E4Tech, 2017). These chemicals have the potential to play a key role in establishing a sustainable, low-carbon chemicals sector, especially when paired with recycling and a focus on factors like low toxicity. Bio-based chemicals can provide low-carbon energy or act as carbon stores as long as their feedstocks are sustainably sourced.

The final list of in-scope technologies and applications can be seen in the table below.

Table 10-2: In-scope technologies and applications

Sector	Tech families	Technologies	Applications
Industry	Fuel switching	Hydrogen	-
	Materials	Recycling and recovery	Packaging for food and drinks
		Low carbon substitutes	Bioplastics
			Bio-based chemicals

10.1.1 Key takeaways

Fuel switching: hydrogen

- Industrial hydrogen end-uses globally have high activity levels, but large-scale plants have yet to be built as they have not yet reached the final investment decisions (FID) stages. The technologies related to the use of hydrogen in the industrial production processes are at varying degrees of commercial readiness, but some viable technologies are already on the market (Hydrogen Council, McKinsey & Company, 2022).
- Excluding refining, the demand is ~50 Mt per year and is expected to grow significantly by 2030 to ~70 Mt per year (IEA, 2023).
- Announced global investments in hydrogen end-uses through 2030 account for about USD 60 billion, mainly targeting the mobility sector and new industry end-uses such as steelmaking, followed by existing industry uses, like ammonia and refining. Various national hydrogen

strategies and incentive schemes have been announced worldwide (Hydrogen Council, McKinsey & Company, 2022).
- However, alternative strategies to industrial decarbonisation exist, so future market growth is uncertain (Source: Ricardo's expert's judgement).
- Pure hydrogen also cannot simply replace coal or natural gas in many industry sectors due to the diverse and specific nature of energy conversion devices (IEA, 2019).
- Overall, the UK has some strong policy and regulatory support in place and has provided significant government funding and economic incentives to hydrogen fuel switching, including the Industrial Hydrogen Accelerator, offering a robust competitive advantage in this technology (BEIS, 2022).

Recycling and recovery: Packaging for foods and drinks

- The need for recycled materials for food and drinks applications is increasing both in the UK and the EU, with commercially viable technologies, especially chemical recycling, which has a significant potential to increase the volume and quality of recycled plastics, estimated to grow from current ~0.2 Mt/y to 3.4 Mt/y in 2030 in the EU+3 region.
- The UK supports chemical recycling through the Plastics Innovation Fund and is developing its regulations to support chemical recycling further. The UK also possesses a strong R&D base, and its current Oil&Gas infrastructure can be adapted or integrated with chemical recycling facilities. It can thus offer a competitive advantage (Source: Ricardo's expert's judgement).
- The global market size potential is significant here; the UK has a competitive advantage due to the number of engineering and manufacturing companies based in the country (Source: Ricardo's expert's judgement).
- However, the sector still presents numerous barriers that need to be addressed to increase the technology development required to improve the country's export capacity:
    - Unclear legal status of advanced chemical recycling technologies – Several policies currently do not provide a clear legal status for these technologies, which sits in an undefined grey area between chemical manufacturing and waste management. This is mainly due to the legal definition of recycling, which does not define the end-of-waste principles for plastic recycled materials obtained via alternative routes (e.g., depolymerisation, pyrolysis, or dissolution).
    - Another critical factor is the commercial competitiveness between waste export and in-house recycling. This is due to the absence of an extended plastic waste value chain in the country, which strongly limits the financial viability of developing new technical solutions, making exports more financially suitable. However, given that most non-OECD countries are currently limiting or banning waste plastic exports, this may lead to a potential and disruptive market inversion in the short- and medium-term.

Low-carbon substitutes: Bioplastics

- The global bioplastics market size was estimated at USD 11,600 million in 2022 and is expected to reach USD 46,400 million by 2030 (Grand View Research, n.d.). Another source estimates growth from USD 7,616 million in 2021 to USD 15,552 million in 2028 (Fortune Business Insights, 2023).
- The production is estimated to increase from ~2,200 kt in 2023 to ~7,400 kt in 2028 (Bioplastics, 2023).
- The estimated UK market share in the global bioplastics market is ~4.5% by 2030, based on Grand View Research (n.d.) and BBIA (2015).
- The bioplastics market is growing with the increasing environmental awareness of consumers and the adoption of corporate ESG policies (Nanda & Bharadvaja, 2022). On the other hand, bioplastics are currently more expensive compared to petroleum-based plastics. (Doehler et al., 2022). Several countries, i.e., the US, EU and China, are introducing policies to increase the use of bio-based plastics.
- Some barriers to bioplastics deployment include the competition from petroleum-based plastics due to their well-established processes. Bioplastics are also currently more expensive than petroleum-based plastics, and the evolution in the coming years will heavily depend on the trajectory of conventional plastics prices (Doehler et al., 2022).
- The UK has a strong research base in various fields, including materials science and sustainable technologies, which can be leveraged for bioplastics innovation. UK's competitive advantages in bioplastics include its world-leading engineering biology sector (Royal Academy of Engineering, 2019), established agricultural sector (that can provide a source of raw materials), and strong R&D base,

which can be leveraged for bioplastics innovation. The consumer demand for bioplastics is growing due to increasing environmental awareness (Source: Ricardo's expert's judgement).

Low-carbon substitutes: Bio-based chemicals

- The current level of production of bio-based chemicals and polymers is ~90 Mt, and the future developments are uncertain (IEA, 2020).
- The global production of bio-based chemicals remains limited due to the widespread dominance of petrochemicals, driven by the low cost of oil (E4Tech, 2017).
- Also, despite being less carbon-intensive than conventional chemicals, bio-based chemicals still pose several unknowns regarding their actual environmental impact (Ogmundarson, Herrgard, Forster, & al., 2020).
- To enable further development, bio-based chemicals will need government support to de-risk the technology development for the private sector partially. Moreover, stimulating the availability of the primary bio-based chemical feedstock would de-risk part of the business market penetration strategies (Source: Ricardo's expert's judgement).
- Securing the feedstock for this sector is another crucial element, as waste biogenic sources are currently in high demand for other applications like Sustainable Aviation Fuel, Energy, and fuel production. However, this competition varies considerably among the geographical areas considered (source: Ricardo's expert's judgement).
- In the UK, several manufacturers and universities are progressing in the field of bio-based chemicals. However, most of the UK's industrial activities are in the early stages of development (E4Tech, 2017).
- There is a range of promising bio-based chemicals with good market opportunities where the UK has promising strengths, especially by building on existing activities and capabilities (E4Tech, 2017).
- The UK has a world-leading engineering biology and strong agricultural and chemical sectors. The UK holds a competitive advantage, especially in synthetic biology, biocatalysis, chemistry, and polymer research and development capabilities, and its primary opportunity lies in manufacturing specialised bio-based chemicals characterised by high market values and low volume demands. The UK also possess an expanding academic and industrial foundation in bio-based fuels and chemicals (E4Tech, 2017).

10.2 RQ1: Potential market size and UK market shares

10.2.1 Quantitative analysis at the sector level

10.2.1.1 Market size

This section presents the hydrogen consumption projection by industrial sectors as simulated by the GEM-E3 model. Hydrogen holds significant promise as a versatile and sustainable energy carrier with the potential to address key challenges in transitioning to a low-carbon economy. It offers a clean alternative to fossil fuels, emitting only water vapour when used in fuel cells or combustion processes, thereby reducing greenhouse gas emissions and mitigating climate change. Hydrogen can also support RES deployment as a storage option and contribute to GHG emission reduction in hard-to-abate sectors.

Table 10-3 and Figure 10-1 show the main industries in which hydrogen is used across the different scenarios. The main industries are ferrous metals, refineries, chemicals, non-metallic minerals, paper products and non-ferrous metals.

Hydrogen is expected to be used in the ferrous metals sector mainly through its involvement in various metallurgical processes. A key application of hydrogen within the metals sector lies in the reduction of iron ore to produce iron, a process known as direct reduction. Here, hydrogen acts as a reducing agent, removing oxygen from iron ore to produce sponge iron or direct reduced iron (DRI). Projections indicate that hydrogen consumption in the ferrous metals sector is expected to reach around 6.67 million tons of oil equivalent (mtoe) over the cumulative period from 2020 to 2050 in the Below 2°C scenario and 9.58 mtoe in the Net Zero scenario.

Hydrogen serves as a component in the chemicals sector and is used in various chemical manufacturing processes. One of the primary uses of hydrogen in the chemicals industry is as a feedstock for producing ammonia, a key ingredient in fertilisers, explosives, and other chemical products. In this regard, hydrogen consumption in the chemical sector is projected to reach 1.89 mtoe over the cumulative period from 2020 to 2050 in the Below 2°C scenario and 21.70 mtoe in the Net Zero scenario.

Refineries use hydrogen in processes to enhance the quality of refined petroleum products and improve overall efficiency. Hydrogen is also used to lower the sulphur content of diesel fuel. Hydrogen consumption in the refinery industry is projected to reach 13.71 mtoe over the cumulative period 2020-2050 in the Below 2 ºC scenario and 17.69 mtoe in the Net Zero scenario.

Hydrogen contributes to various processes and product manufacturing endeavours in the non-metallic minerals sector. For instance, in cement production, hydrogen aids in reducing emissions during the calcination process, a step wherein limestone is heated to produce lime. Over the cumulative period from 2020 to 2050, hydrogen consumption in the non-metallic mineral sector is estimated to reach 2.37 mtoe in the Below 2°C scenario and 3.02 mtoe in the Net Zero scenario.

Moreover, hydrogen contributes to various stages of the paper manufacturing process in the paper industry. One key application of hydrogen is in the bleaching of pulp, a crucial step in producing high-quality paper products. Projections of the GEM-E3 model suggest that hydrogen consumption in the paper industry will reach 0.21 mtoe in the Below 2°C scenario and 0.31 mtoe in the Net Zero scenario over the cumulative period from 2020 to 2050.

In the non-ferrous metals industry, hydrogen serves various critical functions, contributing to multiple stages of metal production and processing. One significant application of hydrogen is in the reduction of metal ores, particularly in processes involving hydrometallurgy or pyrometallurgy. Hydrogen consumption in the paper industry is projected to reach 0.37 mtoe over the cumulative period 2020-2050 in the Below 2 ºC scenario and 0.50 mtoe in the Net Zero scenario.

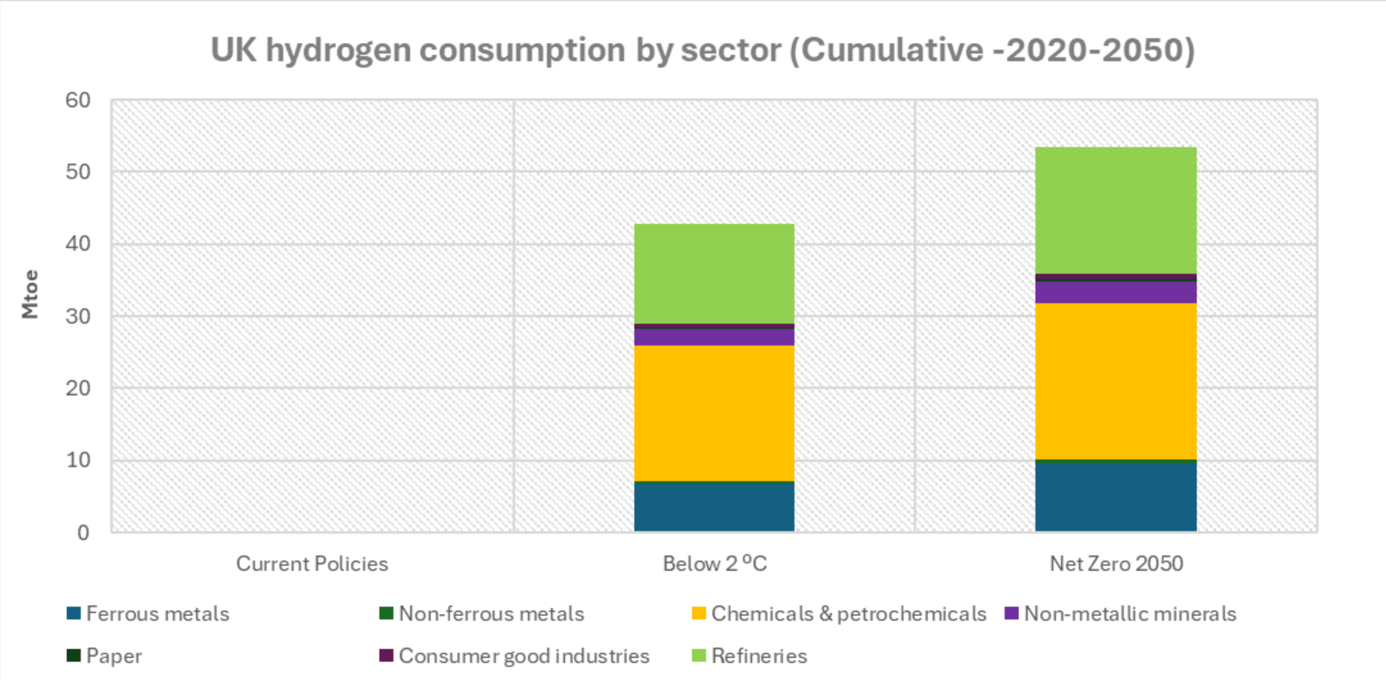
In the consumer goods industries, particularly the food industry, hydrogen contributes to different food processing and production stages. One significant application of hydrogen is in hydrogenation processes, commonly used in producing fats and oils. Projections indicate that hydrogen consumption in the consumer goods industry, mainly within the food sector, will reach 0.54 mtoe in the Below 2°C scenario and 0.75 mtoe in the Net Zero scenario over the cumulative period from 2020 to 2050.

Table 10-3: UK Cumulative Hydrogen consumption by industry over the period 2020-2050 (Mtoe).

	Current Policies	Below 2 ºC	Net Zero 2050
Ferrous metals	0.00	6.67	9.58
Non-ferrous metals	0.00	0.37	0.50
Chemicals	0.00	18.89	21.70
Non-metallic minerals	0.00	2.37	3.02
Paper	0.00	0.21	0.31
Consumer goods industries	0.00	0.54	0.75
Refineries	0.00	13.71	17.69

Source: Ricardo analysis based on GEM-E3 outputs

Figure 10-1: UK Cumulative Hydrogen consumption by industry over the period 2020-2050.



Source: Ricardo analysis based on GEM-E3 outputs

10.2.2 Qualitative analysis: market size

In the following sections, market size trends by technology application are discussed. In case of the absence of information on the annual demand in monetary terms, deployment and technology readiness levels of specific technologies and applications are used as a proxy for market size. Industrial demand for **hydrogen** is currently at ~90 Mt per year, mostly in refining, chemical industries and steel-making (Optimat, 2022). Excluding refining, the demand is ~50 Mt per year and is expected to grow significantly by 2030 to ~70 Mt per year (IEA, 2023). Industrial hydrogen end-uses globally have high activity levels, but large-scale plants have yet to be built as they have not yet reached the final investment decisions (FID) stages. The technologies related to the use of hydrogen in the industrial production processes on the market are at varying degrees of commercial readiness, but some viable technologies are already on the market (Hydrogen Council, McKinsey & Company, 2022). In recycling and recovery, the need for recycled materials for food and drinks applications is increasing both in the UK and the EU, with commercially viable technologies, especially chemical recycling, which has a significant potential to increase the volume and quality of recycled plastics, estimated to grow from current ~0.2 Mt/y to 3.4 Mt/y in 2030 in the EU+3 region (CEFIC, 2024). The global **bioplastics** market size was estimated at USD 11,600 million in 2022 and is expected to reach USD 46,400 million by 2030 (Grand View Research, n.d.). Another source estimates growth from USD 7,616 million in 2021 to USD 15,552 million in 2028 (Fortune Business Insights, 2023). The production is estimated to increase from ~2,200 kt in 2023 to ~7,400 kt in 2028 (European Bioplastics, 2023). The current level of production of **bio-based chemicals** and polymers is ~90 Mt, and the future developments are somewhat uncertain (IEA, 2020).

10.2.2.1 Fuel switching: Hydrogen

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

- **Existing uses** – these applications present opportunities for low carbon hydrogen in both the short and long term (i.e., refining, chemicals – ammonia and methanol),
- **Likely uses** – in areas where future demand is expected to be significant, development may require some time (i.e., hydrogen used for industrial heat in the steel sector, ammonia as maritime fuel, synfuels in the aviation sector, hydrogen to support power balancing),
- **Transitional uses** – providing immediate yet transformative opportunities for hydrogen (i.e., co-firing – coal and gas plants),
- **New uses** –could include potentially large future applications, but the relative advantages of hydrogen over other options are very uncertain (e.g. heavy-duty vehicles, rail, heating) (Wood & Optimat, 2022).

Currently (as of 2022), most hydrogen usage worldwide occurs in industrial sectors, primarily in refining, chemical industries, and steelmaking, totalling around 90 million tonnes (Mt) per year. Other sectors have minimal hydrogen consumption. Refining accounts for 40 Mt annually, serving as a feedstock, reagent, or energy source. The chemicals industry consumes approximately 45 Mt per year, with 75% allocated to ammonia production and 25% to methanol production. Steelmaking utilises an additional 5 Mt per year through the direct reduced iron process. This distribution of hydrogen usage has mainly remained consistent since 2000. For comparison, the annual global demand for hydrogen in transport in 2022 is only 0.02 Mt per year (Wood & Optimat, 2022).

Another estimated industrial demand for hydrogen in the IEA Net Zero scenario shows growth of 70Mt by 2030 from 50Mt in 2022. The sectors considered include ammonia, methanol (ammonia and methanol exclude fuel applications), steel and dedicated hydrogen production for high-temperature heat applications. Therefore, this estimate is lower compared to Wood & Optimat (2022) as it excludes refining. The study specifies that meeting this need would require a 4% annual increase in production, compared to just 2% over 2021-2022 (IEA, 2023).

Announced investments in hydrogen end-uses until 2030 amount to approximately USD 60 billion, covering methanol and ammonia synthesis plant deployment and hydrogen utilisation in clean steelmaking or power applications. Around USD 23 billion is allocated to feasibility or front-end engineering design (FEED) studies, while USD 6 billion is committed capital. Ground transport holds the most significant portion of committed capital, representing 25% of total investment proposals at the final investment decision (FID) stage or more advanced, followed by power with a share of about 15%. The majority of announced investments are directed towards the transport sector and emerging industrial applications such as steelmaking, each accounting for approximately 30% of total investments. This is followed by investments in established industrial uses like ammonia and refining, representing about 25% of the total announced investments. Investments in existing industrial uses, where clean hydrogen directly replaces fossil-based ("grey") hydrogen, have more than tripled from USD 5 to 16 billion between 2021 and 2022. Meanwhile, investments in new industrial applications have grown by approximately 25% since 2021, primarily driven by the emergence of 26 steel projects, with 20 of them located in Europe. (Hydrogen Council, McKinsey & Company, 2022).

Energy and heating end-uses are also progressing. This includes blending hydrogen with natural gas in turbines, advancing hydrogen-ready turbine technology, and utilising hydrogen for high-grade heat applications. Moreover, power plants are shifting towards replacing coal with clean ammonia. Additionally, there are plans to increase hydrogen-based fuel cell manufacturing capacity from 11 GW in 2021 to 28 GW by 2025 (Hydrogen Council, McKinsey & Company, 2022).

Industrial hydrogen end-uses have high activity levels globally, but large-scale plants have yet to be constructed. About 27 renewable hydrogen projects have reached the FID stage, with roughly 20 in Europe. These projects cover clean ammonia, methanol, steel, and synthetic fuel production. Ammonia projects lead with seven at the FID stage and three operational projects with up to 20 MW electrolysers. Seven clean methanol projects are at the FID stage, with the largest operational plant featuring a 10 MW electrolyser. Other projects focus on refining, small-scale hydrogen-based steelmaking, and synthetic fuel production. Despite unclear regulatory frameworks and government support, private sector commitments drive much of this progress. However, no full-scale plants have reached the FID stage yet. (Hydrogen Council, McKinsey & Company, 2022).

Regarding the specific technologies related to the use of hydrogen in the industrial production process, many equipment manufacturers are developing hydrogen-ready technologies; however, these are at varying degrees of commercial readiness. Nevertheless, several viable technologies are already on the market, from well-established brands producing natural gas equipment to new technology developers producing disruptive technologies like fuel cells (Source: Ricardo's expert's judgement).

10.2.2.2 Recycling and recovery

The need for recycled materials for food applications is increasing in the UK and EU regions, mainly driven by the recent implementation of circular-economy-related policies (e.g., packaging waste rules - PPWR, Plastic Tax) (WRAPP, 2022). The need for these recycled materials will likely be filled by a series of different recycled sources, like bioplastics and advanced mechanical and chemically recycled materials. These technologies are now commercially viable due to the new policy framework implemented in several geographical regions (US, UK, and EU) (CEFIC, 2024). This is mainly due to a combination of circular economy targets and higher carbon costs (EUR or USD/Tonne).

Among the new techniques, **chemical recycling** emerges as a disruptive technology in fighting plastic waste. Currently, the presence of chemical recycling facilities in the UK is limited. The British Plastic Federation (BPF) Recycling Roadmap indicates that only 5 kt of waste plastics in 2020 is currently processed via chemical recycling technologies, equal to 2% of the overall waste plastic volume (British Plastics Federation, 2021). However, the same report shows how, by 2030, the same processing route could increase its throughput to 300 kt per year, corresponding to a 6000% increase in the short term. This growth is expected to increase further due to a combination of better collection and segregation waste strategies, limited exported volumes and the implementation of dedicated policy tools (Extended product responsibilities, Return Schemes, Carbon Adjustments Tools and others). The same trend can be expected in the wider European Region. At the moment, only 0.2 Mt/y of waste plastic packaging is currently recycled in the EU+3 region (EU, UK, Norway and Switzerland) via chemical recycling (ICIS, 2023). However, Plastic Europe has indicated that the overall recovery capacity via chemical recycling will increase to 1.2 Mt/y in 2025 and 3.4 Mt/y in 2030 (Plastic Europe, 2023). This can translate to an investment of over 8 billion euros in 2030 (Plastic Europe, 2023). The Wood Mackenzie's Cross-Polymer Demand Model also predicts a considerable increase in chemical recycling for both plastics-to-fuel (P2F) and plastic-to-plastic (P2P) in the short- and medium-term, increasing the overall recycling rate for plastic packaging up to 50% by 2040 (Wood Mackenzie, 2021). These new techniques have several advantages over traditional mechanical recycling, which relies on sorting plastic by type and melting it. Chemical recycling adopts a more transformative approach. It utilises various techniques, such as depolymerisation and solvolysis, to break down plastic waste into its basic chemical building blocks, reverting it to its pre-polymer state. These reclaimed chemicals can then be utilised to create virgin-quality plastic or other valuable products, offering a closed-loop solution for previously unrecyclable plastics and complex waste streams. While still in its early stages, chemical recycling holds immense potential to significantly increase the volume and quality of recycled plastic, paving the way for a more circular economy for plastic packaging (Source: Ricardo's expert's judgement).

The same trend is expected for conventional mechanical recycling plastics, like PET bottles and hard-plastic containers. Globuc has reported an increase, in 2020 alone, of 1.1 Mt/y of waste plastic packaging in the EU+3 region, equivalent to a growth rate of 13% (Globuc, 2021).

10.2.2.3 Low carbon substitutes: Bioplastics

After stagnation in recent years, global plastic production is experiencing a resurgence in 2023. This revival is fuelled by increased demand coupled with the emergence of more advanced applications and products (European Bioplastics, 2023).

Bioplastics currently represent around 0.5% of the over 400 million tonnes of annual plastic production. Global bioplastics production capacity is estimated to increase significantly from 2,200 kt in 2023 to 7,400 kt in 2028 (European Bioplastics, 2023).

Regarding the global biodegradable biobased plastics projections, Doehler et al. (2022) estimate that the production will reach around 950 kt by 2025 and 1,100 kt by 2030 (under the baseline scenario). Another study by (European Bioplastics, 2023) estimates that the production of biodegradable biobased plastics will reach 2,500 kt by 2025 and 4,600 kt by 2030.[1]

This growth is estimated to result from the combined influence of several factors: general economic growth, an increase in oil prices making conventional plastic production more expensive, a slight decline in prices of agricultural feedstocks, and the presence of cost-reducing learning effects (Doehler et al., 2022).

In monetary terms, the global bioplastics market size was estimated at USD 11,600 million in 2022 and is expected to expand at a compound annual growth rate (CAGR) of 18.8% from 2023 to 2030, therefore reaching USD 46,400 million by 2030 (Grand View Research, n.d.). Another source estimates that the global bioplastics market size is projected to grow from USD 7,616.0 million in 2021 to USD 15,552.3 million in 2028 at a CAGR of 10.7% (Fortune Business Insights, 2023).

Bioplastic alternatives are available for nearly every conventional plastic material and its corresponding application. With the robust development of polymers like PLA (polylactic acid), PHA (poly-hydroxy-alkanoates), PAs (polyamides), and the steady growth of PP (polypropylene), production capacities are expected to experience substantial growth over the next five years. (European Bioplastics, 2023). Certain bioplastic materials have reached a developmental stage where they can provide nearly identical technical properties as fossil-based plastics. Consequently, they are suitable for various applications (Thakur, 2018).

Bioplastics applications span packaging and consumer goods to electronics, automotive, and textiles. Packaging is the largest market segment for bioplastics, constituting 43% (934,000 tonnes) of the total bioplastics market in 2023 (European Bioplastics, 2023). The market size for bioplastics and bio-based plastics is expected to grow in line with the expected growth in these sectors.

10.2.2.4 Low carbon substitutes: Bio-based chemicals

The current global production of bio-based chemicals and polymers is estimated to be around 90 Mt. While the level of research and industrial activity in this sector is generally promising, there have been instances in recent years where companies have ceased operations or acquired by other companies. This trend is concerning and suggests some instability within the industry (IEA, 2020). The global production of bio-based chemicals continues to be constrained by the prevailing dominance of petrochemicals, primarily influenced by the low cost of oil (E4Tech, 2017). Challenges in the transition include competing with the cost-effectiveness of well-established large-scale oil refineries and the lack of dedicated incentives for bio-based chemicals. Moreover, shifting from a fossil-based to a bio-based chemical industry demands significant resources, time, and capital investment (IEA, 2020).

The recent EU Bioeconomy Strategy Progress Report shows that platform chemicals and adhesives have the highest potential for growth among biobased chemical categories, with an expected CAGR of 10% by 2025. Polymers for plastics and surfactants also show promising development, with an expected CAGR of 4% by 2025 (European Commission, 2022).

10.2.2.5 Summary: global market size trends

Based on the above information, the table below shows a summary assessment of the in-scope technology applications ranked according to whether we believe the global market size growth potential is low, medium, or high.

Table 10-4: Global market size growth potential: RAG rating by technology

Tech family	Technology	Rating	Application
Fuel switching	Hydrogen	Medium	-
Materials	Recycling and recovery	High	Packaging for food and drinks
	Low carbon substitutes	High	Bioplastics
		Medium	Bio-based chemicals

10.2.3 Qualitative analysis: UK market shares

10.2.3.1 Trade flows analysis

The table below shows the annual average of UK exports (2021-2022) for some selected Harmonised System (HS) subheading codes (provided by DESNZ) relating to components used in the manufacture of equipment and parts relevant to the 'Industry' sector. These numbers can be interpreted as proxies of the UK's share of tradable export markets. The total average for this sector stands at 2.9% of the global tradable market.

Table 10-5: UK share of global exports, selected HS subheadings, 2021-2022

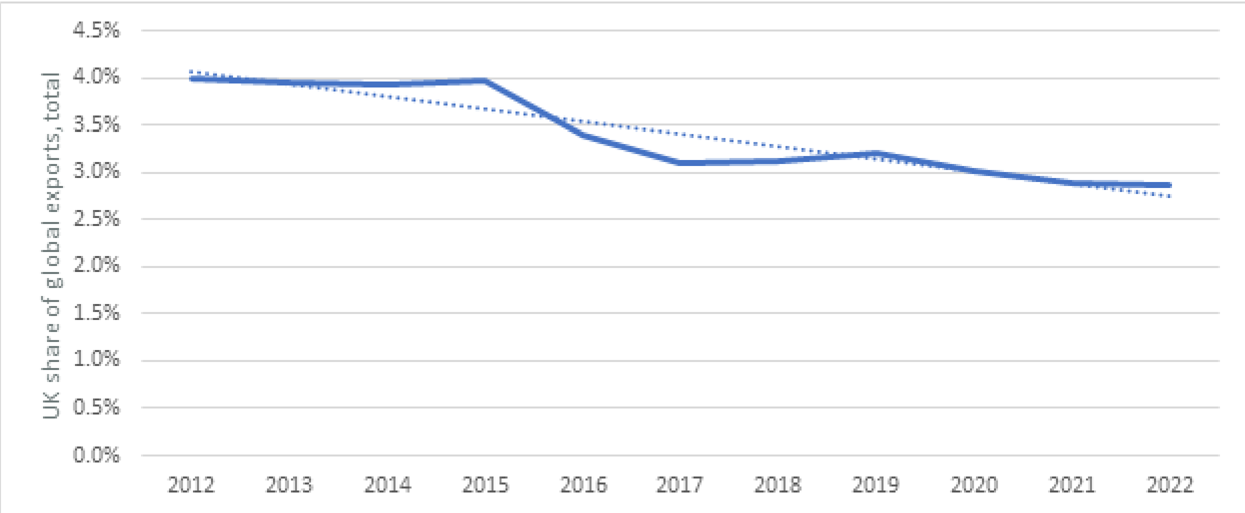
Group	Subheading included in group	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
35 Albuminoidal substances; modified starches; glues; enzymes	• 3507 Enzymes; prepared enzymes not elsewhere specified or included	USD 109M	1.5%
38 Miscellaneous chemical products	• 3815 Reaction initiators, reaction accelerators and catalytic preparations, not elsewhere specified or included	USD 789M	2.7%
83 Miscellaneous articles of base metal	• 831110 Coated electrodes of base metal, for electric arc-welding • 831120 Cored wire of base metal, for electric arc-welding	USD 14M	0.6%
84 Nuclear reactors, boilers, machinery and mechanical appliances; parts thereof	• 8402 Steam or other vapour generating boilers (other than central heating hot water boilers capable also of producing low pressure steam); superheated water boilers • 8404 Auxiliary plant for use with boilers of heading 8402 or 8403 (for example, economisers, superheaters, soot removers, gas recoverers); condensers for steam or other vapour power units • 8413 Pumps for liquids, whether or not fitted with a measuring device; liquid elevators • 8414 Air or vacuum pumps, air or other gas compressors and fans; ventilating or recycling hoods incorporating a fan, whether or not fitted with filters; gas-tight biological safety cabinets, whether or not fitted with filters • 8416 Furnace burners for liquid fuel, for pulverised solid fuel or for gas; mechanical stokers, including their mechanical grates, mechanical ash dischargers and similar appliances • 8417 Industrial or laboratory furnaces and ovens, including incinerators, non-electric • 8438 Machinery, not specified or included elsewhere in this chapter, for the industrial preparation or manufacture of food or drink, other than machinery for the extraction or preparation of animal or fixed vegetable or microbial fats or oils • 8439 Machinery for making pulp of fibrous cellulosic material or for making or finishing paper or paperboard • 8441 Other machinery for making up paper pulp, paper or paperboard, including cutting machines of all kinds • 8464 Machine tools for working stone, ceramics, concrete, asbestos-cement or like mineral materials or for cold working glass	USD 9,178M	2.8%

Group	Subheading included in group	Annual UK exports, average 2021-2022 (nominal)	UK share of global exports
	• 8474 Machinery for sorting, screening, separating, washing, crushing, grinding, mixing or kneading earth, stone, ores or other mineral substances, in solid (including powder or paste) form; machinery for agglomerating, shaping or moulding solid mineral fuels, ceramic paste, unhardened cements, plastering materials or other mineral products in powder or paste form; machines for forming foundry moulds of sand • 8481 Taps, cocks, valves and similar appliances for pipes, boiler shells, tanks, vats or the like, including pressure-reducing valves and thermostatically controlled valves		
85 Electrical machinery and equipment and parts thereof; sound recorders and reproducers, television image and sound recorders and reproducers, and parts and accessories of such articles	• 8514 Industrial or laboratory electric furnaces and ovens (including those functioning by induction or dielectric loss); other industrial or laboratory equipment for the heat treatment of materials by induction or dielectric loss	USD 134M	2.3%
90 Optical, photographic, cinematographic, measuring, checking, precision, medical or surgical instruments and apparatus; parts and accessories thereof	• 9026 Instruments and apparatus for measuring or checking the flow, level, pressure or other variables of liquids or gases (for example, flow meters, level gauges, manometers, heat meters) • 9028 Gas, liquid or electricity supply or production meters, including calibrating meters therefor	USD 1,342M	4.0%
Total		**USD 2,071M**	**2.9%**

Source: Ricardo elaboration on UN Comtrade data

The figure below shows a downward trend in the UK's share of global exports for the total HS codes analysed, from 4.0% in 2012 to 2.9% in 2022.

Figure 10-2: UK share of global exports, 2012-2022



Source: Ricardo elaboration on UN Comtrade data

10.2.3.2 Qualitative analysis: UK market shares

This section provides an overview of the UK's supply side in hydrogen (in fuel switching) and materials (recycling and recovery and low carbon substitutes). In cases where the information on the UK market share is missing, the key manufacturers and manufacturing plants with a presence in the UK are presented (regardless of company ownership).

Fuel switching: Hydrogen

The **UK Industrial Decarbonisation Strategy**[2] outlines various policies and initiatives to support industry decarbonisation, including investments in infrastructure to facilitate the transition to low-carbon alternatives like hydrogen. As set out in the **Energy White Paper**[3]**,** the UK government aims to achieve complete decarbonisation of the power system by 2050. This objective necessitates rapidly expanding renewable and other low-carbon energy generation sources. Hydrogen is identified as potentially contributing to flexible power generation to address short- and long-term peaks in energy demand (Wood & Optimat, 2022).
Regarding the hydrogen equipment manufacturers in the UK, below are some of the leading players in this space, together with their key manufactured products.

Table 10-6: Selection of manufacturers in the UK (hydrogen)

Company	Key information on the products
Rolls Royce /MTU	Reciprocating engines and gas turbines
Centrax	Gas turbines
ITM Power	Onsite hydrogen production
Protium	Onsite hydrogen production
Ceres Power	Hydrogen production and fuel cells
AFC Energy	Fuel cells
Intelligent Energy	Fuel cells
Cummins	Hydrogen combustion technology
Dunphy	Hydrogen burners
Worchester Bosch	Hydrogen boilers
Baxi	Hydrogen boilers
Babcock & Wilcox	Hydrogen steam boilers and combustion
2EA	Hydrogen CHP

Recycling and recovery

While the field of chemical recycling in **packaging for food and drinks applications** is still evolving, here are some of the major chemical recycler technology providers in the UK:

Table 10-7: Selection of manufacturers in the UK (recycling and recovery)

Company	Key information
Neste	A Finnish company with a significant presence in the UK is a major player in developing chemical recycling technologies. It has invested in several chemical recycling projects worldwide, including a joint venture with REPIC in France to build a plant for mixed plastic waste.
Plastic Energy	Plastic Energy is a global leader in advanced plastic recycling, with a unique technology called Thermal Anaerobic Conversion (TAC). While technically not falling under the strict definition of chemical recycling, TAC shares some similar principles and offers a valuable solution for managing end-of-life plastics. Similarly to Neste, Plastic Energy has a significant presence in the UK. However, no facility is present in the UK.

Company	Key information
ReNew ELP	This company utilises a depolymerisation process to break down plastic waste into its base chemicals, which can then be used to create new plastic products. Their technology focuses on converting PET (polyethene terephthalate) waste, commonly found in plastic bottles, into high-quality recycled PET.
Mura Technology	This company has developed a hydrothermal liquefaction process that breaks down various types of plastic waste, including mixed and contaminated plastics, into bio-crude oil. This oil can then be used to produce new plastic products or other valuable chemicals.

All the above-mentioned companies have factories and/or engineering offices in the UK. This means that some of them can actually manufacture products from chemical recycling and sell engineering designs and licenses to third parties across the country.
While Shell, BP, and other major oil and gas firms have investments and partnerships related to chemical recycling, they do not necessarily fall under the "chemical recycler technology providers" category as defined previously. Here's how they contribute to the UK's chemical recycling landscape:

Table 10-8: Other key manufacturers in the UK (Shell and BP)

Company	Key information
Shell	• Invested in BlueAlp, a Dutch company developing technology for pyrolysis of mixed plastic waste into recycled feedstock. • Aims to recycle 1 million tonnes of plastic waste annually through its global chemical plants by 2025, potentially incorporating some technologies developed by partners like BlueAlp.
BP	• Developed its own Infinia technology for depolymerisation of specific types of plastic waste, particularly unrecyclable PET plastics. • Currently focusing on pilot projects and collaborations to test and scale up its Infinia technology, not acting as a standalone technology provider.

It is essential to differentiate these contributions from companies like Recycling Technologies or ReNew ELP, which solely focus on developing and offering their chemical recycling technologies.

Low carbon substitutes: Bioplastics

In 2022, the UK government announced a GBP 20 million investment in bioplastics innovation to support research and development in this field (UKRI, 2020).
The global bioplastics market size is expected to reach 46,400 million USD by 2023 (Grand View Research, n.d.). A report by the Bio-based and Biodegradable Industries Association (BBIA) suggests the UK bioplastics industry could generate GBP 2.1 billion and create 34,000 jobs by 2030 (BBIA, 2015). Therefore, the estimated UK market share is ~4.5% by 2030.
A growing community of young engineering biology companies is emerging in the UK, with 146 synthetic biology startups and spinout companies established between 2000 and 2016. Many of these enterprises have also received support from public investment sources (Royal Academy of Engineering, 2019).

Low carbon substitutes: Bio-based chemicals

E4tech (2017) has identified around 25 manufacturers (ranging from start-up companies to large corporates), and around 10 universities are actively developing bio-based chemical routes in the UK. As of 2017, when the report was published, most of the UK's industry activities were in the early stages of bio-based chemicals development, typically between technology readiness level (TRL) 3 and 5.

Early-stage technology development and product innovation remain the primary focus of the UK industry. Assuming a leading role during these early stages of sector development will unlock global opportunities for the UK industry and generate significant economic value within the country. Few companies in the UK produce bio-based chemicals at commercial or near-commercial scales. Companies like Green Biologics, Butamax, or Croda, which have well-established R&D centres in the UK, are showcasing production in the USA or Brazil due to factors such as costs, support programs, and infrastructure.

According to E4Tech, the following table shows the 10 most promising bio-based chemicals for the UK industry that could be the focus of near-term development in the UK and generate benefits to the UK economy.

Table 10-9: 10 most promising bio-based chemicals for the UK industry

Bio-based chemical	Market size	Market potential	Growth drivers	Industry leaders	UK presence
Lactic Acid	Approximately 800kt annually	N/A	The increasing global demand for polylactic acid (PLA) is driven by consumer awareness of sustainability, biodegradability, and green packaging. The market is predicted to grow at a 6-8% rate.	Natureworks holds a prominent position as a leading lactic acid producer.	The UK boasts competitive lactic acid development with successful ventures by companies like Plaxica and Cellulac, contributing to technology development, licensing, and manufacturing.
2,5-Furandicarboxylic Acid (FDCA)	N/A	Considerable potential in displacing petroleum-derived chemicals in various polymer applications.	N/A	N/A	N/A
Levoglucosenone	N/A	N/A	N/A	N/A	The UK holds promise in commercialising levoglucosenone production, with companies like Circa Sustainable Chemicals making notable contributions.
5-Hydroxymethylfurfural (HMF)	HMF technology is not fully commercial; global production is approximately 100kt annually.	Identified as one of the most valuable platform chemicals by the US Department of Energy.	N/A	N/A	Limited current activity, focusing on research, particularly at Imperial College and the University of Liverpool.
Muconic Acid	Exceeds USD 22 billion.	N/A	The rise in demand is linked to the increasing consumption of nylon 6,6 and caprolactam in applications like carpets and textiles.	N/A	Strong synthetic biology and polymer science capabilities position the UK favourably for muconic acid technology development.
Itaconic Acid	Approximately 80kt annually, primarily produced in China.	Envisions tapping into a market exceeding GBP 10 billion.	N/A	N/A	Itaconix and academic activities at the University of York and the University of Nottingham play a leading role in bio-based polymer development.
1,3-Butanediol (1,3-BDO)	N/A	Derivatives could lead to significant market opportunities in the millions of	N/A	N/A	CHAIN Biotechnology Ltd in the UK patented a technology for Clostridial fermentation, emphasising potential small standalone plants.

Bio-based chemical	Market size	Market potential	Growth drivers	Industry leaders	UK presence
		tonnes per year.			
Glucaric Acid	N/A	Potential market expansion worth several billion dollars.	N/A	N/A	Rennovia and UK-based Johnson Matthey collaborate with Archer Daniels Midland to commercialise glucaric acid in agriculture.
Levulinic Acid	Relatively small, forecasted to reach USD 9.65 million revenue by 2020, with a CAGR of 4.8%.	N/A	N/A	N/A	Levulinic acid technology relies on the pretreatment and thermochemical conversion of biomass, but the UK lacks strength in scaling up and demonstrating these technologies.
n-Butanol	Large, estimated at 3Mt annually.	N/A	N/A	N/A	Green Biologics in the UK uses bacterial fermentation to produce n-butanol and acetone, which aligns with diverse industry applications. The UK is well positioned in this market, with several industrial activities related to technology development and scale-up.

Overall, a diverse range of promising bio-based chemicals presents favourable market opportunities due to enhanced functionality and increased sustainability. The development of these bio-based chemicals and their derivatives is still in a phase where innovation and competition are feasible, and the UK possesses promising strengths in this regard. The economic potential of accessing markets for these bio-based chemicals is substantial. While the list of top bio-based chemicals for the UK is not exhaustive, it provides a preliminary assessment of market opportunities and the UK's current positioning. Priority is given to bio-based chemical opportunities with the highest market attractiveness. Although the UK may not currently hold a strong position in developing some of these opportunities, there is potential for improvement by leveraging existing activities and capabilities. The analysis reveals a variety of bio-based chemicals with promising market opportunities, where the UK could competitively position itself based on its existing activities related to these bio-based chemicals.

On the other hand, interviews analysed as part of this report indicated that UK companies are often looking for technology testing and scale-up services outside the UK and that there is a demand for open-access piloting and demonstration facilities that can provide affordable service to the UK’s bio-based sector.

10.2.3.3 Summary: UK market share

Based on the information presented above, the table below shows a summary assessment of the in-scope technology applications based on a ranking that reflects our assessment of the potential UK market share growth. Note that this table's interpretation is different from that of other sectors. The Industry sector is too broad and encompasses various applications in various industries. Therefore, assessing the relative potential of selected applications with respect to the sector average would not have been particularly meaningful. Consequently, we indicate the potential for the UK to grow its market share in these selected technologies and applications.

Table 10-10: Technologies that have the potential to attract significantly higher/lower market shares compared to the sector average

Tech family	Technology	Application	Rating	Justification/rationale and key sources
Fuel switching	Hydrogen	-	Higher than average	The UK has strong policy support for decarbonising industry, including fuel switching to hydrogen. Significant funding and economic incentives are provided by the government, including the Industrial Hydrogen Accelerator. A number of manufacturers are present in the UK.
Materials	Recycling and recovery	Packaging for food and drink applications	Higher than average	Multiple companies have factories and/or engineering offices in the UK, and the major Oil&Gas companies contribute to the country's chemical recycling landscape.
	Low carbon substitutes	Bioplastics	Higher than average	The UK government significantly supports R&D in bioplastics. By 2030, the UK is expected to reach ~4% of the global market.
	DACCS	Bio-based chemicals	Average	There are ~25 manufacturers and ~10 universities actively developing bio-based chemicals in the UK. Although the activities are in the early stages of development, there is a range of bio-based chemicals with good market opportunities for the UK to position itself competitively.

10.3 RQ2: UK COMPETITIVE ADVANTAGE

10.3.1 Key drivers of competitive advantage

This section provides an overview of the drivers and enablers of key policy and market developments globally related to fuel switching (to hydrogen) and materials technologies.

10.3.1.1 *Fuel switching: Hydrogen*

Firstly, there is an increasing recognition of the importance of using hydrogen in industry to achieve climate change-related commitments. Various national hydrogen strategies and incentive schemes have been announced. Global political and economic trends also influence the trends in hydrogen deployment.
For barriers and enablers, a red/amber/green (RAG) rating is also provided to reflect the importance of the barrier or enabler, according to the process and guiding matrix outlined in Section 2.4.1. Please refer to the cross-cutting barriers and enablers section of Chapter 3 of the report for a description of the methodology used to assign these RAG ratings.

Table 10-11: Key drivers of energy policy and market developments globally (hydrogen)

Category	Driver	Description	RAG
Driver	Cost of hydrogen compared to other low-carbon alternatives	The suitability of decarbonisation options is primarily determined by the temperatures and types of heating processes involved, which, in turn, depend on the specific sub-sector of the industry a particular site belongs to. Competing decarbonisation options may include bioenergy, electric kilns/furnaces, and electric heaters for direct heating processes. Meanwhile, for indirect heating processes, alternative decarbonisation options could consist of bioenergy, electric boilers, heat pumps (in select scenarios), and electric heaters (source: Ricardo's expert's judgement).	
Driver	Global political and economic trends	Global political and economic trends significantly impact hydrogen deployment, including factors like the state of the global economy, geopolitics, commodity prices, and the condition of global supply chains. Economic development varies across regions, and the growth outlook is uncertain. While these factors affect hydrogen deployment, recent developments indicate that they have intensified the focus on hydrogen in recent months, which may not necessarily be negative. However, on-	

Category	Driver	Description	RAG
		the-ground deployment is not progressing swiftly enough and must accelerate to fully realise the benefits of hydrogen (Hydrogen Council, McKinsey & Company, 2022).	
Enabler	Climate change-related commitments	While the recent momentum in the hydrogen economy is promising, it is essential to recognise that ambition and proposals alone will not address climate change. Concrete investments and on-the-ground implementation are crucial. Joint efforts between the public and private sectors are urgently needed to move beyond project proposals to FIDs. Globally, 40 national hydrogen strategies have been announced, reflecting countries' efforts to leverage hydrogen's potential for decarbonisation, energy security, and sustainable economic growth. Stakeholders, from governments to industries and consumers, increasingly understand that hydrogen is crucial for achieving net-zero emissions, aligning with countries' climate-related commitments. (Hydrogen Council, McKinsey & Company, 2022). For example, automakers clearly demand green steel, with 3.2 million tonnes of near-zero emissions steel already in demand by 2030, according to the Rocky Mountain Institute (Fastmarkets, 2024).	
Enabler	Incentive schemes to accelerate hydrogen adoption	Incentive schemes aimed at accelerating hydrogen adoption are emerging worldwide. Time is of the essence, and it is crucial to adjust significant controls and bureaucratic processes to align with the situation's urgency and the typical commercial product development timeline (Hydrogen Council, McKinsey & Company, 2022).	
Enabler	Installation of pipeline networks for industrial hydrogen use	For widespread adoption of hydrogen by end users, the hydrogen will be piped from production to user. As the emphasis goes towards greener hydrogen production, the industrial users are not co-located with areas of high renewable opportunity. Therefore, either the electron or the hydrogen molecule must be transported. Furthermore, if hydrogen is to be used for intra-seasonal electricity generation, then the potential areas for large-scale storage are only in some geographical regions, so connecting this to the wider grid will require a national network (source: Ricardo's expert's judgement).	
Enabler	Installation of pipeline networks for industrial hydrogen use	For widespread adoption of hydrogen by end users, the hydrogen will be piped from production to user. As the emphasis goes towards greener hydrogen production, the industrial users are not co-located with areas of high renewable opportunity. Therefore, either the electron or the hydrogen molecule must be transported. Furthermore, if hydrogen is to be used for intra-seasonal electricity generation, then the potential areas for large-scale storage are only in some geographical regions, so connecting this to the wider grid will require a national network (source: Ricardo's expert's judgement).	
Barrier	Non-convertibility of existing facilities	Pure hydrogen cannot replace coal or natural gas in many industry sectors due to the diverse and specific nature of energy conversion devices (i.e., kilns, furnaces, boilers, reactors) used in these sectors. For instance, various factors would necessitate equipment and practice changes in the cement industry, thereby increasing conversion costs. Existing burners might need redesigning to accommodate new media, such as handling the abrasive properties of clinker dust. Moreover, hydrogen can cause corrosion and brittleness when in contact with certain metals, requiring the implementation of new coatings and protective measures (IEA, 2019). If the commitment to decarbonisation stays constant or increases, steel or cement producers will be compelled to invest in new equipment. This necessity will drive up demand for technologies adapted for hydrogen use.	

10.3.1.2 *Recovery and recycling: packaging for foods and drinks*

In **recovery and recycling**, the environmental impact of excessive packaging waste has become a pressing concern recently, and public awareness is growing. Continued research will enable further development and increase the efficiency and scalability of existing chemical recycling technologies. Implementing supportive policies and regulations can incentivise further demand for recycled plastic products. On the other hand, there are several barriers to development, such as the difficulty of recycling some plastics.

Table 10-12: Key drivers of energy policy and market developments globally (recovery and recycling)

Category	Driver	Description	RAG
Enabler	Collaboration	Collaboration among various stakeholders, including researchers, technology developers, waste management companies, brand owners, and policymakers, is crucial for accelerating the development and implementation of effective chemical recycling solutions. By working together, these entities can address challenges, share knowledge, and move towards a more circular economy for plastic packaging (source: Ricardo's expert's judgement).	
Enabler	Environmental and climate-change-related commitments	The environmental impact of excessive packaging waste has become increasingly concerning. According to the OECD, approximately 50% of global plastic waste ends up in landfills each year, totalling around 175 million tonnes. Less than 15% of the remaining material is recycled, and 35% of plastic waste is either incinerated or released into the environment. A study published in the journal Nature Sustainability estimated that 1.9 million tonnes of plastic waste entered the ocean in 2016 alone. Another study from 2022 projected that approximately 8 million tons of plastic leak into the oceans annually (Nanda & Bharadvaja, 2022). Without changes to our current production and consumption patterns, this figure is expected to rise to 23-37 million tonnes per year by 2040.	
Enabler	Technological progress	Continued research and development are essential to improving the efficiency and scalability of existing chemical recycling technologies. Additionally, it is crucial to explore new and innovative approaches that can handle a broader range of plastic waste types and offer even higher-quality recycled products (Source: Ricardo expert).	
Enabler	Growing environmental awareness of consumers	Fostering a strong market demand for recycled plastic products made through chemical recycling is crucial. This involves educating consumers about the benefits of recycled plastics, collaborating with brand owners to increase the use of recycled content in their products, and ensuring the price competitiveness of recycled plastics compared to virgin alternatives (source: Ricardo's expert's judgement).	
Enabler	Legal and regulatory frameworks	Implementing supportive policies and regulations, such as extended producer responsibility (EPR) schemes and mandatory recycled content quotas, can incentivise the adoption of chemical recycling by creating a stable demand for recycled plastic products. Additionally, regulations setting clear standards for the quality and safety of recycled materials are essential for building trust and market acceptance (source: Ricardo's expert's judgement).	
Barrier	Challenges in the recycling process	Several challenges exist to achieving the plastic recycling targets. One is that some types of plastic are difficult or impossible to recycle. Another is that plastic waste often needs to be cleaned and sorted before it can be recycled, which can be costly and time-consuming (source: Ricardo's expert's judgement). Packaging for food or other contact-sensitive applications requires a higher degree of commercial-grade purity for its components. This has been a substantial limitation for the recycling industry, particularly plastic recyclers, which struggle to reach those targets via conventional mechanical recycling processes (source: Ricardo's expert's judgement).	

10.3.1.3 *Low carbon substitutes: Bioplastics*

The bioplastics market is also growing in low-carbon substitutes, with consumers' increasing environmental awareness and corporate ESG policies. However, bioplastics are currently more expensive than petroleum-based plastics.

Table 10-13: Key drivers of energy policy and market developments globally (bioplastics)

Category	Driver	Description	RAG
Enabler	Corporate ESG policies	The bioplastic market is rapidly gaining attention as businesses worldwide face pressure to adopt environmentally friendly and carbon-neutral practices (Nanda & Bharadvaja, 2022). Companies like Coca-Cola and Lego are investing significantly in making their products from 100% bio-based plastics (E4Tech, 2017). Notable multinational companies across diverse sectors have integrated bioplastic into their product packaging. Some examples include supermarket chains like Walmart, Carrefour, Sainsbury, Billa, Spar, and Hofer (BCC, 2021). Danone, for instance, has adopted a sugarcane-derived bioplastic material for its yoghurt containers, reducing the product's carbon footprint by 55% and significantly minimising the company's ecological impact (Casey, 2015).	
Enabler	Use of co-products from production	Co-products from animal processing, such as skins and tallows, can be effectively utilised in producing biodegradable films and PHA (polyhydroxyalkanoates). This not only helps reduce the production costs of bioplastics but also ensures the efficient utilisation of waste materials (Marousek & Stavkova, 2021).	
Enabler	Environmental, climate change and health threats caused by conventional plastics	Conventional plastics pose a significant threat to the ecosystem as they do not biodegrade and consequently accumulate in the environment. These plastics are persistent and leach harmful chemicals into water bodies. Plastic debris in oceans and seas adversely impacts aquatic species through ingestion, entanglement, and suffocation, often resulting in fatalities (Quero & Luna, 2017). Replacing a ton of synthetic plastics with biobased ones reduces 1.8 tons of CO2 emissions (Nanda & Bharadvaja, 2022). Microplastics are increasingly concerning due to their widespread presence in water, food, and air samples and their detection inside the human body (Nanda & Bharadvaja, 2022).	
Enabler	Governments' environmental and climate-change-related commitments	To combat plastic pollution and bolster global climate action, a shift from plastics derived from virgin fossil feedstock to non-fossil alternatives is needed. The future legally binding instrument should encompass the entire lifecycle of plastics, following a circular economy approach, from raw materials extraction to production and from design to use, consumption, and disposal (European Bioplastics, 2023). Last year, 170 nations committed to "significantly reduce" plastic usage by 2030, and many have already taken action by proposing or implementing regulations on specific single-use plastics (World Economic Forum, 2020). Additional policy support is essential to enable bioplastics to become cost-competitive. Standards and legislation should incentivise new product development while addressing associated risks (IBioIC, n.d.).	
Enabler	Growing environmental awareness of consumers	As an expression of a growing environmental awareness of consumers, the demand for bioplastics is rising (European Bioplastics, 2020). Moreover, an overall increase in the purchasing power of consumers should stimulate demand for plastic products in general, thereby also demand for bioplastics (Doehler et al., 2022). Empirical studies document that consumers' willingness-to-pay for environmental protection increases with increasing income (Franzen & Vogl, 2013), potentially giving rise to a more than average demand response for sustainable products. However, whether this materialises for bioplastics as well will depend on the public image of these products (Doehler et al., 2022).	
Enabler	Significance of plastic material and recent increases in usage	Plastic is essential in modern times, contributing significantly to any country's economy through substantial revenue generation and a diverse range of end products across various sectors. The growing population has resulted in a continuously rising demand for plastic goods. An average annual demand of 140 Mt of plastic requires 150 Mt of fossil fuel as an input.	

Category	Driver	Description	RAG
Enabler	Technological progress	Factors such as technological progress and economies of scale influence the development of bioplastics (Doehler et al., 2022).	
Barrier	Competition from petroleum-based plastics	Petroleum-based plastics have been widely utilised for their convenience, versatility, durability, and affordability. This is owing to the well-established processes and mature technology associated with their production (Nanda & Bharadvaja, 2022). Bio-based plastics currently tend to be more expensive than petroleum-based plastics. The overall production costs are influenced by the prices of raw materials, as well as electricity and natural gas prices (Doehler et al., 2022). On the other hand, crude oil prices are at an all-time high, and our fossil reserves are fast depleting (Nanda & Bharadvaja, 2022). The evolution of bioplastic product production in the coming years will heavily depend on the trajectory of conventional plastics prices (Doehler et al., 2022).	
Barrier	Mixed environmental balance	The current generation of food plant-based resources used in bioplastic production has an overall environmental impact that is somewhat mixed. Potential competition exists with food production, and emissions from land use and transformation can be significant (Brizga, 2020).	

10.3.1.4 *Low carbon substitutes: Bio-based chemicals*

A similar situation to bioplastics is in bio-based chemical applications, where petrochemicals dominate the market. There are still some uncertainties regarding their real environmental impact. Bio-based chemicals will need government support to partially de-risk technology development for the private sector to enable further growth. Moreover, stimulating the availability of the primary bio-based chemical feedstock would de-risk part of the business market penetration strategies.

Table 10-14: Key drivers of energy policy and market developments globally (bio-based chemicals)

Category	Driver	Description	RAG
Enabler	Stimulating Availability of Bio-resources	Stimulating the availability, cost, and quality of the primary bio-based chemical feedstock would de-risk part of the business's market penetration strategies. Securing this sector's feedstock is crucial as waste biogenic sources are currently in high demand for other applications like Sustainable Aviation Fuel, Energy, and other fuel production. However, this competition varies considerably among the different geographical areas considered. Examples of viable ways to improve feedstock availability are: • Waste Management Policies; • International trade agreements; • Improve regulation efficiency; • Biomass Sustainability assessment and strategy (*Source: Ricardo experts' judgement*).	
Enabler	Catalyse investment and R&D	Ultimately, biobased chemicals production will most likely require targeted governmental investment programs to support the R&D and commercialisation phases (First of a Kind, FOAK processes), partially de-risking their technology development for the private sector. Other examples of supporting activities to catalyse the technology development are: • Flagship project support; • Targeted Investment Programs; • Techno-economic feasibility studies (*Source: Ricardo experts' judgement*).	

Category	Driver	Description	RAG
Barrier	Competitive position of petrochemicals	Currently, global-scale production of bio-based chemicals is limited primarily because petrochemicals dominate the market. This dominance is due to the cost-effectiveness of oil, the challenge of competing with large-scale integrated oil refineries, and the lack of dedicated incentives for bio-based chemicals (E4Tech, 2017).	
Barrier	Unclear Environmental impact	Despite being less carbon-intensive than conventional chemicals, bio-based chemicals still pose several unknowns regarding their environmental impact (Ogmundarson, Herrgard, Forster, & al., 2020).	

10.3.2 Geographical benchmarking

10.3.2.1 Fuel switching: Hydrogen

Momentum around proposed projects targeting hydrogen end-uses is strongest in Europe, where half of the proposed investments have been announced, followed by the Asia-Pacific region and North America (each about 15% of announced investments). There is significant variation in the focus segments across regions. In Europe, most end-use investments focus on steel (60%), whereas Latin America sees 60% of investments related to ammonia production (the majority of which is intended for export). The Asia-Pacific region focuses on power and transport (about 40% each), while in North America about half of the investments target mobility (ground transportation and sustainable fuels). (Hydrogen Council, McKinsey & Company, 2022).

Table 10-10-15: Major UK competitors globally (hydrogen)

Country	Answer
US	The US has allocated USD 9 billion in funding to develop clean hydrogen hubs and to advance and scale up electrolyser technology. Additionally, tax credits have been granted for carbon capture and storage (Hydrogen Council, McKinsey & Company, 2022). California's Low Carbon Fuel Standard (LCFS) has proven to be a cost-effective demand-pull measure that incentivises fuel switching from fossil fuels to low-carbon alternatives in the transport sector (Source: Ricardo's expert's judgement).
EU	Several EU Member States have introduced policies to foster and support fuel switching. The Netherlands have enacted SDE++, a carbon contract-for-difference scheme that provides a reliable and robust carbon price to support decarbonisation projects. Germany is implementing the H2Global scheme to facilitate hydrogen imports by matching long-term supply contracts with shorter-term offtake contracts. Several national hydrogen strategies have pledged funding to expand hydrogen deployment (e.g., Germany, Spain) (Source: Ricardo's expert's judgement).
Japan and South Korea	Japan's Green Innovation Fund is allocating about USD 2 billion to develop carbon-neutral projects, including advancing liquid hydrogen value chains, among other technologies. Around 60% of the world's fuel cell manufacturing capacity is concentrated in Japan and South Korea, home to some leading vehicle OEMs globally. Japan and South Korea have installed approximately 425,000 combined heat and power (CHP) fuel cell systems that can operate on hydrogen across Japan (Hydrogen Council, McKinsey & Company, 2022).

10.3.2.2 Recycling and Recovery: Packaging for Foods and Drinks

While the US does not apply a single overarching policy promoting chemical recycling in packaging for foods and drinks, it recognises chemical recycling as "recycling", and a national recycling strategy is currently being developed, which will consider how chemical recycling might fit in. In the EU, policies to revolutionise packaging waste management are being implemented, emphasising the exploration of innovative technologies. While no single policy would promote chemical recycling, discussions are ongoing, and the chemical recycling capacity in the EU is expected to grow significantly.

Table 10-16: Major UK competitors globally (recycling and recovery)

Country	Answer
US	While there is no single, overarching policy promoting chemical recycling in the US, several initiatives exist at both the state and federal levels: State-level policies: • Classification as manufacturing: eighteen states have passed laws classifying chemical recycling facilities as manufacturers, not waste-handling facilities. This reduces regulatory hurdles and can incentivise investment in the technology (C&EN, 2022). • Financial incentives: some states offer tax breaks or other financial incentives for companies building or operating chemical recycling facilities (Best Company, 2020).
EU	While there is no single, definitive estimate for the future processing capacity of chemical recycling in the EU, current trends and projections provide some insights: • Current capacity: as of June 2023, the operational chemical recycling capacity in Europe sits at around 364,000 tonnes per year, with 60% of that focusing on pyrolysis technology (Chemical Industry Journal, 2024). • Expected growth: projections indicate a significant increase in the coming years. Industry groups like CRE (Chemical Recycling Europe) expect the total installed capacity to reach 1.7 million tonnes by 2028 in Europe, primarily focused on pyrolysis (Chemical Recycling Europe, 2024).

10.3.2.3 Low carbon substitutes: bioplastics

In bioplastics, the US has set goals to become a leader in bioeconomy technology and to explore innovative technologies to displace the majority of its plastics and other commercial polymers. In the EU, the European Commission adopted a policy framework to promote the use of bio-based plastics and has several policies addressing aspects and applications of bio-based, biodegradable and compostable plastics. In China, the manufacturers plan to increase their biodegradable plastics output significantly. However, there is a lack of infrastructure to support biodegradable plastics production.

Table 10-17: Major UK competitors globally (bioplastics)

Country	Answer
US	In a report released in 2022, the White House Office of Science and Technology Policy (OSTP) outlined what it called bold goals for helping the U.S. to be a leader in bioeconomy technology, produce low carbon-intensity chemicals to fight climate change and shore up domestic supply chains. "In 20 years, [the U.S. should] demonstrate and deploy cost-effective and sustainable routes to convert bio-based feedstocks into recyclable-by-design polymers that can displace more than 90 per cent of today's plastics and other commercial polymers at scale," the report said (Sustainable Plastics, 2023).
EU	The EU has set a target that at least 20% of the carbon utilised in chemical and plastic products should originate from sustainable non-fossil sources by 2030 (European Bioplastics, 2023). The EU could potentially be a significant competitor to the UK in the biobased plastic space, but no specific evidence was identified.
China	Chinese material manufacturers intend to ramp up their production of biodegradable plastics derived from plants significantly, spurred by China's ban on the disposal of plastic bags in 2020 (Nikkei, 2021). However, many major Chinese cities have little or no infrastructure to cope with expanding biodegradable plastics production (BBC, 2020). In response to China's 2020 ban on the disposal of plastic bags, ~40 companies in China have either planned or constructed new biodegradable plastic manufacturing facilities. This expansion is expected to add a production capacity of over 4.4 million tonnes per year, representing a more than sevenfold increase in less than 12 months.
Singapore	Singapore announced in January 2018 the investment of USD 25 million over five years in synthetic biology R&D projects.

10.3.2.4 Low carbon substitutes: Bio-based chemicals

While the US is a global leader in chemical production, biochemicals currently make up only a tiny segment. Iowa has a tax credit program that supports the production of bio-based chemicals. The most significant policy development in the EU was establishing a public-private partnership to replace at least 30% of petroleum-based chemicals and materials with bio-based and biodegradable ones by 2030. In China, significant progress and investment are going into scaling up several industries that make bio-based products, including bio-based chemicals.

Table 10-18: Major UK competitors globally (bio-based chemicals)

Country	Answer
US	Biochemicals currently make up a tiny segment— estimated at less than 1% of the overall revenue and 4% of the overall annual production— of the chemical industry, in which the United States is a global leader in chemical production, second only to China. Iowa has a Renewable Chemical Tax Credit Program, which allocates USD 100 million in tax credits spread over 10 years. These credits are designated for the manufacturing of 40 essential building block chemicals. Under this program, companies can receive a tax credit of USD 0.05 for each pound of biobased chemicals produced in a given year (USDA, 2019).
EU	A public-private partnership between the EU and the Bio-based Industries Consortium allocated approximately 3.7 billion Euros for R&D and innovations from 2014 to 2020. The primary objective is to substitute at least 30% of petroleum-based chemicals and materials with bio-based and biodegradable alternatives by 2030 (E4Tech, 2017).
China	Substantial progress and investment are being made in China to scale up various industries that produce biobased products. These include biobased chemicals such as lactic acid, 1,3-propanediol, and succinic acid. Additionally, investments are directed towards biodegradable biobased polymers like co-polyester of diacid, diol, and polylactic acid. Furthermore, efforts are underway to scale up non-biodegradable biobased polymers, such as bio-based polyamide, polytrimethylene terephthalate, biobased polyurethane, and biobased fibres (USDA, 2019).

10.3.3 UK Competitive advantage: qualitative analysis

Various funds in the UK support industry decarbonisation measures in hydrogen, which might accelerate fuel switching to hydrogen.

10.3.3.1 Fuel switching: Hydrogen

Table 10-19: UK competitive advantages (hydrogen)

Advantage	Description
Economic incentives	Industrial Decarbonisation Challenge Fund invest GBP 170 million in developing technologies such as CCS and hydrogen fuel switching (Department for Business & Trade, 2024). Additionally, the UK launched the sixth competition round of the GBP 289 million Industrial Energy Transformation Fund in October 2022 to support industry investments in energy efficiency and decarbonisation measures, including hydrogen fuel switches. Moreover, the UK government continues to fund innovation in hydrogen end-use through initiatives such as the Net Zero Innovation Portfolio. For instance, the GBP 26 million Industrial Hydrogen Accelerator competition has supported nine feasibility projects focusing on industrial fuel switching to hydrogen. The GBP 55 million Industrial Fuel Switching 2 competition has progressed 21 phase 1 feasibility projects, many involving hydrogen or its derivatives. Furthermore, the GBP 40 million Red Diesel Replacement competition is advancing 17 phase 1 projects related to hydrogen use in construction, mining, quarrying equipment, and hydrogen dispensing at remote sites (BEIS, 2022).
Experimentation	In 2018, BEIS appointed Arup+ to investigate the potential use of hydrogen for heating homes and businesses. This program was funded under the Hy4Heat initiative.

Table 10-20: UK competitive disadvantages (hydrogen)

Disadvantage	Description
Demand uncertainty	The UK's potential to develop an export market is closely tied to its ability to create a domestic market. Although there are economic incentives to produce hydrogen to meet the UK's 10 GWO low carbon hydrogen target, there is only a viable project if there is demand for the hydrogen. Until there is a significant demand, investors will be very cautious in investing, which will slow the innovation needed. To address uncertainties, the UK government needs clear policy frameworks, regulatory support and financial commitments (House of Commons, 2022).

10.3.3.2 Recycling and recovery

In packaging for food and drink applications, the UK supports chemical recycling through the Plastics Innovation Fund and is developing its regulations to support chemical recycling further. The UK also possesses a strong R&D base, and its current Oil&Gas infrastructure can be adapted or integrated with chemical recycling facilities and can thus offer a competitive advantage.

Table 10-21: UK competitive advantages (recycling and recovery)

Advantage	Description
Policy and Innovation Support	The UK government has actively supported chemical recycling through initiatives like the **Plastics Innovation Fund**, aiming to create an environment for the technology's development and commercialisation (Source: Ricardo's expert's judgement).
Regulatory Framework	The UK is currently developing its regulations for chemical recycling, potentially allowing for a more streamlined and efficient approach compared to the ongoing discussions and uncertainties within the EU. This clarity could attract investors and businesses looking to enter the market (Source: Ricardo's expert's judgement).
Existing Infrastructure	The UK already possesses a developed waste management and Oil&Gas infrastructure, which can be adapted or integrated with chemical recycling facilities. This can offer cost advantages compared to starting with a grassroots approach (Source: Ricardo's expert's judgement).
Feedstock availability	The UK is one of the largest producers of waste plastic, and its efficient waste segregation and collection system would allow the generation of consistent feedstock streams for chemical recycling or advanced recycling businesses (Source: Ricardo's expert's judgement).
R&D	The UK has a strong research base focused on sustainability and circular economy solutions. This could lead to further advancements in chemical recycling technologies, offering innovative solutions to the global plastic waste challenge (Source: Ricardo's expert's judgement).

Table 10-22 UK competitive disadvantages (recycling and recovery)

Disadvantage	Description
Legal Status Unclear	Chemical recycling technologies still present an unclear legal status in the UK. Most technologies may sit between the chemical manufacturing and the waste management sector, potentially increasing the risk associated with its implementation. This is mainly due to the following elements: 1) The definition of recycling is still unclear at the policy level. 2) Several products or by-products (e.g., Biochar and Pyrolysis oil) do not have an appropriate End-of-Waste status. Therefore, it is currently unclear whether they should be considered products or waste. 3) The Industrial Emission Directive (IED) presents some ambiguities regarding its application for a chemical recycling process, which, in some cases, demands the application of the same emissions standards that larger waste management plants require (e.g., Energy from Waste) rather than the ones needed for the chemical sector. This considerably impacts both CAPEX and OPEX on these plants, increasing their feasibility and technology development (Source: Ricardo's expert's judgement).
Waste export & financial viability	Currently, a large volume of plastic waste is still exported from the UK. This is due to several factors, including the absence of an extended plastic recycling value chain in the country and the limited cost associated with the export fees. Similarly to the previous point, this has partially limited the viability of the development of these technologies in the country (Source: Ricardo's expert's judgement).

10.3.3.3 Low carbon substitutes: Bioplastics

The UK's competitive advantages in **bioplastics** include its world-leading engineering biology sector, established agricultural sector, and strong R&D base, which can be **leveraged for bioplastics innovation**. The consumer demand for bioplastics is growing due to increasing environmental awareness.

Table 10-23: UK competitive advantages (bioplastics)

Advantage	Description
World-leading engineering biology sector	The UK is home to a world-leading engineering biology sector, leveraging its robust life sciences base, which encompasses both health-related and non-health-related bioscience and biotechnology. This advantageous position presents a unique opportunity for the UK to establish technological leadership and unlock economic and societal value through engineering biology. Regarding research investment and excellence, the UK ranks among the global leaders in engineering biology, second only to the US (Royal Academy of Engineering, 2019).
Strong agricultural sector	The UK's established agricultural sector can provide a readily available source of raw materials for bioplastic production, creating a strong foundation for the industry. Feedstock like crop residues and waste, non-edible plant parts, and similar can be used for bio-based plastics. The new generation of bioplastic production (2010 -2020) is focused on adopting only waste biogenic feedstock to limit the competition with food production (Source: Ricardo's expert's judgement).
R&D	The UK has a strong research base in various fields, including materials science and sustainable technologies, which can be leveraged for bioplastics innovation (Source: Ricardo's expert's judgement).
Growing consumer demand	As consumer awareness of environmental issues increases, the demand for sustainable products like bioplastics is expected to rise, offering a potential market advantage for the UK and the EU regions as well (Source: Ricardo's expert's judgement).

Table 10-24 UK competitive disadvantages (bioplastics)

Disadvantage	Description
Direct and Indirect Pricing supporting Mechanism	As mentioned, bioplastics' cost is still higher than most conventional, fossil-derived materials, either locally or imported. A combination of direct and indirect price-supporting mechanisms and mandates should be adopted to increase the technology development rates. Examples are: • Carbon adjustment mechanisms • Carbon tax • Bioplastic Mandate (Binding targets for replacing part of packaging materials with biogenic-derived ones). • Direct support mechanism (Capex, Opex taxation regimes). At the moment, the UK lacks several of these mechanisms in place, which limit technology development and inhibit investors' interest in the sector (Source: Ricardo's expert's judgement).
Feedstock Availability	The raw materials used to produce bioplastics need to be sustainable. However, ensuring a consistent and reliable supply of these feedstocks can be challenging, especially for large-scale production, considering the direct competition with other production processes (Source: Ricardo's expert's judgement).
Infrastructure and Standardisation	The infrastructure for collecting, sorting, and processing bioplastics is not as developed as conventional plastics. Additionally, there's a need for further standardisation across the bioplastics industry to ensure quality and consistency (Source: Ricardo's expert's judgement).

10.3.3.4 Low-carbon substitutes: bio-based chemicals

The UK has a strong research base in various fields, including materials science and sustainable technologies, which can be leveraged for bioplastics innovation. It has a world-leading engineering biology and chemical sector. The UK holds a competitive advantage in synthetic biology, biocatalysis, chemistry, and polymer research and development capabilities. Its primary opportunity lies in the manufacturing of specialised bio-based chemicals characterised by high market values and low volume demands. The UK possesses an expanding academic and industrial foundation in bio-based fuels and chemicals.

Table 10-25: UK competitive advantages (bio-based chemicals)

Advantage	Description
Manufacturing of specialised bio-based chemicals	In the UK, a significant opportunity exists in manufacturing specialised bio-based chemicals characterised by high market value and relatively low volume demands, typically ranging from 5 to 20 kilotons per year. These bio-based chemicals could seamlessly integrate into the UK's supply chain, benefiting from both feedstock supply and integration into downstream sectors. However, deriving value from bio-based chemicals in the UK does not necessarily require local manufacturing. Significant value can be generated through various aspects of the value chain and diverse business models, including technology licensing and the exportation of services and knowledge. The UK possesses a competitive advantage in synthetic biology, biocatalysis, chemistry, and polymer research and development capabilities (E4Tech, 2017). This positions the country favourably to establish intellectual property in this domain, offering the potential for monetisation through the sale of technology licenses and services.
Expanding academic and industrial foundation	The UK possesses an expanding academic and industrial foundation in bio-based fuels and chemicals, complementing a robust and well-established chemical industry (E4Tech, 2017). This positions the UK favourably to capitalise on and leverage emerging growth opportunities within the biobased chemicals sector.

Table 10-26 UK competitive disadvantages (bio-based chemicals)

Disadvantage	Description
National feedstock (biomass) availability and prices	The UK may not be strongly positioned for the manufacturing of large quantities of bio-based chemicals. Native feedstock (biomass) availability and feedstock prices are likely to limit the potential of drop-in commodity-type bio-based chemicals, which are often needed in larger volumes, above 100 kilotons per year. Thus, for the UK, the opportunity may mostly be in the manufacturing of specialty-type bio-based chemicals that have high market value and relatively low volume demands (E4Tech, 2017).

10.3.3.5 UK Competitive advantage: key conclusions per technology

In the following table, we classify each technology as being either:

- A “**primary focus area**”, i.e., an area where the UK is expected to have a consolidated advantage;
- A “**further opportunity**”, i.e. an area where the UK could gain a competitive advantage from positioning itself as a potential early mover; or
- A “**lower potential”** area, in red, i.e. an area on which the UK does not appear to have potential.

Table 10-27: Technologies classification based on UK competitive advantage

Tech family	Technology	Application	Classification	Description
Fuel switching	Hydrogen	-	Primary focus area	Although there remains some uncertainty as to which technologies will dominate decarbonisation strategies, some estimates of the future global market size for hydrogen switching in industrial applications indicate good levels of growth. The UK may be well positioned to focus on this market, as it has strong regulatory and policy support in place, such as the UK industrial decarbonisation plan, and significant funding and economic incentives are provided by the government, including the Industrial Hydrogen Accelerator. There are also several manufacturers of the technologies used for fuel switching present in the UK.
Materials	Recycling and recovery	Packaging for food and drinks applications	Primary focus area	The UK presents a unique mix of enabling factors that, if combined with its extensive knowledge of waste management and Oil&Gas technology, could generate a considerable competitive advantage, especially against the European and North American regions.

Tech family	Technology	Application	Classification	Description
				It is worth noting that the UK government is already supporting the generation of alternative fuels from waste (i.e., SAF) via chemical recycling (DfT Advanced Fuels Program or AFF) in the country, which would enable the application of this technology to the recycling sector as well. Given the recent and estimated trends in the sector, recycling and recovery of contact-sensitive applications (food and healthcare applications that require low contamination and high purity), especially plastic packaging, should be a priority (source: Ricardo's expert's judgement).
	Low carbon substitutes	Bioplastics	Primary focus area	Given the long legacy that the UK has in producing chemicals and petrochemical products, bio-based chemicals represent the natural evolutionary step for the sector. As discussed in the previous sections of the present report, the sector is mature in the UK and able to compete on a worldwide scale. A combination of extensive chemical manufacturing know-how and continuous support of R&D projects in the country are the key elements to enhancing the UK's already-existing competitive edge within this sector (source: Ricardo's expert's judgement).
		Bio-based chemicals	Further Opportunity	Similarly to Bioplastics, the UK presents some key advantages in the sector. However, the use of bio-based chemicals and their real environmental impact compared to conventional products still present several gaps, which would make this sector less attractive than others (source: Ricardo's expert's judgement).

As mentioned previously in the present report, Ricardo has focused the scope of this study only on three promising applications out of many possible industry applications. However, given the maturity of the country's manufacturing sector, additional technologies might be considered Primary Focus Areas or Further opportunities.

11. RQ3: BENEFITS AND COSTS OF BEING AN EARLY MOVER

11.1 INTRODUCTION

This chapter aims to draw lessons from other countries that have been early movers in green technology. These lessons are intended to inform decisions on the likely benefits and drawbacks of the UK's attempt to seize a first-mover advantage in currently developing technologies, such as floating offshore wind power generation.

A long list of country case studies was presented to DESNZ based on a preliminary review of relevant literature and in consultation with Ricardo experts on in-scope technologies to this report. DESNZ then selected three case studies they deemed most informative for review. This selection process yielded the following three case studies, which span a range of geographies and time periods, allowing us to draw insights using both historical data and the recent geopolitical context:

- **Morocco**: Concentrated solar power (CSP), mid-2000s onwards
- **Denmark**: 3rd generation heat networks[38], 1970s onwards
- **France**: Nuclear power, 1970s onwards

A literature review has been conducted on these case studies. Within each case study, the context of the early adoption is explained first. Then, the advantages and disadvantages to the 'host country' of the relevant technology's early adoption are reported. Finally, conclusions are drawn on the extent to which the benefits outweighed the disadvantages.

11.1.1 Key takeaways

- While learnings can be drawn from case study examples, realised outcomes are highly technology-dependent and should be considered in the context of contemporary external drivers. This is particularly evident in the French nuclear case study, where political path-dependence is evident.
- Arguments *for* the UK trying to develop an early mover advantage include the potential to dominate the export market if sufficient **entry barriers** are generated (as Denmark managed to achieve in the district heating sector), to the extent that efficiencies gained from early investment can be prevented from diffusing across borders into other countries. The Morocco case also highlights that **spillover benefits** in other industries can be significant.
- Arguments *against* the UK committing to early investment in green technology primarily include the **technology selection risk,** where the technology is replaced or not adopted globally to the same extent as a competitor technology. Morocco experienced this in their early adoption of CSP, as did France, with investments in particular specifications of nuclear reactors, where learnings were not transferable into more widely adopted variants. Furthermore, to the extent that **cost efficiencies can be imported** from other countries, it may be better for the UK to wait and avoid the costs of early investment and associated early inefficiencies.
- On balance, decisions to attempt to become an early mover should stem from a degree of confidence in the global adoption of the technology and the UK's capacity to retain its early advantage into the future. This decision should also depend on policy goals and government priorities, particularly balancing the benefits of potentially becoming a global leader in that technology and the potential stimulation of related domestic industries with the risk of replacement by competitor technologies.

11.2 CASE STUDY 1: MOROCCO, CSP

11.2.1 Context

There is supporting empirical evidence to suggest that countries promoting renewable electricity policies and installing renewable capacity earlier than others lead to competitive advantage in renewable power exports[39], which is sustained in wind power and briefer (tapering off after 4-5 years) in solar power (Kuik, Branger, &

[38] 3rd generation heat networks as defined by (Lund, et al., 2014)

[39] The authors found that a country where wind power represented 10% of electric capacities three years earlier will have exports 112% higher than a country where wind power represented 5% of electric capacities. For solar PV the exports would be 35% higher under the same configuration.

Quirion, 2019). While late adopters, often lower GDP countries, appear to be able to utilise the experience of early movers to accelerate domestic market growth[40], early movers seem to continue to capture more of this growing global market, suggesting that late adopters have difficulties accessing and/or utilising the global experience pool (Gosens, Hedenus, & Sandén, 2017).

While Morocco has also been an earlier adopter of wind technologies, Morocco's early commitment to CSP capacity is more unusual in the international context, where there is again evidence of an early mover advantage. Morocco made an early commitment to renewable energy, starting in the mid-2000s and accelerating in 2009 with an ambitious plan for 42% of its installed electrical capacity to be renewable by 2020. Morocco fell short of this target, achieving the capacity to produce 37% of its energy consumption from renewables and ultimately achieving a renewable share of around 20% of final energy consumption (BBC, 2021), but this commitment had various benefits, as will be described in the next section. Since then, this target has risen to 52% by 2030 and 80% by 2050, and a large proportion of the 2030 target is to be delivered by solar power (20% solar, 20% wind, 12% hydro) (IEA, 2019). The goal is to reduce the Kingdom's dependency on oil (95% of energy needs in 2014) and develop a competitive advantage in renewable energy production over the longer term.

The hallmark project demonstrating Morocco's early commitment to solar power is the Ouarzazate Solar Complex Programme (500 MW), a large-scale concentrated solar power (CSP) project scheduled to be implemented in phases. The first phase (Noor I) is designed to demonstrate that CSP projects are both viable and profitable (EY, n.d.) and became operational in 2016. Later phases (Noor II, III and IV) went live in 2018. These capacities have enabled Morocco to develop export potential - Projects have already reached sufficient scale to allow the exportation of renewable power to Spain, Algeria, and Portugal (ITV, 2021), and the announced Xlinks project will have the capability to supply 8% of Great Britain's electricity needs via dedicated sub-sea cables (Xlinks, n.d.)

11.2.2 Advantages and disadvantages of being an early mover

In the tables below, we discuss the advantages and disadvantages of being an early mover, which we were able to extract from researching the available literature for this case study.

Table 11-1: Advantages of being an early mover, Morocco CSP case study

Advantage	Discussion
Technological advances and reductions in technology cost	Early development of skills and learning effects in implementing CSP technologies has led to technological improvements that have improved Morocco's competitive advantage. To illustrate, NOOR I can store three hours' worth of energy, while NOOR II and III will store seven hours' worth, improving its grid balancing capabilities. Electricity generated by NOOR I cost USD 0.245 per kilowatt-hour (kWh) – this has dropped to USD 0.19/kWh for NOOR II (World Bank, 2016). In this regard, it is too early to judge whether Morocco gained from moving early in CSP: to do so, one would have to demonstrate that other countries did not achieve similar learning effects. To the extent that the global average levelised cost of CSP generation fell to the same degree globally as it did in Morocco over the NOOR I/II period[41], this suggests that this benefit was more limited in Morocco's case. However, Morocco comprised 8% of global installed CSP capacity in 2022, so it is challenging to disentangle Morocco's impact from international trends.

[40] The authors find that late adopter countries have managed market growth for wind power that was up to 4.7 times faster than it was in early adopters, and up to 16 times faster for PV.

[41] The global weighted average LCOE for CSP projects is reported as falling from USD 0.24-USD 0.28/kWh in 2016 to USD 0.16-USD 0.23 in 2018 **Invalid source specified.**.

Advantage	Discussion
Spillover benefits to adjacent industries	The rapid scale-up of cheaper renewable energy has led to the realisation of Morocco's potential to generate green hydrogen[42], created speculation that Morocco will become a seedbed for automotive production for export to the EU[43], and decarbonised agricultural value chains via solar agri-voltaics (ESI Africa, 2023), to name but a few. Steam, a by-product of the CSP process, is also currently being used for the extraction of hard-to-reach oil deposits but could be used for other processes that address the region's needs, such as water desalination (World Bank, 2016). These benefits would occur whether Morocco was an early mover or not, but here, it is evident that benefits arise from stimulating economic development in other sectors earlier rather than later, especially given rising water scarcity and the uptick in demand for low-carbon vehicles.
Capacity building and skills development	The NOOR I project was expected to demonstrate how major construction and engineering projects can develop local skills while improving infrastructure. There was a requirement in Noor I to source 30% of its components locally (World Bank, 2016), which incentivised higher value-added manufacturing for the supply of parts. Empiric evidence shows that the local population has benefitted from local employment opportunities, strengthened capacity and improved local infrastructure, although these are linked predominately to the construction phase and are not expected to remain throughout the operational phase (Terrapon-Pfaff, Fink, Viebahn, & Jamea, 2019). Given that late adopters tend to have difficulties accessing and/or utilising the global experience pool (Gosens, Hedenus, & Sandén, 2017), there is potential for Morocco to continue to benefit from greater domestic CSP skills relative to other countries, but this effect is difficult to substantiate.

Table 11-2: Disadvantages of being an early mover, Morocco CSP case study

Disadvantage	Discussion
Premature technology selection	Whilst CSP and photovoltaic (PV) installations are not directly comparable given the added flexibility CSP provides in being able to store energy and release overnight, the World Bank point out CSP has struggled to compete with PV on price, for which capital costs have dropped further and faster, to half that of CSP (World Bank, 2016). Morocco could have supported solar PV instead and benefitted from decentralised, smaller-scale generation systems relying on PV, allowing for more local autonomy from the grid, technically and economically (Aoui, Amrani, & Rignall, 2020). This has had moderate financial ramifications for the Moroccan state, which faces a deficit of around EUR 80 million every year to prop up the price differential (Friedrich Naumann Foundation, 2021).

11.2.3 Conclusions

On balance, whilst the potential for Morocco to gain competitive advantage through early adoption of CSP is evident in the literature on renewable energy in general, the early evidence suggests that the technology cost learning effects have not directly led to revealed competitive advantage as demonstrated through levelised cost of energy data. Moreover, Morocco continues to have to financially subsidise the cost of CSP electricity, given that the cost of alternative renewables (solar PV, wind) has fallen faster, demonstrating the risk posed in committing to technology for early movers. There are some (potentially substantial) spillover benefits into other industries, like green hydrogen and low-carbon automotive production, where early adoption of one

[42] Early commitment to solar power led to independent assessments being made for the country's potential to produce green hydrogen. One estimate puts daily annual production between ~6,500-8,300 tonnes/km^2 , at a cost of 5.79–4.64 USD /Kg **Invalid source specified.**. Consequently, Morocco has formed a partnership the International Renewable Energy Agency, received pledges of EUR 300 million from Germany to support green hydrogen development, and an agreement from France's Total Eren to invest USD 10 billion in a hydrogen and green ammonia project. (IEA, 2019)

[43] analysts from Fitch Solutions argue that Morocco will be a strong contender for FDI inflows given (a) Renault and PSA have well-developed supply chains in Morocco, (b) both giants have large markets to service in Europe, and European regulations are driving the shortening and greening of supply chains, (c) labour is cheaper in Morocco compared to competitor nations in central and eastern Europe **Invalid source specified.**. Linked to green hydrogen production above, the likelihood of FDI would only grow if Morocco continued to explore moving up the supply chain to produce green steel in automotive production (IEA, 2019).

technology can lead to a competitive edge in other sectors, but it is difficult to separate these effects from Morocco's concurrent adoption of other forms of renewable energy (wind, hydro).

There are two crucial lessons in this regard:

(a) **Technology selection is a substantial risk** – there should be sufficient confidence that the technology selected at least has the potential to be cost-competitive before large-scale commitments are made. Otherwise, there is a risk that this technology will be replaced on a global scale, and the UK will be the only one trying to develop it.

(b) **Spillover benefits in other industries can be significant** – especially in renewable power, where carbon is increasingly being priced into products and services, it will be increasingly important to decarbonise the entire value chain, starting with energy generation. Creating low-carbon goods and services can now future-proof exports from forthcoming regulations that are expected to penalise those with high embedded carbon.

11.3 CASE STUDY 2: DENMARK, 3RD GENERATION HEAT NETWORKS

11.3.1 Context

Heat networks (also known as district heating) supply heat from a central source to consumers via a network of underground pipes carrying hot water. Heat networks can cover a large area or even an entire city or be fairly local, supplying a small cluster of buildings. This avoids the need for individual boilers or electric heaters in every building (BEIS, n.d.).

After the energy crisis in the 1970s, where petroleum supply fell sharply, and energy prices correspondingly spiked, Denmark sought to rapidly reduce its nearly 100% dependency on imported energy and considered two alternative solutions: district heating and nuclear power. These were both relatively novel technologies at the time. While district heating was a well-established technology, the Danes proposed a lower temperature distribution than what was traditional, later named '3rd generation'. Following public backlash to the nuclear route, the 1979 Danish Heat Supply Act established a legal framework for the large-scale collective heat infrastructure planning initiatives, and a vote was taken in 1985 against the inclusion of nuclear power in the Danish energy system, solidifying the beginning of their early adoption of this form of district heating (Johansen & Werner, 2022). [44]

11.3.2 Advantages and disadvantages of being an early mover

In the tables below, we discuss the advantages and disadvantages of being an early mover, which we were able to extract from researching the available literature for this case study.

Table 11-3: Advantages of being an early mover, Denmark district heating case study

Advantage	Discussion
Dominant global market position	In its domestic market, 63% of all private Danish households are connected to district heating for space heating and domestic hot water, most of which are supplied and operated by Danish entities (State of Green, 2018). This has benefited the country domestically and created opportunities for Danish companies to export their knowledge and technologies to other countries pursuing sustainable energy solutions. A Danish company currently holds approximately half the global market of heat meters (Kamstrup), and Denmark is a market leader in prefabricated district heating pipes, substations, and district heating consulting services[45] (Johansen & Werner, 2022). To emphasise the point, a recent assessment of Scotland's competitive potential in district heating identified "significant market entry barriers" in the manufacturing of equipment used in district heating, citing Denmark as a key competitor (Ramboll, 2024). This market position would not have been possible without the aggressive government support for district heating in the latter part of the 20th century.

[44] In June 2022, Denmark reached a broad agreement that supports 100% biomethane in heating by 2030. Denmark had already decided to phase out natural gas use by switching to district heating and heat pumps – arguably, replacement of natural gas with renewables would have been more challenging if not for their widespread adoption of district heating (IEA, 2023)

[45] Companies representative of the market-leading positions include Løgstør Rør/Logstor for prefabricated district heating pipes, Danfoss and Grundfos for prefabricated district substation, and Ramboll and COWI for district heating consulting services.

Advantage	Discussion
Positive international reputation	Denmark's early knowledge gained and implementation experience allow the Danish government to pro-actively export the fundamental idea of district heating via the government programme 'Global Cooperation', of which district heating comprises a substantial part of this programme (Johansen & Werner, 2022). This enables Denmark to cooperate with other countries on lessons learned, stay on top of evolving and innovative technologies (creating new opportunities), and market itself for further export opportunities (State of Green, 2018).
Technological development and cost reductions	Costs for investment in district heating have fallen in Denmark to the point where, in 2013, it was the cheapest method of decentralised building heating compared to competitor technologies[46] when expressed in total cost of ownership terms (Gudmundsson, Thorsen, & Zhang, 2013). As a result, the average price of district heating for Danish consumers has decreased significantly in recent years[47] (Johansen & Werner, 2022). Early adoption has enabled Denmark to stay cost-competitive with emerging competitor technologies. Still, it is unclear how much costs would have fallen if Denmark had waited for another country to make the investments and then adopted the new practices themselves.

Table 11-4: Disadvantages of being an early mover, Denmark district heating case study

Disadvantage	Discussion
Suboptimal operation and inefficiency	There is evidence of large inefficiencies in the historical implementation of district heating in Denmark (Agrell & Bogetoft, 2005). The sector was characterised by heavy governmental involvement on the supply and demand side, by subsidies for investments, fuels, preferential feed-in tariffs and connection rights. This evidence shows that the impact of governmental action (plant size, fuel choice, network configuration) is likely to be three times more important than managerial performance in creating these inefficiencies (Agrell & Bogetoft, 2005). This highlights the risk for early movers to make decisions based on early results that may not reflect the optimal strategy, which later adopters can learn from and avoid the early inefficiencies.

11.3.3 Conclusions

Denmark's example demonstrates that the advantage of being an early mover depends on the relationship between the benefits of early scaling (and associated with technology cost reductions) and the drawback associated with other nations potentially capitalising on Denmark's learnings that lead to those cost reductions (by eliminating inefficiencies). Despite Denmark's international activity in spreading knowledge on good district heating practices and novel technologies, other countries still do not seem to be able to compete with Denmark. Therefore, this activity does not seem to have diminished Denmark's hold over the global market.

One main lesson can be learned from Denmark:

- Waiting for technology costs to fall elsewhere (i.e., for other countries to make the initial investment) may not necessarily lead to falling domestic costs. If the UK waits for another country to be the first mover instead of investing itself in the hope that the other country will reduce costs for everyone, there is a risk that the UK will then need to import those technologies from the early mover rather than producing them domestically.

[46] The other decentralised building heating solutions were gas boilers, air source heat pumps, ground source heat pumps, solar thermal, and electric boilers.

[47] The number of companies charging more than 20,000 DKK annually for heating an average household fell from 53 companies in 2014 to 15 companies in 2019. Likewise, those charging less than 10,000 DKK annually for heating an average household rose from 13 companies in 2014 to 29 companies in 2019.

11.4 CASE STUDY 3: FRANCE, NUCLEAR POWER

11.4.1 Context

During the post-WWII reconstruction period, the French economy relied heavily on energy-intensive industries. To meet increasing energy needs, France depended on energy imports. Accounting initially for 38% of France's energy consumption, energy imports increased to over 75% by 1973 (IAEA, 2022). This heavy reliance on imports coincided with the first global oil crisis and the associated increased volatility in energy prices. The economic consequences of dependence on energy imports strongly drove France to push for more energy security. To achieve this, France implemented the world's largest nuclear power program at the time, ordering 26 reactors within three years (Perrier, 2018). The rapidly implemented program was successful and cemented France's position as one of the first adopters of nuclear power (i.e., France, the UK, the USA, and the USSR) (Brutschin, Cherp, & Jewell, 2021).

Several reasons placed France in the unique position of being able to implement the nuclear program successfully:

- As discussed above, France pushed for energy independence from fossil fuel imports.
- France could leverage its advancements in nuclear technology for military applications for implementing nuclear energy technologies (Stuart, 2017), (Kim, Yasmine, Yim, & Chirayath, 2023).
- France had a close connection between its nuclear industry, the government, and the traditional French technocracy, providing a homogenous background in education (Stuart, 2017).
- France's institutional structure and centralised decision-making enabled France to rapidly and substantially increase its nuclear capacity more easily than other countries (Grubler, 2010). Enabling state support for technological developments proved to be essential for nuclear power (Brutschin, Cherp, & Jewell, 2021).

11.4.2 Advantages and disadvantages of being an early mover

In the tables below, we discuss the advantages and disadvantages of being an early mover, which we were able to extract from researching the available literature for this case study.

Table 11-5: Advantages of being an early mover, France nuclear power case study

Advantage	Discussion
Global dominant market position	Evidence from the literature suggests that the global market for nuclear technology was tight between 1955 and 1980 (De la Torre, Rubio-Varas, Sánchez-Sánchez, & Sanz Lafuente, 2022). Over the last 70 years, only five countries out of twelve manufacturers have become exporters of nuclear technology[48] (Rubio-Varas, De la Torre, & Connors, 2022). A tight market implies early movers can consolidate their market share, establishing high entry barriers for competitors.
Geoeconomic lock-in	Nuclear technologies differ according to the fuel powering the reactors. Choosing a nuclear technology implies selecting one or more fuel suppliers. As Roitto, Nevalainen and Kaarkoski (2022) discussed, this choice mirrored the political path-dependence of the country sourcing nuclear technology and fuel from abroad. At the beginning of their nuclear industry, the UK and West Germany were atomically dependent on the US, as was France, which imported and adapted technology from the US, while Finland had to show neutrality (Roitto, Nevalainen, & Kaarkoski, 2022). From this perspective, being an early mover and building a dominant market position can affect the choice of the fuel supplier, strengthening or weakening the geoeconomic ties of the customer country with its allies.

Table 11-6: Disadvantages of being an early mover, France nuclear power case study

Disadvantage	Discussion
Potential adoption of inefficient design	France's nuclear energy development was initially based on gas graphite reactors. However, after international developments, France decided to shift its focus to light water reactors (LWRs), resulting in a rapid re-development of the country's nuclear industry, which involved significant monetary and

[48] The US, Russia, France, Canada and Germany have managed to become true exporters of nuclear technology between 1950s and 2020, while China, Czech Republic, India, Japan, South Korea, Sweden and the UK have not managed to reach this results despite having manufactured at least one commercial nuclear reactor (Rubio-Varas, De la Torre, & Connors, 2022).

Disadvantage	Discussion
	infrastructure investments (Lee & Gloaguen, 2015). Additionally, in the late 1960s, France recognised that its reactor design did not compare favourably to other light reactor designs internationally in terms of efficiency and had to make significant additional investments to procure and develop an alternative reactor design, i.e. the Westinghouse nuclear reactor, which became the new French standard in the period 1974-1981 (IAEA, 2022). Due to the early adoption of nuclear energy technologies, France set itself upon multiple technological paths, requiring additional investment. This represented a disadvantage compared to the experience of late adopters waiting until an effective design was identified before procuring nuclear reactors. Indeed, as an early mover, a country can adopt a technology that could not emerge as the winning one in the long run.
Non-transferable expertise	While the skills needed to develop a specific type of reactor can be utilised to create a new model, transferring expertise is not usually straightforward. This can lead to a loss of expertise gained as an early mover in the case of innovation. According to Berthélemy and Escobar Rangel (2015), learning-by-doing spillovers are relevant only when reactors of the same model are built by the same architect-engineer firm. A possible explanation could be that technology scale-up leads to an increase in systems complexity that translates into an increase in costs or "negative learning" ((Grubler, 2010). In this sense, moving early in a technology with a small range of models could reduce the economic opportunities in the future.

11.4.3 Conclusions

Adopting nuclear energy and nurturing a State-led manufacturing landscape have made France one of the top five exporters of nuclear technology worldwide. However, as discussed above, France has enjoyed advantages but has faced drawbacks due to being an early mover. On the one hand, France has established a market position in a tight market as an early mover. This anticipated entry allowed the setting of technological standards, increasing the market barriers for potential competitors and fostering a technological lock-in for customers. In addition, fostering a technological lock-in has implied the selection of the fuel needed to power that technology. Selecting a fuel means choosing a supplier. From this point of view, as an early mover, it is possible to strengthen or weaken the geoeconomic ties of customers with their allies. Despite these benefits, disadvantages have been present, too. Indeed, France had to undertake several investments to adapt to innovation. On the one hand, being an early mover implies adjusting prior industrial choices if another technology establishes itself as the prominent one. On the other hand, expertise gained with a technology model cannot be translated into a different model. In this sense, innovation in the nuclear sector can reduce the potential benefits of learning effects as an early mover if another model emerges as the prominent one.

For the UK, one main lesson can be learned from France:

- **Being an early mover means betting on a specific technology**, hoping it will emerge as dominant. This risk can translate into investment losses, requiring additional adaptation costs to keep current market shares. In this sense, picking up winners can also mean picking up losers.

11.5 SUMMARY

The case studies on the early adoption of green technologies offer valuable insights into the benefits and challenges associated with the UK's earlier commitment to investment in green technologies relative to other countries (being an 'early mover').

There is clearly potential for early investment to achieve technology cost reductions that could put the UK in a favourable position in international price competition. The Denmark and France case studies highlight that associated benefits could include the establishment of the UK as a global leader in that technology, creating barriers to entry, restricting access to competitors, and building domestic skills to facilitate longer-term export potential. The Morocco case highlights that this can also stimulate other domestic industries, which could increase competitive advantage in those industries.

However, there is an alternative strategy of allowing other countries to invest first, whereby the UK could import knowledge and expertise learned in other countries and avoid the initial investment costs (and associated low initial production efficiencies). This strategy has the added benefit of preventing technology displacement risk – if other competitor technologies displace the one that the UK has invested in, as renewables have done to nuclear power and solar PV has the potential to do to CSP in Morocco, global focus on cost reduction research skews to the competitor technology, and the UK's export potential shrinks.

Optimal investment decisions, therefore, depend on long-term national objectives and priorities of governments when deciding whether to pursue early adoption of green technologies. If the goal is to minimise technology costs, importing knowledge and expertise from other countries might be more cost-effective. However, this comes with the risk that other countries will generate barriers to entry, and the UK may have to import those technologies in the future. If the government's priority is establishing the UK as a global leader in manufacturing, creating barriers to entry and stimulating domestic industries, being an early mover may be more advantageous.

12. RQ4: THE IMPACT OF FASTER TRANSITIONS ON COST CURVES

12.1 INTRODUCTION

This section presents the impact of different GHG mitigation pathways on the capital costs of key technologies, how this affects production costs, and how it may generate potential competitive advantages. The analysis considers the impact of learning by doing and learning by R&D on production costs. Impacts on costs are evaluated for each scenario and clean energy technology.

Not all clean energy technologies are at the same technological readiness/maturity level in terms of capital costs. Some technologies (like EV batteries and hydrogen) are at the early stages of their learning curve, whereas others are much more mature (like Wind turbines and PV). Escalation of GHG emission reduction targets, increase the demand/supply of clean energy technologies and drive cost reductions through economies of scale and innovation acceleration. Cost reductions are achieved through:

- **Learning by doing:**
    a) Over time, as industries repeat the production of technologies, they become more adept at manufacturing, installing, and maintaining them.
    b) Scale: Where fixed costs are high, increasing the production volume allows significant cost reductions.
- **Learning by research (innovation):** Knowledge created directly through R&D or indirectly through knowledge spillovers allows technology to improve in many aspects (design, material requirements, efficiency, etc.).

Other aspects of the cost reductions through the learning curve regard human capital upgrades and skills development, where the workforce involved in the clean energy sector gains specialised skills and knowledge. This skilled workforce can contribute to enhanced productivity and reduced labour costs economy-wide. The following sections present the methodology adopted in GEM-E3 to capture these effects and show the cost reductions per technology and scenario (attributing the reductions to different learning factors).

The methodology applied for this task is discussed in Chapter 2, Section 2.2.

12.2 LEARNING BY RESEARCH

This section presents the cost curve connecting the UK's Research and Development (R&D) expenditures with cost reductions within clean energy technologies. Increased decarbonisation efforts result in higher R&D expenditures, which, based on the assumed learning rates, translate to greater cost reductions through research-driven learning.

The table below provides details on the cost curves showing the “R&D stock index” (a measure of the cumulative R&D expenditure, where 2020 = 100) and the “Price index” (a measure of the corresponding cost reduction) in 2020, 2025, 2030, 2040, 2045, and 2050.

Table 12-1: UK learning by research cost curve by technology and scenario

Technology:	Index:	Scenario:	2020	2025	2030	2035	2040	2045	2050
Ethanol	Price index	Current policies	100	99	98	96	96	95	94
		Below 2 ºC	100	99	98	96	94	92	90
		Net Zero 2050	100	99	97	95	93	91	89
	R&D stock index	Current policies	100	106	113	119	125	131	138
		Below 2 ºC	100	106	113	125	138	153	168
		Net Zero 2050	100	107	116	129	143	158	174
Biodiesel	Price index	Current policies	100	99	99	98	98	97	97
		Below 2 ºC	100	99	99	98	98	97	96

Technology:	Index:	Scenario:	2020	2025	2030	2035	2040	2045	2050
		Net Zero 2050	100	99	99	98	98	97	96
	R&D stock index	Current policies	100	103	106	109	112	114	117
		Below 2 ºC	100	103	106	110	113	117	120
		Net Zero 2050	100	103	106	110	113	116	119
Batteries	Price index	Current policies	100	94	83	75	68	62	57
		Below 2 ºC	100	94	83	73	65	59	54
		Net Zero 2050	100	84	73	66	59	54	50
	R&D stock index	Current policies	100	115	149	190	237	289	345
		Below 2 ºC	100	115	149	198	259	325	396
		Net Zero 2050	100	148	197	251	317	386	460
Wind equipment	Price index	Current policies	100	99	99	98	98	97	97
		Below 2 ºC	100	99	99	97	96	94	93
		Net Zero 2050	100	99	97	96	94	92	91
	R&D stock index	Current policies	100	103	105	107	109	112	114
		Below 2 ºC	100	103	105	110	117	128	132
		Net Zero 2050	100	106	111	117	126	139	145
PV equipment	Price index	Current policies	100	99	99	99	99	98	98
		Below 2 ºC	100	99	99	98	97	97	97
		Net Zero 2050	100	98	97	97	97	96	96
	R&D stock index	Current policies	100	103	106	107	108	109	110
		Below 2 ºC	100	103	106	112	115	117	119
		Net Zero 2050	100	111	115	117	120	122	123
CCS equipment	Price index	Current policies	100	100	100	99	99	99	99
		Below 2 ºC	100	100	100	98	97	97	96
		Net Zero 2050	100	100	99	97	97	96	96
	R&D stock index	Current policies	100	105	109	114	117	120	125
		Below 2 ºC	100	105	109	163	200	225	245
		Net Zero 2050	100	111	122	186	219	245	263
Hydrogen	Price index	Current policies	100	100	100	99	97	92	86
		Below 2 ºC	100	100	100	97	85	73	64
		Net Zero 2050	100	98	93	85	75	65	58
	R&D stock index	Current policies	100	100	100	103	112	132	167
		Below 2 ºC	100	100	100	113	179	302	483
		Net Zero 2050	100	108	131	174	277	438	655

Across all clean energy technologies, the current policy scenario has the lowest cost reduction. Conversely, in the Net Zero 2050 scenario, the highest reduction is achieved due to the heightened need for R&D expenditures to meet ambitious decarbonisation targets.

Mature technologies with a high cumulative R&D stock are harder to reduce production costs substantially through additional R&D expenditures (e.g., wind equipment). Conversely, immature technologies can potentially reduce production costs through learning by research.

The reduction in the production cost index depends on the learning rates assumed and the R&D expenditures. In the UK, the highest reductions in production costs occurred in batteries due to the high learning rate that has been assumed and hydrogen due to the high ratio of R&D expenditures to R&D stock of the base year.

By increasing the Research and Development (R&D) stock by 4.6 times from 2020 to 2050, batteries show a 50% reduction in production costs in the net-zero scenario. In the current policy scenario, where the R&D stock increases by 3.45 times, a 43% reduction in production costs is achieved. Similarly, in the Below 2 ºC scenario, with a 3.96 times increase in the R&D stock, there is a significant 46% reduction in production costs. The lowest reduction of production costs is in the CCS equipment technology, where there is low deployment in the UK, and low learning rates have been assumed.

The figures in the annex show the cost curves, i.e. the relationship between cumulative R&D stock (x-axis) and the resulting reduction in cost (y-axis). For each scenario, the arrows indicate the cumulative R&D stock and cost reduction that the UK will attain by the year 2050. According to the model's projections, varying scenarios achieve different levels of R&D investment, leading to corresponding decreases in capital costs. For instance, in the case of ethanol, the R&D stock index stands at 138, 168, and 174 for the current policy, below 2 ºC, and net zero scenarios in 2050. This translates to reductions in capital costs of 6%, 10%, and 11%. (Figure).

12.3 LEARNING BY DOING

This section presents the cost curve that establishes the connection between global production and cost reduction within clean energy technologies through learning by doing. The figures for each scenario depict the cumulative production that the world will attain by the year 2050. Increased decarbonisation efforts result in higher adoption of clean energy technology, and based on the assumed learning rates, this translates to greater reductions in costs through learning by doing. We assume that the result of gained experience contributes to the global knowledge stock available to all regions simultaneously.

The table below provides details on the cost curves showing the “Global Production index” (a measure of cumulative global production, where 2020 = 100) and the “Price index” (a measure of the corresponding reduction in costs) in 2020, 2025, 2030, 2040, 2045 and 2050.

Table 12-2: UK learning by doing cost curve by technology and scenario

Technology	Index:	Scenario:	2020	2025	2030	2035	2040	2045	2050
Ethanol	Price index	Current policies	100	91	87	84	81	79	78
		Below 2 ºC	100	91	87	80	75	72	69
		Net Zero 2050	100	84	77	73	70	68	66
	Global Production index	Current policies	100	211	327	441	557	677	803
		Below 2 ºC	100	211	327	650	1098	1620	2163
		Net Zero 2050	100	423	840	1337	1885	2438	2973
Biodiesel	Price index	Current policies	100	91	86	84	81	80	78
		Below 2 ºC	100	91	86	79	74	70	67
		Net Zero 2050	100	83	76	72	68	70	67
	Global Production index	Current policies	100	216	335	447	554	661	772
		Below 2 ºC	100	216	335	684	1229	1923	2678
		Net Zero 2050	100	457	950	1595	2351	3140	3900
Batteries	Price index	Current policies	100	74	60	52	47	43	41
		Below 2 ºC	100	74	60	52	47	42	39
		Net Zero 2050	100	68	55	49	44	40	38
	Global Production index	Current policies	100	254	487	747	1029	1331	1652
		Below 2 ºC	100	254	487	757	1076	1429	1824
		Net Zero 2050	100	335	631	941	1291	1676	2091
Wind equipment	Price index	Current policies	100	91	86	82	80	77	75
		Below 2 ºC	100	91	86	80	76	74	71
		Net Zero 2050	100	86	80	77	74	71	69
	Global Production index	Current policies	100	214	347	499	661	841	1051
		Below 2 ºC	100	214	347	632	942	1278	1640
		Net Zero 2050	100	336	611	925	1259	1632	2064
PV equipment	Price index	Current policies	100	79	70	65	61	60	56
		Below 2 ºC	100	79	70	55	51	50	49
		Net Zero 2050	100	58	54	52	50	48	46
	Global Production index	Current policies	100	232	344	461	558	589	737
		Below 2 ºC	100	232	344	813	1016	1092	1249
		Net Zero 2050	100	689	885	1010	1161	1265	1451
CCS equipment	Price index	Current policies	100	100	99	98	98	97	97
		Below 2 ºC	100	100	99	95	93	91	90
		Net Zero 2050	100	97	94	92	90	89	88
	Global Production index	Current policies	100	107	116	126	137	149	161
		Below 2 ºC	100	107	116	188	263	344	428
		Net Zero 2050	100	152	222	301	386	475	568
Hydrogen	Price index	Current policies	100	100	100	100	99	98	97
		Below 2 ºC	100	100	100	94	73	52	43
		Net Zero 2050	100	97	83	58	47	40	36
	Global Production index	Current policies	100	100	100	101	103	107	113
		Below 2 ºC	100	100	100	126	302	955	1898
		Net Zero 2050	100	110	190	651	1435	2447	3649

In the Net Zero 2050 scenario, the highest reductions in production costs are achieved, driven by elevated deployment of clean energy technologies compared to other scenarios. Within the sectors analysed, hydrogen experiences the highest reductions in production costs, attributed to the significant deployment of hydrogen production. On the other hand, CCS equipment exhibits the lowest cost reduction, characterised by low learning rates and limited deployment.

In both the current policy and Below 2 ºC scenarios, batteries emerge as the sector with the highest reductions in production costs. This trend is driven by the surge in electric vehicle adoption, leading to a rise in demand for battery technologies. Hydrogen and CCS equipment, however, exhibit small cost reductions in these scenarios. The restrained cost reductions in these sectors are linked to their comparatively lower deployment levels within the current policy framework and Below 2 ºC scenarios. Overall, the varying degrees of cost reduction across sectors show the links between technology deployment, learning rates and reduction in production costs.

The figures in the annex show the cost curves, i.e., the relationship between the cumulative Global production index (x-axis) and the resulting reduction in cost (y-axis). For each scenario, the arrows indicate the cumulative global production index and cost reduction the UK will attain by 2050. According to the model's projections, varying scenarios achieve different levels of cumulative production, leading to corresponding price decreases. For instance, in the case of ethanol, the global cumulative production index stands at 803, 2163, and 2973 for the current policy, below 2 ºC, and net zero scenarios in 2050. This translates to reductions in capital costs of 22%, 31%, and 34% (Figure).

12.4 CONCLUSIONS

The cost curve analysis presented in this section shows the link between the UK's Research and Development (R&D) expenditures and cost reductions within clean energy technologies. The cumulative R&D stock, projected for each scenario up to 2050, shows the impact of heightened decarbonisation efforts on R&D expenditures. This connection, guided by assumed learning rates, signifies that increased investment in R&D results in reductions in production costs through research-driven learning.

Across various clean energy technologies, the current policy scenario stands out with the lowest cost reduction. In contrast, the Net Zero 2050 scenario achieves the highest reduction, driven by the need for additional R&D expenditures to meet ambitious decarbonisation targets. The challenge is evident with mature technologies, such as wind equipment, which has already accumulated high R&D stock, facing difficulties in achieving significant reductions in production costs through additional R&D investments. Conversely, immature technologies with a high potential for cost reduction through learning by research, such as batteries(EV batteries), demonstrate notable decreases. The reduction in the production cost index is intricately tied to assumed learning rates and the projected R&D expenditures outlined by the GEM-E3 model.

The analysis of different climate mitigation scenarios reveals different trajectories in reducing production costs for key clean energy technologies through learning by doing. The Net Zero 2050 scenario emerges as the most impactful, showcasing significant cost reductions due to the heightened deployment of clean energy technologies. Hydrogen experiences remarkable reductions, driven by widespread adoption in various sectors. Conversely, CCS equipment faces challenges with lower cost reductions, which reflects its slower learning rates and limited deployment.

In the current policy and Below 2 ºC scenarios, batteries take the forefront in achieving significant reductions in production costs. This trend is strongly influenced by the surging battery demand, particularly in the electric vehicle sector. Meanwhile, hydrogen and CCS equipment witness smaller cost reductions in these scenarios, which are closely tied to their lower deployment levels.

These findings show the critical role of technology deployment, learning rates, and contextual scenarios in shaping the cost dynamics of clean energy technologies. Overall, the highest reductions in production cost occur in the Net Zero 2050 scenario for all clean energy technologies, while the current policy scenario has the lowest reductions.

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APPENDIX 1: MAPPING OF GEM-E3 AND NACE SECTOR COVERAGE

The following table provides a mapping showing the correspondence between the GEM-E3 sectoral coverage and NACE 2-digit codes.

Table A-5: Mapping between the GEM-E3 sectoral coverage and NACE 2-digit codes.

GEM-E3 Sectors	NACE 2-digit
Agriculture	*A01: Crop and animal production, hunting and related service activities*
Wheat, Cereal Grains, Sugar cane, sugar beet	A03: Fishing and aquaculture
Oil Seeds	
Forestry	A02: Forestry and logging
Biomass Solid	
Coal	B05: Mining of coal and lignite
Crude Oil	B06: Extraction of crude petroleum and natural gas
Gas Extraction	B07: Mining of metal ores
	B08: Other mining and quarrying
	B09: Mining support service activities
Consumer Goods Industries	C10: Manufacture of food products
Ethanol	C11: Manufacture of beverages
	C12: Manufacture of tobacco products
	C13: Manufacture of textiles
	C14: Manufacture of wearing apparel
	C15: Manufacture of leather and related products
	C16: Manufacture of wood and of products of wood and cork, except furniture manufacture of articles of straw and plaiting materials
Paper products, publishing	C17: Manufacture of paper and paper products
	C18: Printing and reproduction of recorded media
Oil	C19: Manufacture of coke and refined petroleum products
Chemical Products	C20: Manufacture of chemicals and chemical products
Bio-diesel	
Basic pharmaceutical products	C21: Manufacture of basic pharmaceutical products and pharmaceutical preparations
Rubber and plastic products	C22: Manufacture of rubber and plastic products
Non-metallic minerals	C23: Manufacture of other non-metallic mineral products
Ferrous metals	C24: Manufacture of basic metals
Non-ferrous metals	
Metal products	C25: Manufacture of fabricated metal products, except machinery and equipment
Computer, electronic and optical products	C26: Manufacture of computer, electronic and optical products
Electrical equipment	C27: Manufacture of electrical equipment
Advanced Electric Appliances	
Advanced Heating and Cooking Appliances	

GEM-E3 Sectors	NACE 2-digit
Machinery and equipment	C28: Manufacture of machinery and equipment n.e.c.
Equipment for wind power technology	
Equipment for PV panels	
Equipment for CCS power technology	
CO_2 Capture	
Transport equipment (excluding EV)	C29: Manufacture of motor vehicles, trailers and semi-trailers
Batteries	C30: Manufacture of other transport equipment
EV Transport Equipment	
Other Equipment Goods	C31: Manufacture of furniture
	C32: Other manufacturing
	C33: Repair and installation of machinery and equipment
Gas	D35: Electricity, gas, steam and air conditioning supply
Power Supply	
Hydrogen	
Clean Gas	
Coal fired	
Oil fired	
Gas fired	
Nuclear	
Biomass	
Hydro electric	
Wind	
PV	
Geothermal	
CCS coal	
CCS Gas	
CCS Bio	
Construction	F41: Construction of buildings
	F42: Civil engineering
	F43: Specialised construction activities
Trade	G45: Wholesale and retail trade and repair of motor vehicles and motorcycles
	G46: Wholesale trade, except of motor vehicles and motorcycles
	G47: Retail trade, except of motor vehicles and motorcycles
Road -Passenger transport	H49: Land transport and transport via pipelines
Road-Freight transport	
Rail -Freight transport	
Rail -Passenger transport	
Water - Freight transport	H50: Water transport
Water - Passenger transport	
Air transport	H51: Air transport
Warehousing and support activities	H52: Warehousing and support activities for transportation

GEM-E3 Sectors	NACE 2-digit
	H53: Postal and courier activities
Accommodation, Food and service activities	I55: Accommodation
	I56: Food and beverage service activities
Financial services	K64: Financial service activities, except insurance and pension funding
	K66: Activities auxiliary to financial services and insurance activities
Insurance	K65: Insurance, reinsurance and pension funding, except compulsory social security
Education	P85: Education
Recreational and other services	R90: Creative, arts and entertainment activities
	R91: Libraries, archives, museums and other cultural activities
	R92: Gambling and betting activities
	R93: Sports activities and amusement and recreation activities
Other Non Market Services	O84: Public administration and defence compulsory social security
	Q86: Human health activities
	Q87: Residential care activities
	Q88: Social work activities without accommodation
Other Market Services	E36: Water collection, treatment and supply
	E37: Sewerage
	E38: Waste collection, treatment and disposal activities materials recovery
	E39: Remediation activities and other waste management services
	J58: Publishing activities
	J59: Motion picture, video and television programme production, sound recording and music publishing activities
	J60: Programming and broadcasting activities
	J61: Telecommunications
	J62: Computer programming, consultancy and related activities
	J63: Information service activities
	L68: Real estate activities
	M69: Legal and accounting activities
	M70: Activities of head offices management consultancy activities
	M71: Architectural and engineering activities technical testing and analysis
	M72: Scientific research and development
	M73: Advertising and market research
	M74: Other professional, scientific and technical activities

GEM-E3 Sectors	NACE 2-digit
	M75: Veterinary activities
	N77: Rental and leasing activities
	N78: Employment activities
	N79: Travel agency, tour operator and other reservation service and related activities
	N80: Security and investigation activities
	N81: Services to buildings and landscape activities
	N82: Office administrative, office support and other business support activities
	S94: Activities of membership organisations
	S95: Repair of computers and personal and household goods
	S96: Other personal service activities
	T97: Activities of households as employers of domestic personnel
	T98: Undifferentiated goods- and services-producing activities of private households for own use
	U99: Activities of extraterritorial organisations and bodies

APPENDIX 2: DETAILED METHODOLOGY

This appendix includes a detailed methodology summarising the approaches used and targeting a technical audience.

QUANTITATIVE ANALYSIS VIA GEM-E3

Quantitative analysis via GEM-E3 is applied:

- In RQ1 for estimating global and domestic market sizes and the UK's share of both markets under three decarbonisation scenarios;
- In RQ2 for carrying out a geographical benchmarking based on the projected market shares held by key market players in 2050;
- In RQ4 for an analysis of the impact of faster transition scenarios on technology cost curves.

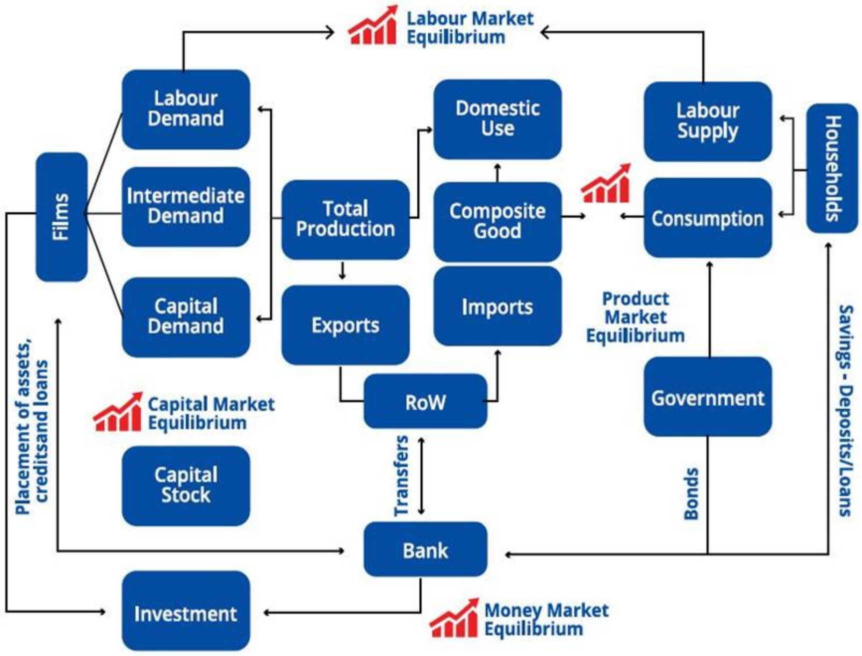
Explanation of the model

The GEM-E3 model[49] is a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium (CGE) model which provides details on the macro-economy and its interaction with the environment and the energy system. The version of the GEM-E3 model used in this study covers 34 countries/regions and 55[50] products, with calibration performed against a wide range of datasets. These datasets include Input-Output (IO) tables (sourced from EUROSTAT and GTAP), financial accounting matrices, institutional transactions, R&D expenditures, greenhouse gas (GHG) emission inventories, and energy balances (obtained from EUROSTAT and IEA). Additionally, the model incorporates data on bilateral trade from sources such as EUROSTAT, COMEXT, and GTAP, as well as investment matrices and household budget surveys, with employment data drawn from EUROSTAT and the International Labour Organization (ILO).

GEM-E3 operates as an optimisation model that includes bilateral trade flows, specifying both the origin and destination countries. The model places particular emphasis on accurately representing the energy system, incorporating specialised bottom-up modules for power generation and the transport sectors. The model adopts a sequential dynamic mechanism, solving period by period. In this approach, agents are myopic in the sense that they assume that the prices and demand they encounter today will persist. GEM-E3 produces projections for the economic and energy systems extending until 2050, with results presented in five-year intervals from 2015 to 2050.

[49] For a detailed description of the model please read its technical manual available at https://e3modelling.com/modelling-tools/gem-e3/
[50] In the ANNEX all economic activities and associated NACE classification is presented

Figure A-1: Schematic representation of the GEM-E3 model



All countries in the model are linked through endogenous bilateral trade transactions (origin – destination). Goods are considered imperfect substitutes following the Armington assumption. In particular, firms buy inputs necessary for their production from either the domestic or international markets. The choice between the two depends on prices but also on the assumption that the domestically produced goods and imported goods are not identical (in quality, taste, etc.); instead, they are treated as imperfect substitutes (Armington assumption). The same holds for households. In this way, all countries' production and consumption decisions are linked through trade – the decisions for which are taken simultaneously by all households and firms in the model (endogenously). Firms and Households consume composite intermediate and final products that are composed of domestically produced and imported goods. Price considerations drive the choice between the two and are largely affected by the choice of substitution elasticity, which also reflects quality considerations and the base-year market shares. GEM-E3 explicitly represents the manufacturers of key clean energy technologies. In each country, a separate column in the IO table is constructed to capture the cost structure and sales of clean energy technologies. Technology costs per country are differentiated through differences in capital cost, wages and cost of intermediate inputs. Capital costs of technologies largely depend on two-factor learning curves (learning by doing and learning by research). The R&D decision is exogenous, but the accruals depend on the learning rate of each technology, which has been assumed to be the same across countries. This study calibrated the model to the 2017 IO tables and adjusted further to the 2020 statistics. The projection of the global economy into the future is a complex, challenging task that involves the simultaneous, consistent representation of the interdependencies and growth dynamics of the global economic and energy system. In GEM-E3, this process occurs through a dynamic baseline calibration of the model to exogenous aggregate GDP and population growth rates using key model instruments such as technical progress, capital accumulation, firms' expectations for growth and saving rates. The exogenous aggregate GDP growth rates are decomposed in the model into GDP components and sectoral production. The model ensures that the whole economy follows a sustainable growth path where excessive surpluses/deficits are gradually reduced. GEM-E3 has a detailed representation of the energy system, GHG emissions (sources and abatement options), and energy and climate policies. Thus, the model projects, in a consistent and informed manner, the demand and supply of clean energy technologies. Demand is mainly driven by the pattern and scale of economic growth and policies/measures/regulations. Supply is driven mostly by technology dynamics and cost advantages.

Assumptions

The baseline projection of the GEM-E3 model is based on extraneous information regarding aggregate GDP growth (for EU countries the long-term projections from the DG-ECFIN Ageing report are used adjusted in the short term, for non-EU countries the corresponding IMF and OECD projections are used). The aggregate GDP projections are then decomposed into GDP components and sectoral added value, adopting a sustainable growth approach (excessive deficits/surpluses are reduced over time) following recent trends. In addition, a basic assumption on dematerialisation and transition to services is made. The key exogenous variables of the model are population/active population/labour force, technical progress and capital accumulation. Projections for the labour force are taken from ILO and the DG-ECFIN ageing report; the technical progress is composed of an autonomous part calibrated to match exogenous economic projections and an R&D-related part that connects/links R&D expenditures with productivity gains. During the calibration of the baseline projection the model ensures that a consistent global economic outlook is produced - closed/balanced demand and supply monetary accounting system. The model results are sensitive to a number of parameters, including price/income elasticities and assumptions on potential reduction in technology costs.

Table A-6: Key features of the GEM-E3 model.

Feature	GEM-E3
Economic agents' behaviour	Optimisation
Price formation	Cost minimisation, market clearing
Growth / Dynamics	Technical progress, capital accumulation, Output Multiplier
Macro-Economic Closure	Savings equal Investment on the national or regional level
Labour Market	Involuntary unemployment through a labour supply curve. Endogenous unemployment through labour supply function.
Elasticities	Nested CES, CET Armington function, LES Consumption functions
Investment	Based on Tobins Q (firms profitability compared to the cost of capital replacement)
Financing	Additional to the Reference scenario financing has to become available from the agent's savings or cancelling of investment projects
Capital Stock / Capacity utilisation rate	Full utilisation rate

Limitations

Despite the wide recognition of the complex interactions between trade and climate (policy), the current tools and methodologies used to assess such interactions face substantial limitations, including:

- lack of data at the required level of granularity;
- dependence on conventional trade theories that fail to adequately capture new evidence of behavioural patterns at the firm/commodity level;
- limited representation of the value and material chain in key sectors as well as new technologies' manufacturing processes,
- reliance on modelling frameworks that only partially account for endogenous technology.

The GEM-E3 model is a state-of-the-art model that features endogenous bilateral trade transactions and semi-endogenous technical change and explicitly represents clean energy producers. Still, there is room for improvement. In particular, the dynamics of the clean energy equipment suppliers in the model are largely constrained by base year market shares unless explicit policies are exogenously introduced (driving investments and/or technical progress). In the scenarios implemented, explicit policies in the UK have not been accounted for (e.g., GIGA policy). This means that changes in the market mix driven by the model's substitution elasticities are not enough to structurally/significantly change the market composition as opposed to explicit R&D investment. Similarly, the model does not assume behavioural changes in consumer preferences but only price-driven changes in consumption. The model's flexibility to represent significant market share changes is limited as it does not represent mergers and acquisitions that would allow a rapid penetration to a market or disruptive technological change (significant success in R&D that would render a company/sector/country market leader). In addition, the model is calibrated to public datasets (commercial and free) that may not always have the necessary sectoral granularity – in which cases information from the scholar literature and journals is retrieved. It should be noted that the lack of representation of the above constraints limits the potential of UK firms to access and significantly increase their penetration of the markets considered.

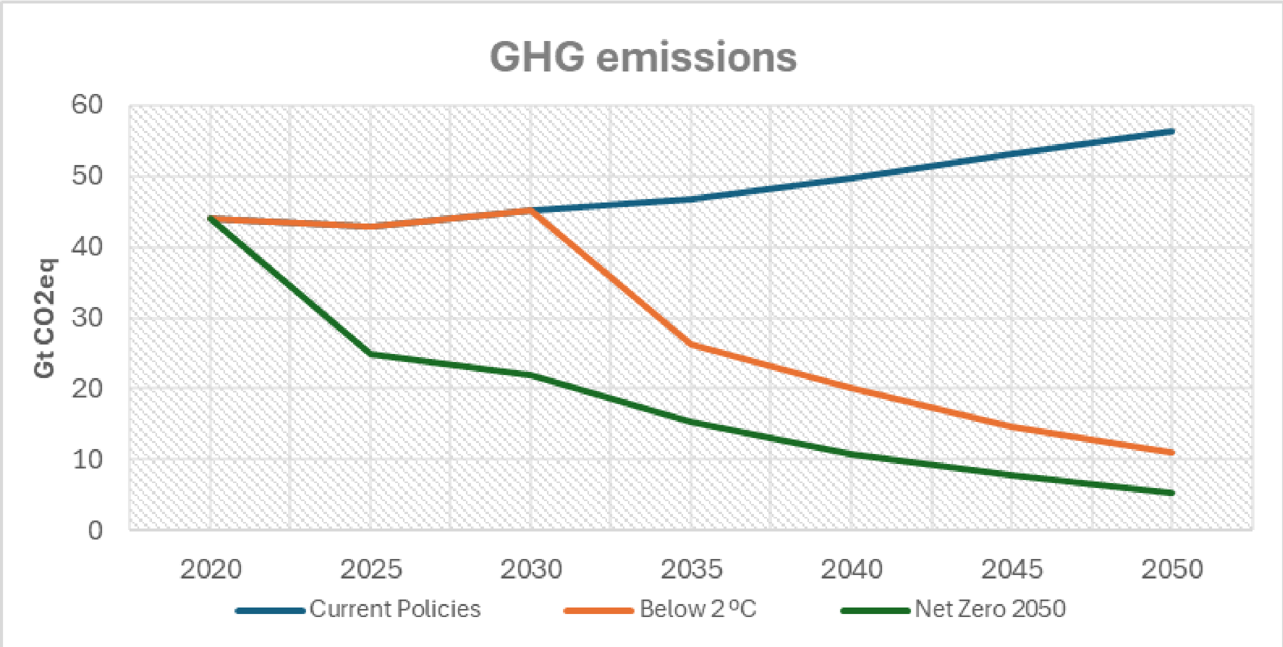
Scenarios

The GEM-E3 model has been used to quantify potential alternative GHG emission pathways and corresponding energy systems. This allows for calculating the demand and supply of key energy technologies under different contexts. The scenarios mainly differ in their ambition regarding GHG emissions reductions. Only the implemented climate policies (until March 2022) have been used in the current policy scenario. In the Below 2 ºC scenario, there is a delayed policy reaction, meaning that until 2030, current policies are preserved. After 2030, a fast technology change occurs to reach GHG emissions reduction targets compatible with the Below 2 ºC end of century warming. In the last scenario considered (Net Zero 2050), an immediate policy reaction is assumed, and the GHG emissions reductions are compatible with the 1.5 ºC end of century warming.

Table A-7: Scenario assumptions

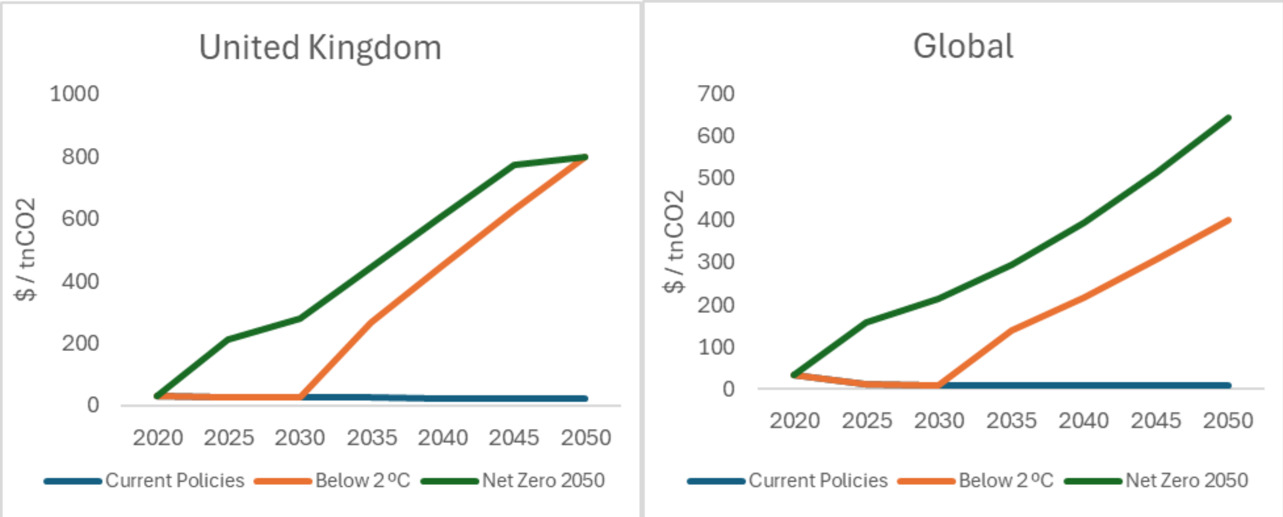
Scenarios	End of century (peak) warming	Description
Current policies	2.8 ºC (3.1 ºC)	• Only currently implemented policies are preserved. • Slow technology change • Low use of carbon dioxide removal
Below 2 ºC	1.7 ºC (1.9 ºC)	• Delayed policy reaction • Slow/Fast technology change • Medium/Low use of carbon dioxide removal
Net Zero 2050	1.4 ºC (1.7 ºC)	• Immediate policy reaction • Fast technology change • Medium/high use of carbon dioxide removal

Figure A-2: Global GHG emissions



A uniform carbon price for the EU and country-based carbon prices for non–EU countries have been used, reflecting national efforts. Carbon prices reflect the GHG mitigation effort, the abatement potential, and each country's different starting points regarding energy and carbon intensity. Different carbon prices also reflect the different ambitions over time to reduce GHG emissions.

Figure A-3: Carbon prices



Methodology for RQ4

The GEM-E3 model determines the supply of clean energy technologies in terms of specific cost curves dependent on decarbonisation pathways.

Technologies that are covered in GEM-E3 and are relevant to this study include:

- Alternative fuels (ethanol, biodiesel)
- Batteries (mainly EV batteries)
- Equipment for wind power technology
- Equipment for PV panels
- Equipment for CCS power technology
- Hydrogen

For each technology, GEM-E3's outputs are summarised in the model's two-factor learning curve, which describes the relationship between cumulative production, R&D expenditures, and reductions in capital costs.

The GEM-E3 model features endogenous technical progress. The model identifies both public and private R&D, each having different characteristics in terms of funding. Learning results from research efforts (Learning by Research, LbR) and the result of gained experience (Learning by Doing, LbD). LbD in GEM-E3 indicates that costs are reduced with the doubling of capacity. However, agents are myopic and not aware of this effect. The learning rates at Table A-8 shows how much capital costs are reduced for each doubling of production capacity / R&D spending.

In the GEM-E3 model, public R&D investment contributes to the global knowledge stock available to all regions simultaneously. In contrast, private R&D investment creates knowledge available to the investing firm/industry. The functions that have been used in GEM-E3 to calculate the technical progress are the following:

Learning by research:

$$TFP_{r,s,t} = TFP(PRIVATE)_{r,s,t} * TFP(PUBLIC)_{r,s,t}$$

$$TFP(PRIVATE)_{r,s,t} = \left(\frac{\{CUMRD_{r,s,t},\}}{\{CUMRD_{r,s,0},\}}\right)^{b_s}$$

$$TFP(PUBLIC)_{r,s,t} = \left(\frac{\sum_r CUMRD_{r,s,t}}{\sum_r CUMRD_{r,s,t}}\right)^{b_s}$$

Learning by Doing:

$$TFP_{r,s,t} = TFP(PUBLIC)_{r,s,t}$$

$$TFP(PUBLIC)_{r,s,t} = \left(\frac{\sum_r CUMPROD_{r,s,t}}{\sum_r CUMPROD_{r,s,t}}\right)^{b_s}$$

Were,

$TFP_{r,s,t}$: Total factor productivity

$TFP(PRIVATE)_{r,s,t}$: Total factor productivity from Private R&D

$TFP(PUBLIC)_{r,s,t}$: Total factor productivity from Public R&D

$CUMRD$: Cumulative R&D

$CUMPROD$: Cumulative production

r: region, s: sector, t-time, 0: base year, LR: learning rates.

$$b_s = -\frac{\log(1 - LR)}{log2}$$

Table A-8: Learning rates[51]

Technology	By research	By doing
Ethanol	13%	8%
Biodiesel	13%	8%
Batteries	27%	20%
Equipment for wind power technology	17%	8%
Equipment for PV panels	12%	18%
Equipment for CCS power technology	3%	5%
Hydrogen	18%	18%

The figures below show the cost curves, i.e., the relationship between cumulative R&D stock (x-axis) and resulting cost reduction (y-axis) for the learning-by-research and learning-by-doing effects. For each scenario, the arrows indicate the cumulative R&D stock and cost reduction that the UK will attain by the year 2050.

Learning by research cost curves

Figure A-4: Ethanol in UK learning by research cost curve

[51] Schoots et. Al. (2008), Handayani et.al. (2019), European Commission (2018), Louwen et al. (2018), IEA 2019, Emmerling et al. (2016), Verdolini et al. (2018), Rubin et al. (2015), Mayer et al. (2012). The learning rates show the capital cost reductions (%) for a doubling of the productive capacity.

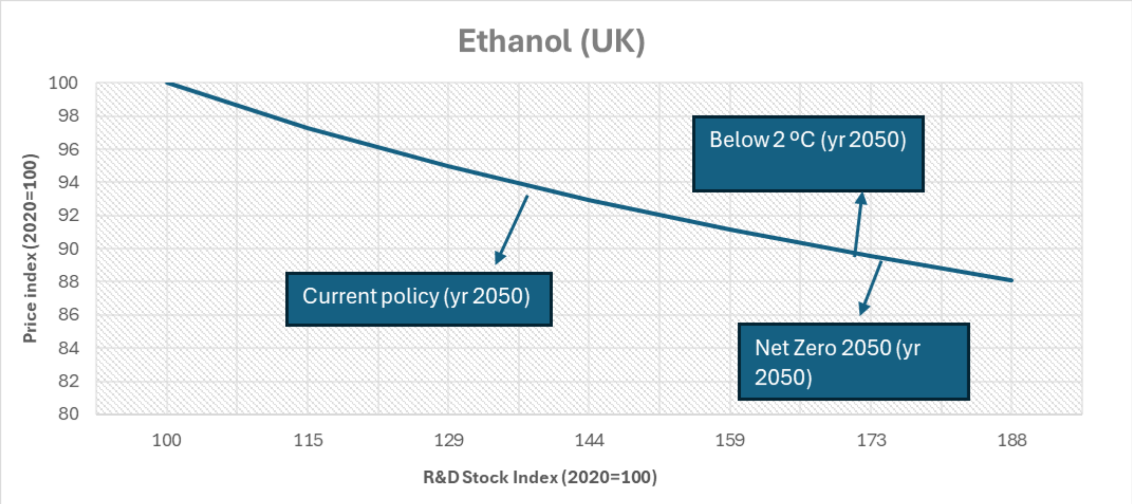


Figure A-5: Biodiesel in the UK learning by research cost curve

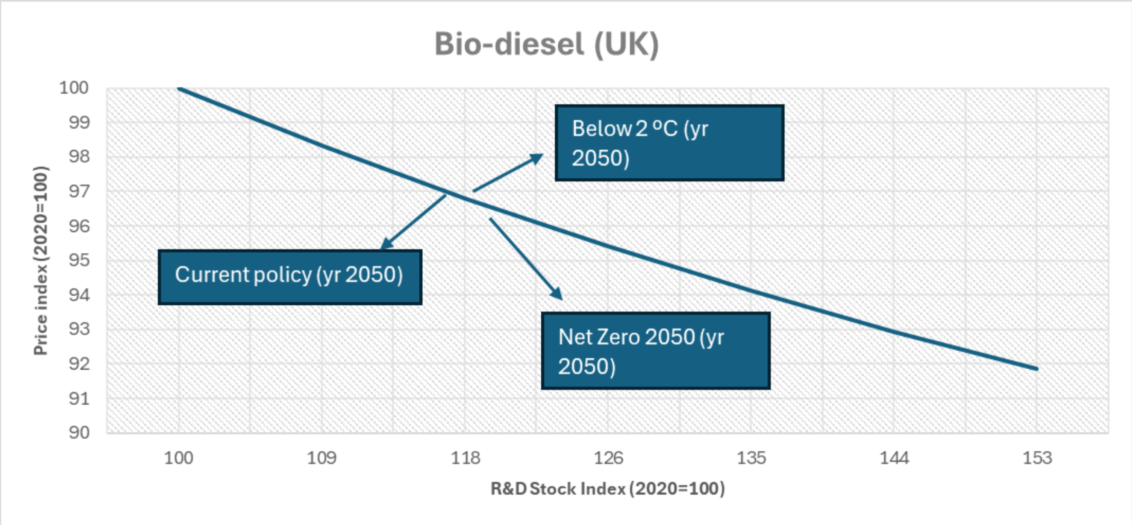


Figure A-6: Batteries in UK learning by research cost curve

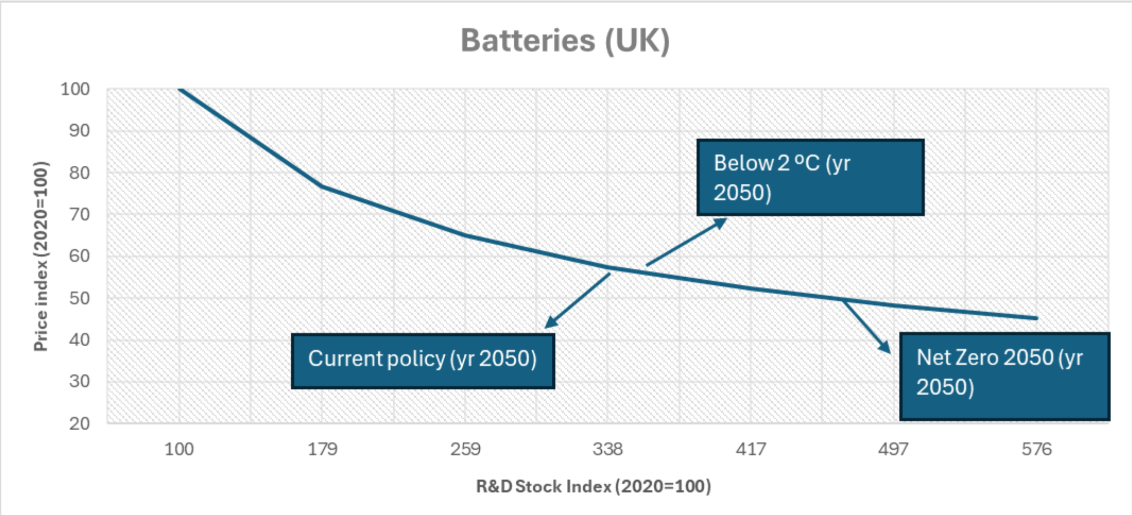


Figure A-7: Wind equipment in UK learning by research cost curve

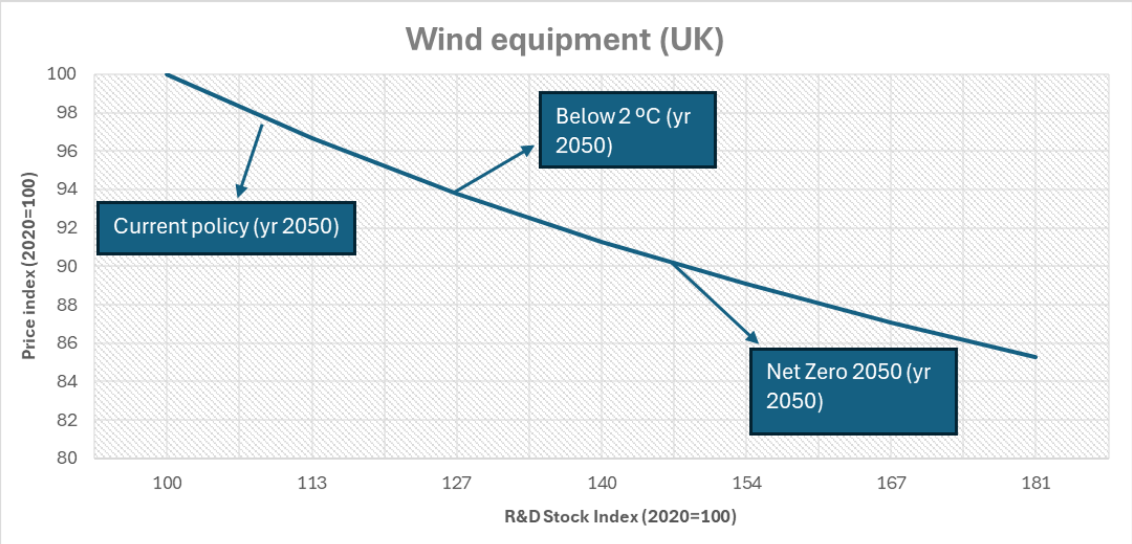


Figure A-8: PV equipment in UK learning by research cost curve

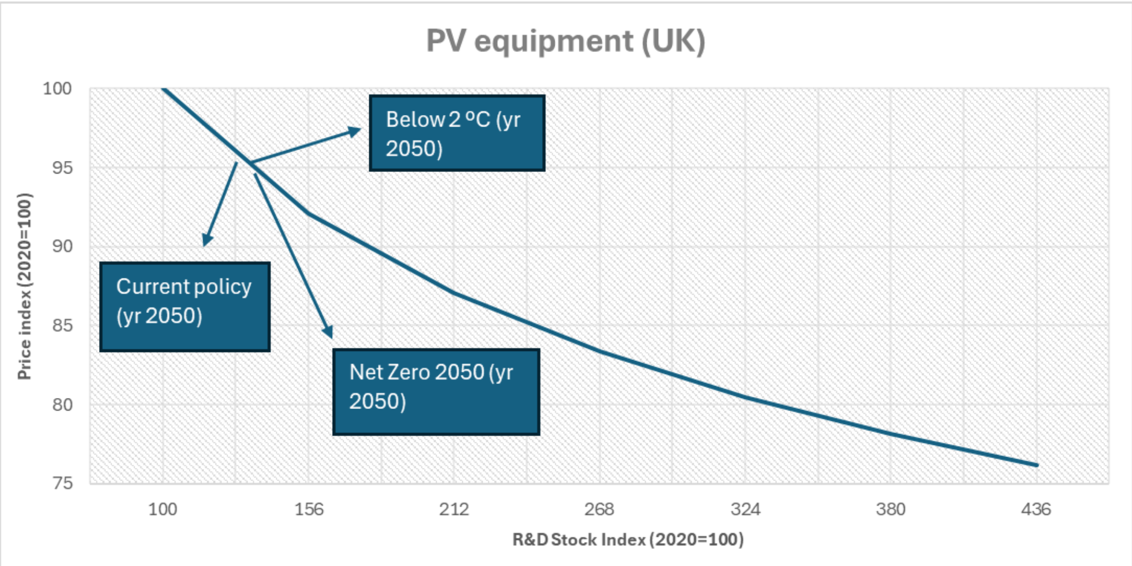


Figure A-9: CCS equipment in UK learning by research cost curve

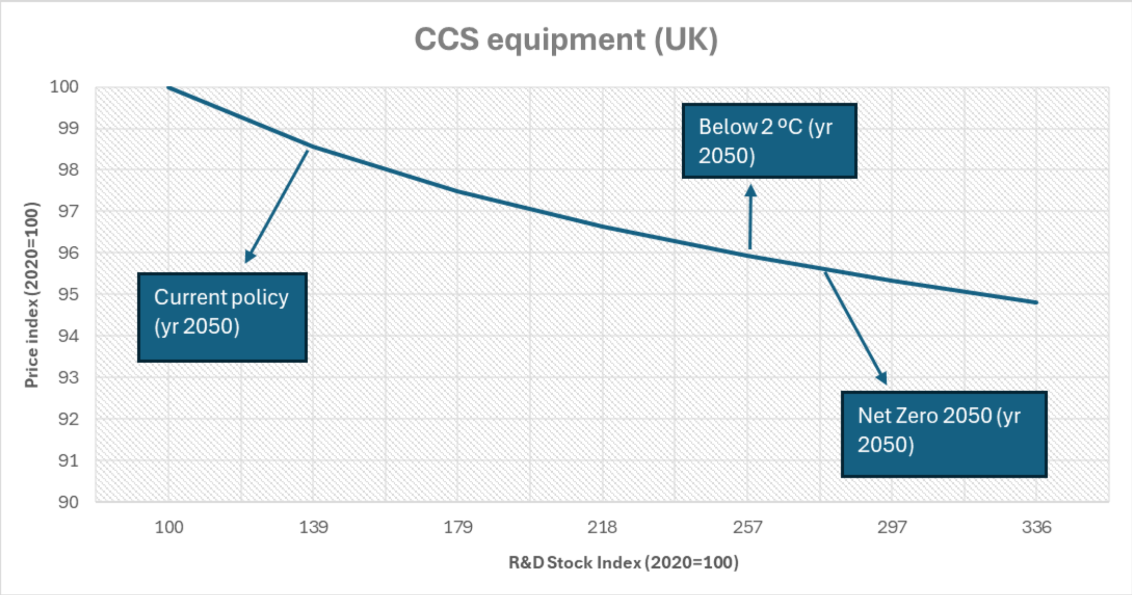
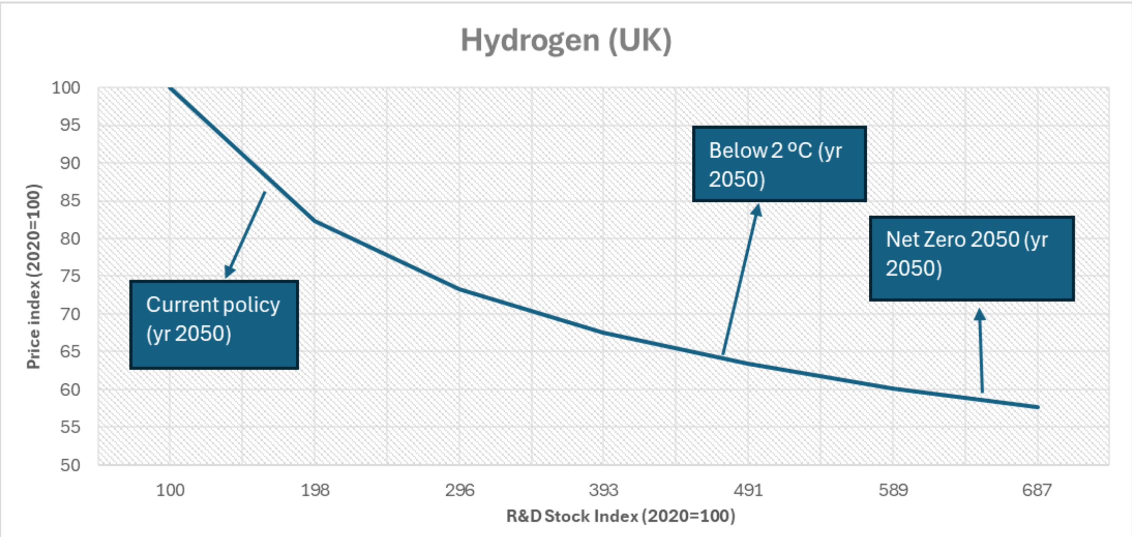


Figure A-10: Hydrogen in the UK learning by research cost curve



Learning by doing cost curves

Figure A-11: Ethanol learning by doing cost curve (global)

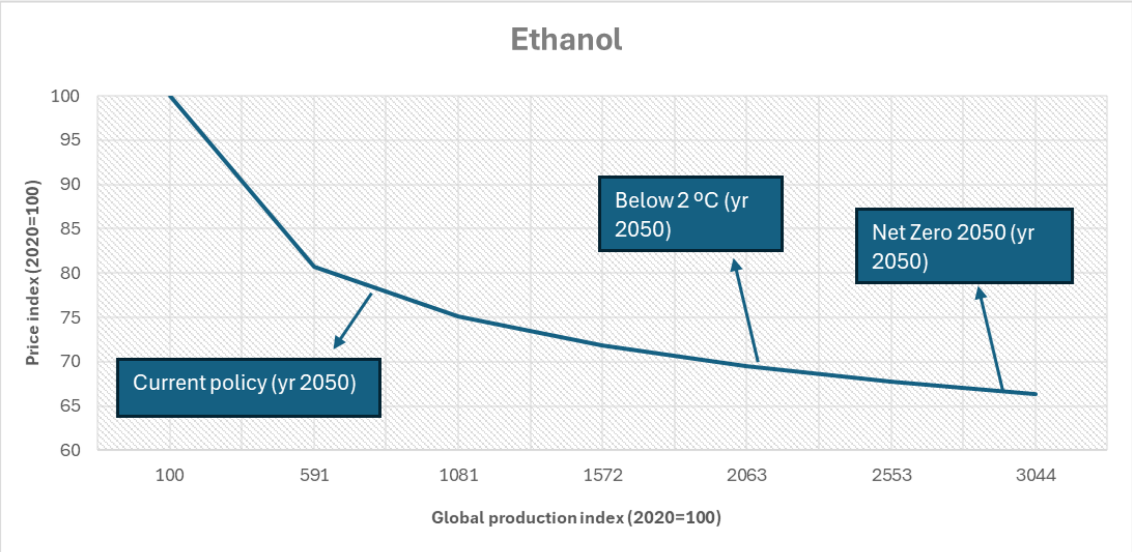


Figure A-12: Biodiesel learning by doing cost curve (global)

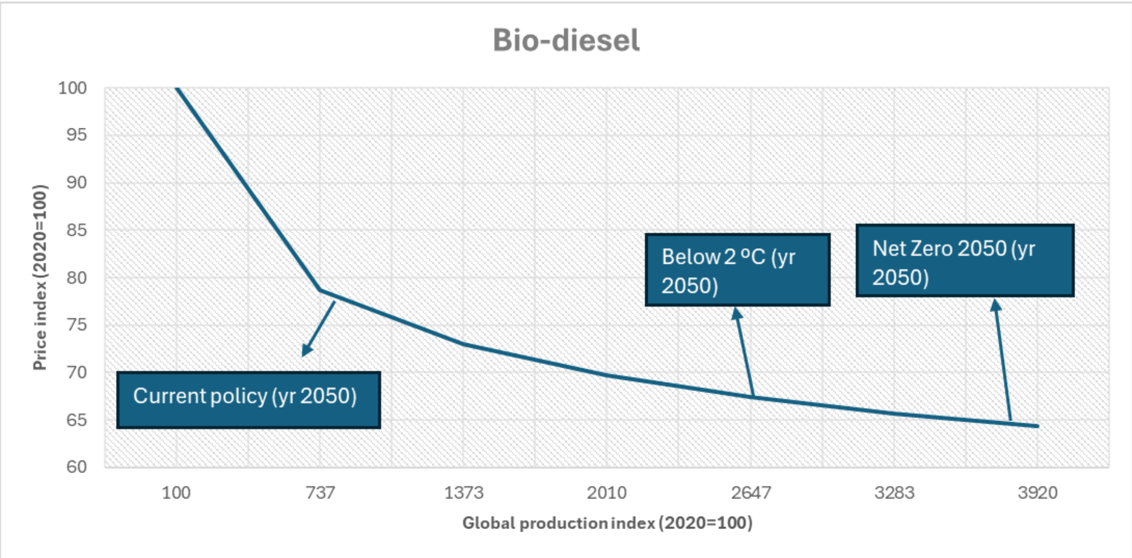


Figure A-13: Batteries learning by doing cost curve (global)

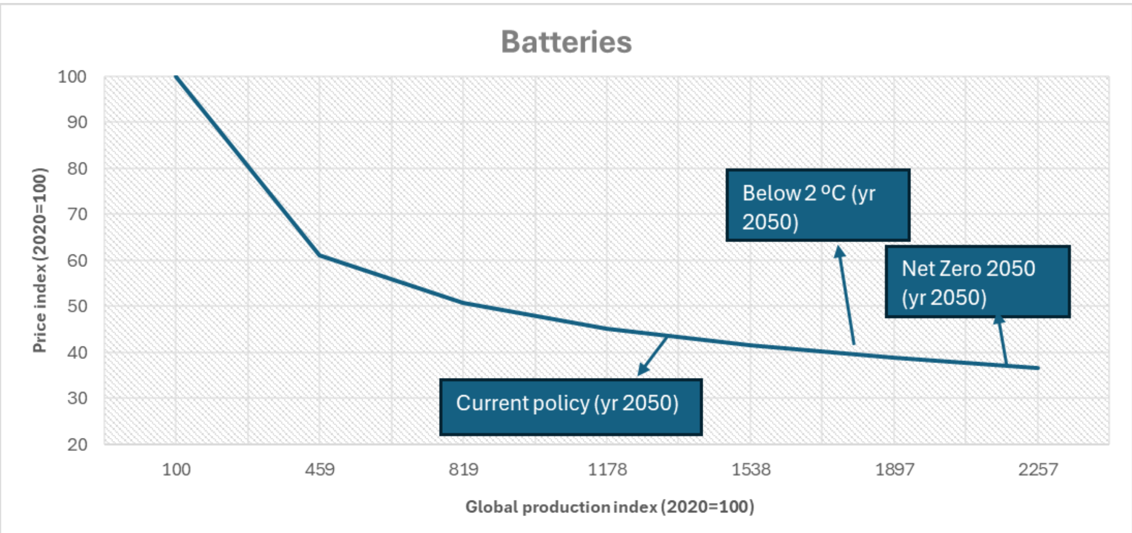


Figure A-14: Wind equipment learning by doing cost curve (global)

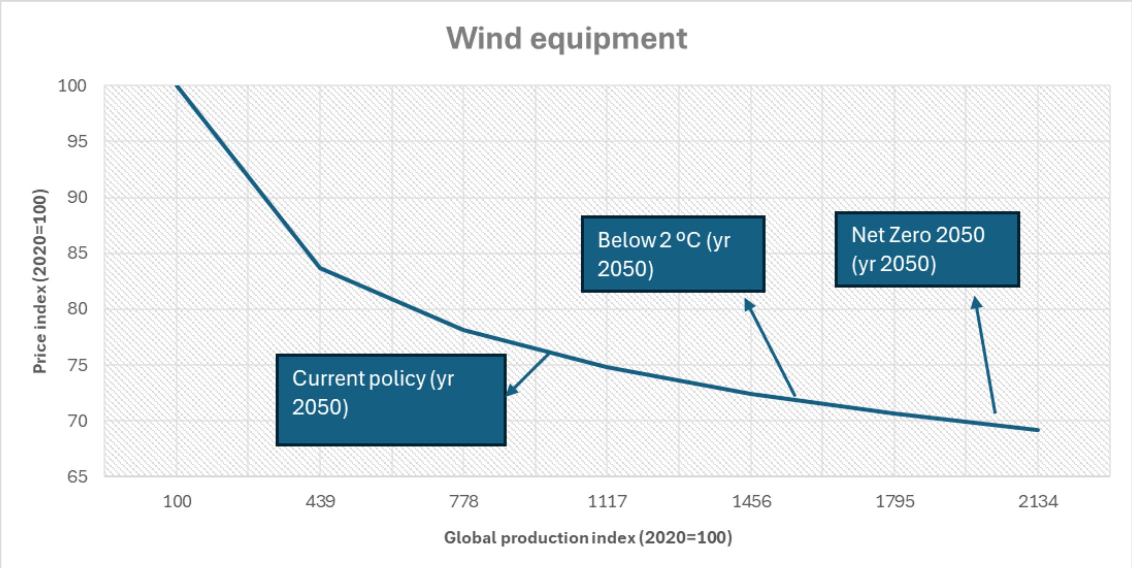


Figure A-15: PV equipment learning by doing cost curve (global)

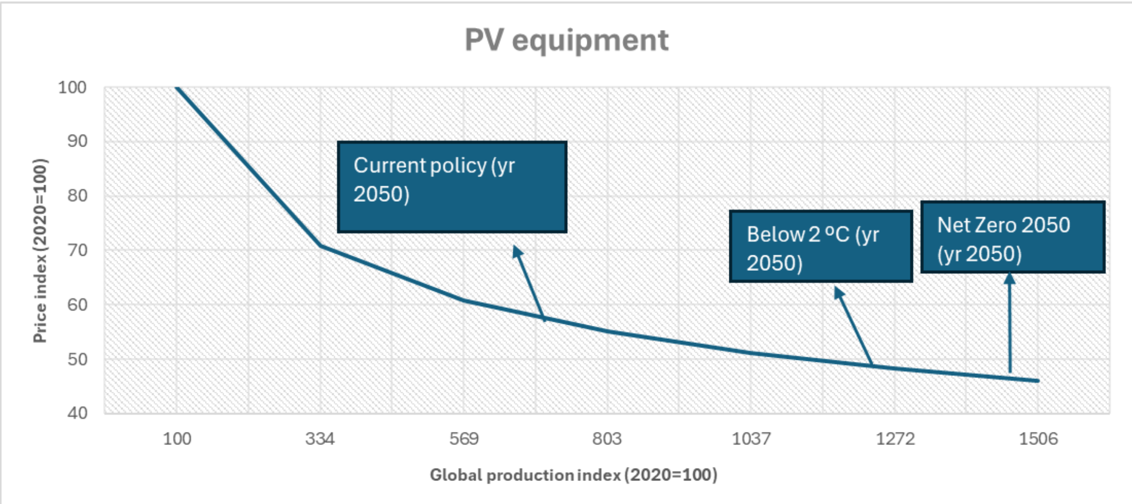


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Figure A-16: CCS equipment learning by doing cost curve (global)

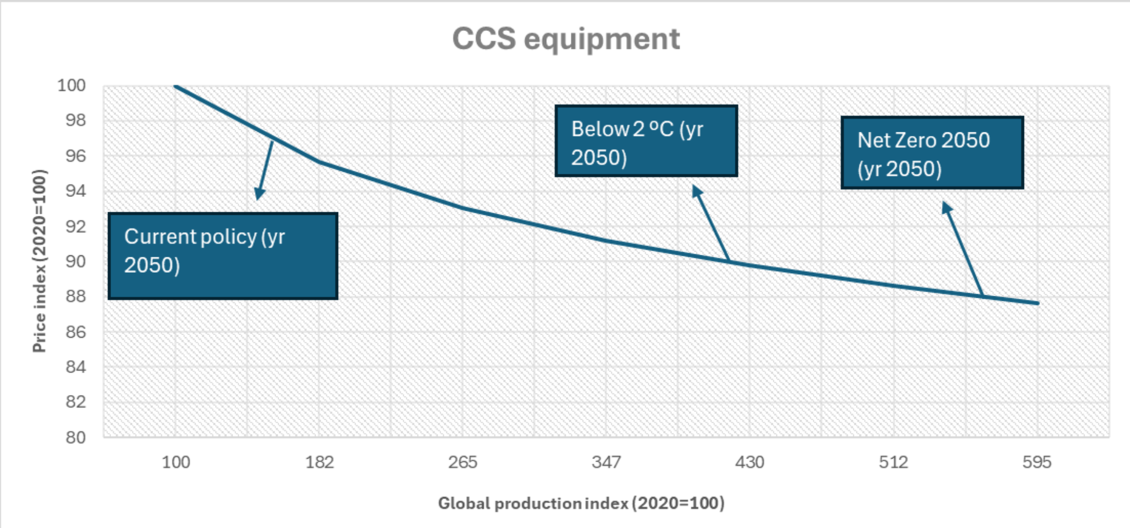
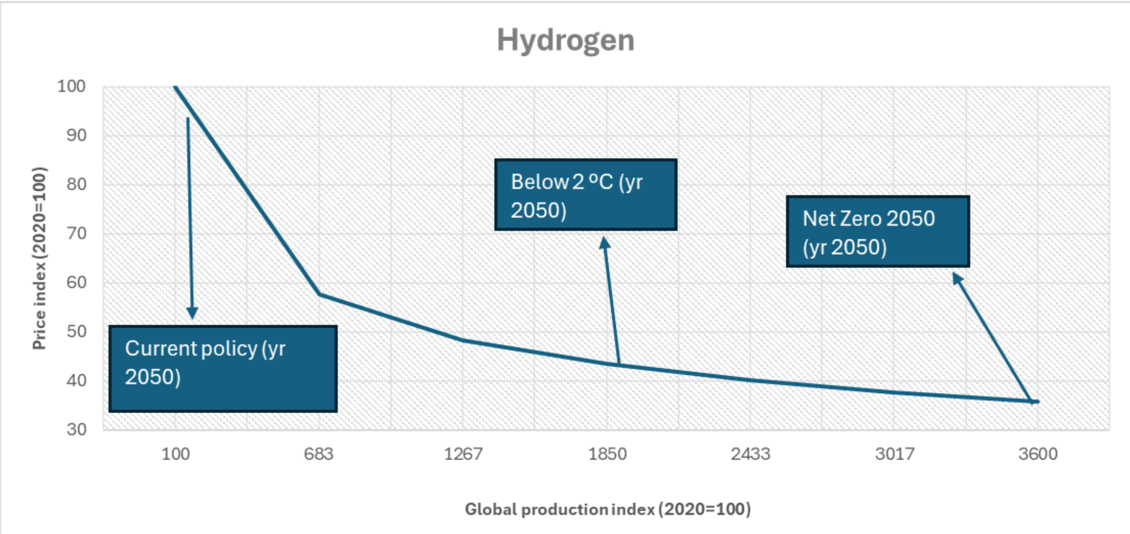


Figure A-17: Hydrogen learning by doing cost curve (global)



TRADE FLOWS ANALYSIS

A trade flow analysis is carried out in RQ1 to estimate the current UK's share of global exports in each sector. This is coherent with the approach taken in the original EINA reports, where estimates of the current market shares based on an analysis of trade flow codes[52] and an assessment of future market shares was based on expert judgement (gathered via workshops with stakeholders).

The trade flow analysis included in the UK market share sections is based on a list of 6-digit HS codes that Ricardo received from DESNZ, which provided details of the reference sectors (e.g., Renewables, Hydrogen, etc.) for each code.

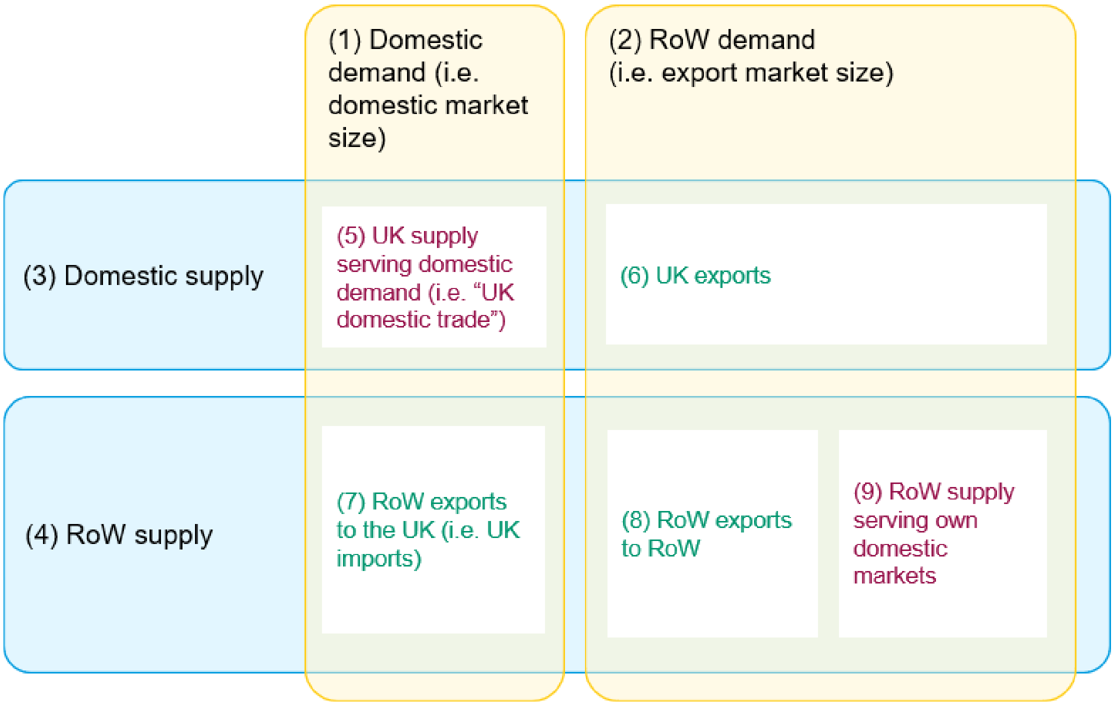
Trade flow data has been downloaded from the UN Comtrade database and analysed in Excel using pivot tables. 6-digit codes have been grouped based on HS Chapters (i.e., 2-digit HS codes), and for each group, the share of UK exports (to all trading partners) in total world exports was obtained, usually averaged between 2021 and 2022. By summing all HS codes for each sector, the time series of UK exports over total world exports between 2012 and 2022 was also obtained to highlight trends in market shares over time.

It is important to acknowledge the limitations of this approach. First, for each sector, not all selected codes are unique to that specific sector, and other relevant codes may not have been captured.

[52] Cf. for example Figure 2 at p. 36 of the Biomass and Bioenergy EINA report (2019)

Secondly, and more importantly, these numbers can only be interpreted as indicative proxies of the UK's share of tradable export markets. This is explained below based on the following diagrammatic representation:

Figure A-18: EINA UK market shares vs. trade flow analysis



Source: Ricardo

In the EINA methodology, UK market share assumptions refer to the following:

- UK domestic market share = UK supply serving the domestic market i.e. "UK domestic trade" (5) / Domestic market size (1)
    - This cannot be calculated as data on (5) is not reported in international trade databases.
- UK export market share = UK exports (6) / Export market size (2)
    - This cannot be calculated as data on (9), i.e. RoW supply serving own domestic markets (i.e. "RoW domestic trade" is not reported in international trade databases.

In contrast, the trade flow analysis included in the UK market share sections is based on the following approach:

- UK share of global trade = (6) / [(6)+(7)+(8)]

Although not perfectly comparable, this measure can be used as a proxy for EINA's export market share.

To summarise, analysing trade flows provides insight into each country's portion of global exports. However, it is important to note that global exports do not encompass the entirety of the global market. "Domestic trade," or production serving a country's domestic market, is not accounted for in international trade databases, which, therefore, offer an incomplete picture of the size of global markets.

QUALITATIVE ANALYSIS

A qualitative analysis is conducted:

- In RQ1 to complement the quantitative analysis of market sizes and UK market shares with evidence at the level of individual technologies;
- In RQ2 to discuss sector-specific barriers and enablers as well as the UK's competitive advantage/disadvantage vis-a-vis other countries (geographical benchmarking).

The qualitative analysis relies on two approaches: (a) desk research and (b) expert judgment. Experts were mainly drawn from Ricardo's teams, who specialise in each sector and, in the case of nuclear, from outside our organisation.

The literature review analysed academic papers, industry reports, and grey literature such as company announcements and press releases. In many cases, relevant pieces of literature were selected based on the suggestions of our sector experts.

Findings from the literature were then complemented by subject matter expertise from our sector expert advisory board. The following table provides a list of Ricardo sector experts involved in the study. For the nuclear sector, we instead consulted external experts. Experts were selected based on how their key areas of expertise mapped with the sectors and technologies considered.

Experts were consulted using various methods, including data and evidence collection templates, in-depth interviews, brainstorming sessions, and email exchanges. Sector experts were also asked to review, validate, and integrate the findings from the literature review based on their knowledge and provide or validate the RAG ratings described in Table 10.

Table A-9: Ricardo sector expert advisory board

Sector	Ricardo experts
Renewables	- **Martin Georgiev**, Principal Consultant, Ricardo Energy Decarbonisation - **Michele Senes Piu**, Principal Consultant, Ricardo Policy Strategy and Economics
CCS and GGR	- **Scott Robertson**, Head of Industrial Heat Decarbonisation, Ricardo Energy Decarbonisation - **Harsh Pershad**, Technical Director, Ricardo Energy Decarbonisation - **Amber Jenevizian**, Senior Consultant, Ricardo Energy Decarbonisation
Hydrogen and alternative fuels	- **Hamish Nichol**, Head of Hydrogen, Ricardo Energy Decarbonisation - **Daniele Pacifici**, Associate Director, Ricardo Energy Decarbonisation - **Eleni Liakakou**, Principal Consultant, Ricardo Policy Strategy and Economics - **Juan Ramirez**, Principal Consultant, Ricardo Policy Strategy and Economics
Nuclear	- **Steve Browning**, Director at Nuclear Industry Association - **Lincoln Hill**, Director at Nuclear Industry Association
Smart Systems	- **Ben Kirley**, Network Innovation Lead, Ricardo Energy Decarbonisation - **Yahya Naderi**, Principal Consultant (Power Engineer), Ricardo Energy Decarbonisation
Heating & cooling	- **David O'Donnell**, Associate Director, Ricardo Sustainable Infrastructure & Ops
Industry	- **Richard Hodges**, Associate Director, Ricardo Energy Decarbonisation - **Daniele Pacifici**, Associate Director, Ricardo Energy Decarbonisation - **Hamish Nichol**, Head of Hydrogen, Ricardo Energy Decarbonisation

The qualitative analysis provides details and evidence on the sectors within scope. It focuses on discussing the available data and evidence at the technology and technology group level (whereas the quantitative analysis via GEM-E3 is carried out at the sector level).

In RQ1, the qualitative analysis focuses on two areas of research:

- **Market size**, i.e. the potential growth of the global market for each technology. Contingent on data/evidence availability, a discussion of the potential growth of the domestic market is also provided for some sectors. To summarise the key findings of these sections, an RAG rating is provided, ranging from red (low growth potential) to green (high growth potential).

- Current and future potential **UK market shares** at the technology level. Similarly to the above, a summary is provided that compares the UK market share growth potential at the technology level with the sector average, assessing it as higher (green), in line with the average (yellow), or lower (red).

In RQ2, the qualitative analysis focuses on a discussion of:

- **Sector-specific barriers and enablers**;
- The competitive positioning of other countries (**geographical benchmarking**);
- The **UK's competitive advantages and disadvantages**.

In both RQ1 and RQ2, for each sector, the discussion of qualitative evidence is complemented and summarised via three tables presenting RAG (Red, Amber, Green) ratings that, based on the assessment conducted in the previous sections within each chapter, classify each technology as detailed in the following table.

These classifications are based on expert judgment (also considering the main results of desk research). Sector experts have not applied a specific framework to arrive at their rating, but the rationale for their choice is provided in the relevant summary tables.

Table A-10: RAG ratings

RAG rating	RQ	Red	Amber	Green
RAG rating 1 Global market size growth potential	RQ1	Low	Medium	High
RAG rating 2 Potential to attract significantly higher/lower market shares compared to the sector average[53]	RQ1	Potential to attract lower market share compared to the sector average	In line with the average	Potential to attract higher market share compared to the sector average
RAG rating 3 Competitive advantage rating	RQ2	**Primary focus area**: an area where the UK is expected to have consolidated advantage	**Further** opportunity: an area where the UK could gain a competitive advantage from positioning itself as a potential early mover	**Lower potential area**: a technology on which the UK does not appear to have potential

Selection of applications for the Industry sector

Specific applications were selected as Ricardo experts indicated them to be the most promising applications in terms of potential for growth for the UK industry:

- For recycling and recovery, we focus on the following application:
  - Packaging for food and drinks applications;
- For low-carbon substitutes, we focus on the following applications:
  - Bioplastics;
  - Bio-based chemicals.

The main reasons behind the selection of packaging for food and drinks include:

- Surge in Investment: Investment in chemical recycling has seen a significant rise. For instance, European plastics manufacturers are planning a EUR 8 billion investment in chemical recycling by 2030, which is a significant jump from the EUR 2.6 billion projected for 2025 (Plastics Europe, 2024). This signifies a strong industry commitment to this technology.
- Driving Forces: There are a few reasons behind this surge. Chemical recycling offers a solution for plastic waste that cannot be mechanically recycled, potentially creating a more circular economy for

[53] The sector average results from (a) the quantitative analysis via the GEM-E3 model and (b) the trade flows analysis. While these values are not exactly the same due to differences in methodology, data sources and time periods, they are normally similar and are taken together to derive an industry average against which the potential UK market share potential is assessed.

plastics. Additionally, the EU's Green Deal emphasises recycling as a key aspect, and chemical recycling is seen as a way to achieve those goals (CEFIC, 2024).

Bioplastics and bio-based chemicals were selected for low-carbon substitutes as they are prospected to grow substantially in the short- and medium-term. As example:

- Market Size and Growth Rate: Forecasts vary slightly, but most reports predict a Compound Annual Growth Rate (CAGR) from 17% to 19% from 2023 to 2030. This translates to a near doubling of the market size within that timeframe (Fortune Business Insights, 2023).
- Market Value: Estimates for the current market size (2023) also differ slightly. Some reports suggest it is around USD 11-12 billion, while others place it closer to USD 10.35 billion (Fortune Business Insights, 2023).

Market Value: Estimates for the current market size (2023) also differ slightly. Some reports suggest it is around USD 11-12 billion, while others place it closer to USD 10.35 billion (Fortune Business Insights, 2023).

This is mainly due to the following key Drivers:

- Rising environmental concerns and growing demand for sustainable solutions.
- Stringent government regulations on conventional plastic usage.
- Increasing consumer preference for eco-friendly products.
- Technological advancements leading to improved performance and cost-competitiveness of bioplastics.

These factors, combined with the current status of technology development in the UK, represent the main reasoning behind Ricardo's selection.

Case studies

In RQ3, case study analysis is conducted to provide an analysis of historical experiences and draw valid conclusions for the UK regarding the advantages and disadvantages of being an early mover in new and emerging sectors.

Three case studies have been developed:

- **Morocco**: Concentrated solar power (CSP), mid-2000s onwards
- **Denmark**: 3rd generation heat networks[54], 1970s onwards
- **France**: Nuclear power, 1970s onwards

The case studies were developed based on desk research, i.e., a review of the relevant literature for each of the three selected cases. Based on the common results, general conclusions are drawn from the three case studies.

[54] 3rd generation heat networks as defined by (Lund, et al., 2014)

APPENDIX 3: KEY TERMS USED IN THE REPORT

The following table details several key terms used in the report.

Part of this study (in particular, RQ1) is closely related to the Energy Innovation Needs Assessment (EINA) framework.

The 2019 EINA project provided evidence to identify the primary innovation needs within the UK's energy system. This information guided the Department for Business, Energy & Industrial Strategy (BEIS) in allocating public sector investments towards low-carbon innovation. The project's findings were instrumental in shaping BEIS's Energy Innovation Programme, designed to expedite the transition of pioneering clean energy technologies and processes into practical applications throughout the 2020s and 2030s.

The findings of this project are intended to feed into the next iteration of the EINA project by providing reliable estimates of market size and share market projections. Consequently, some of the terms listed in the table below (e.g. “market size” and “UK market share”) directly link with the EINA methodology (cf. *Appendix 5: Business opportunities methodology* of the EINA Overview report (EINA, 2019)).

Table A-11: Key terms used in the report

Term	Definition
Domestic market size	A measure of annual demand indicating the market associated with the sale of green technology or related services in the UK
Export market size	A measure of annual demand indicating the market associated with the sale of green technology or related services in the rest of the world (RoW)
Global market size	The sum of domestic and export market size
UK domestic market share	The share of the domestic market that UK-based companies could feasibly capture
UK export market share	The share of the export market that British companies could feasibly capture
UK global market share	The share of the global market that British companies could feasibly capture
GVA	Gross value added, i.e., turnover less the value of intermediate consumption. GVA includes wages and salaries, depreciation, and profit
Competitive advantage	In the context of this study, competitive advantage refers to the unique strengths, resources, or capabilities possessed by a country that allows it to outperform its competitors in the market, achieve superior performance, and gain a favourable position.
Competitive disadvantage	In this study, competitive disadvantage refers to factors or weaknesses within a country that significantly disadvantage it compared to its competitors in the market. These disadvantages can hinder a company's ability to compete effectively, resulting in reduced market shares.
Cost curves	Cost curves represent graphical representations of the relationship between the quantity of goods or services produced and the costs associated with that production. In the context of this study, we define two cost curves, i.e. - Learning by research: a cost curve representing the relationship between the cumulative amount of R&D on a given technology and the costs associated with producing that technology. - Learning by doing: a cost curve representing the relationship between the cumulative quantity produced of a given technology and the costs associated with producing that technology.
Barrier	In the context of this study, barriers refer to international obstacles or risks that may prevent the UK from gaining higher market shares.
Enabler	In the context of the study, an enabler refers to international factors or conditions that facilitate the UK's ability to acquire greater market shares.
Early mover	In this study, an "early mover” refers to a country that takes proactive steps to pioneer and establish itself as a leader in developing, adopting, and commercialising innovative technologies or emerging sectors.

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