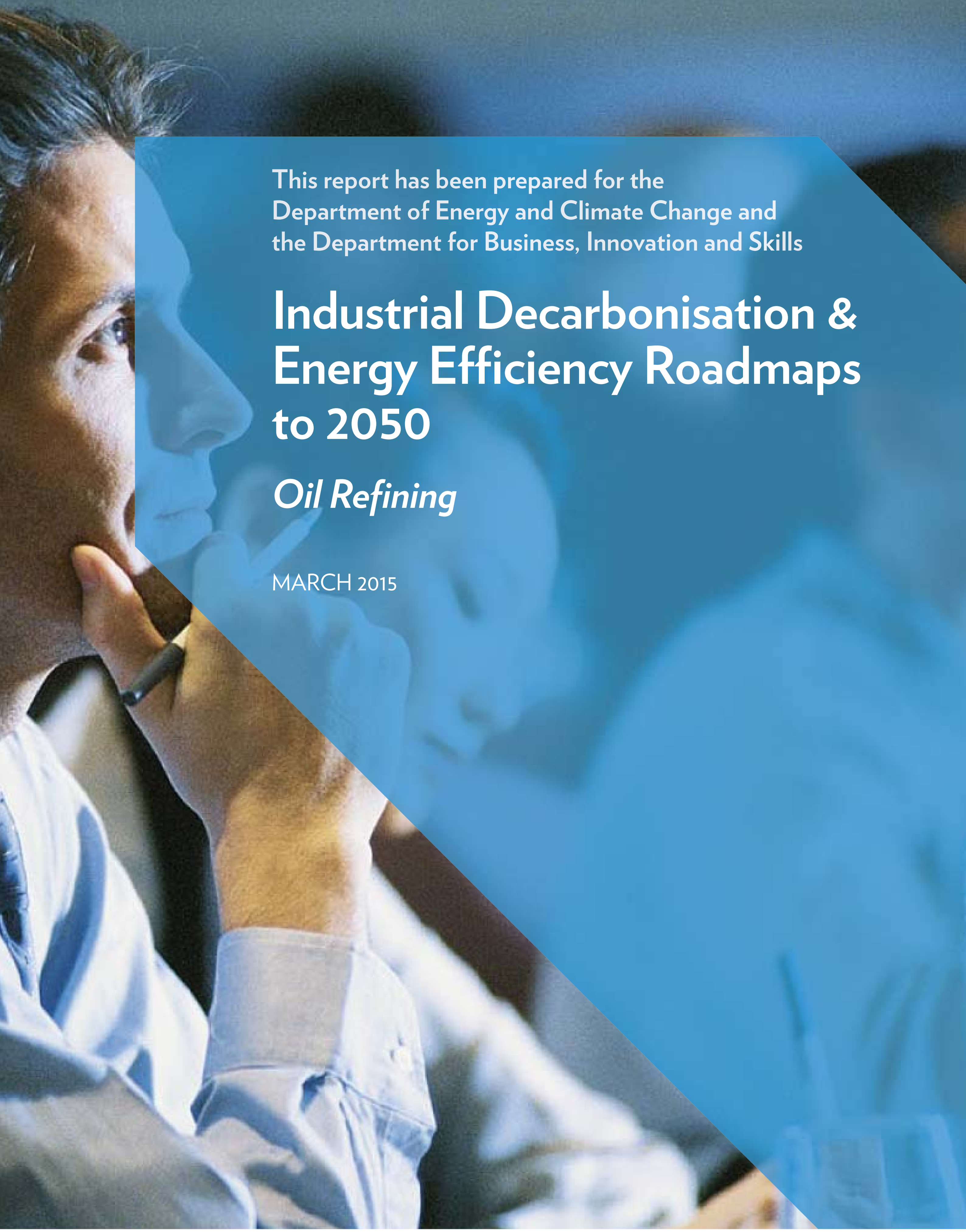

This report has been prepared for the Department of Energy and Climate Change and the Department for Business, Innovation and Skills

Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050

Oil Refining

MARCH 2015

WSP | PARSONS BRINCKERHOFF

DNV·GL

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ACRONYMS

BAT	Best Available Techniques
BIS	Department of Business, Innovation and Skills
CAAGR	Compound Average Annual Growth Rate
capex	capital expenditure
CCA	Climate Change Agreement
CCS	Carbon Capture and Storage
CDU	Crude Distillation Unit
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DECC	Department of Energy and Climate Change
EII®	Energy Intensity Index
EnMS	Energy Management System
ESD	Emergency Shut-Down
EU ETS	European Union Emissions Trading System
EUTL	EU Transaction Log
FCC	Fluid Catalytic Cracking
HCK	HydroCracker
INDEMAND	Industrial Energy and Material Demand
Ktoe	Kilo Tonne oil equivalent
LPG	Liquid Petroleum Gas
opex	Operating expenditure
POX	Partial Oxydation
PRV	Pressure Relief Valve
PSA	Pressure Swing Absorption
RD&D	Research, Development and Demonstration
REA	Rapid Evidence Assessment
ROI	Return on Investment
SA	Solomon Associates
SEC	Specific Energy Consumption
SRU	Sulphur Recovery Unit
TPOD	Total Primary Oil Demand
TRL	Technical Readiness Level
TSC	Total Sales into Consumption
UKPIA	UK Petroleum Industry Association
US EIA	US Energy Information Administration
VDU	Vacuum Distillation Unit

1. EXECUTIVE SUMMARY

1.1 What is the ‘Decarbonisation and Energy Efficiency Roadmap’ for the Oil Refining Sector?

This report is a ‘decarbonisation and energy efficiency roadmap’ for the oil refining sector, one of a series of eight reports that assess the potential for a low-carbon future across the most energy intensive industrial sectors in the UK. It investigates how the industry could decarbonise and increase energy efficiency whilst remaining competitive.

Changes in the international economy and the need to decarbonise mean that UK businesses face increasing challenges, as well as new opportunities. The UK Government is committed to moving a low carbon economy, including the most energy-intensive sectors. These sectors consume a considerable amount of energy, but also play an essential role in delivering the UK’s transition to a low-carbon economy, as well as in contributing to economic growth and rebalancing the economy.

The roadmap project aims were to:

- Improve understanding of the emissions abatement potential of individual industrial sectors, the relative costs of alternative abatement options and the related business environment including investment decisions, barriers and issues of competitiveness.
- Establish a shared evidence base to inform future policy, and identify strategic conclusions and potential next steps to help deliver cost effective decarbonisation in the medium to long term (over the period from 2020 to 2050).

Each roadmap aims to present existing and new evidence, analysis and conclusions to inform subsequent measures with respect to issues such as industry leadership, industrial policy, decarbonisation and energy efficiency technologies, business investments, research, development and demonstration (RD&D) and skills.

This roadmap is the result of close collaboration between industry, academics and government (Department of Energy and Climate Change (DECC) and Department for Business, Innovation and Skills (BIS)), which has been facilitated and delivered by independent consultants Parsons Brinckerhoff and DNV GL; the authors of the reports.

1.2 Developing the Oil Refining Sector Roadmap

The development of the oil refining sector roadmap consisted of three main phases:

1. Collection of evidence relating to technical options and barriers and enablers to invest in decarbonisation and energy efficiency technologies. Evidence was collected via a literature review, analysis of publicly available data, interviews and written responses from industry. Validation of evidence and early development of the decarbonisation potential took place during discussion with the trade association.
2. Development of decarbonisation ‘pathways’ to 2050 to identify and investigate an illustrative technology mix for a range of emissions reduction levels. Draft results were validated at a workshop.
3. Interpretation and analysis of the technical and social and business evidence to draw conclusions and identify potential next steps. These example actions, which are informed by the evidence and analysis, aim to assist with overcoming barriers to delivery of technologies within the decarbonisation pathways.

A sector team comprising representatives from the oil refining industry and its trade association (UK Petroleum Industries Association), the Government, Bath University and the University of Surrey has acted as a steering group as well as contributing evidence and reviewing draft project outputs. In addition, the outputs have been independently peer-reviewed. It should be noted that the findings from the interviews and workshops represent the opinions and perceptions of particular industrial stakeholders, and may not therefore be representative of the entire sector. Where possible we have tried to include alternative findings or viewpoints, but this has not always been possible; this needs to be taken into account when reading this report.

1.3 Sector Findings

The oil refining sector employs specific processes: distillation, conversion, reforming, desulphurisation and hydrogen production to convert crude oil into a combination of intermediate and end-products. The intermediate products are typically blended to produce the remaining desired end-products. The oil refining sector processed 67.07 million tonnes of crude oil in 2012 (Dukes, 2014). The sector contributed a direct value to the economy of £2.3 billion in 2013 (Purvin and Gertz, 2013).

Oil refining is an energy-intensive sector. In 2012 the main fuels used on UK refineries were refinery fuel gas (50.1%), catalyst coke (25.7%), natural gas (17.3%) and fuel oil (6.9%). In 2012, oil refining emitted 16.3 million tonnes of CO_2 (UKPIA, 2014). The combustion of hydrocarbons (mostly gases) in boilers and furnaces, hydrogen production, catalyst regeneration, and other process equipment and reactions makes up the oil refining sector carbon footprint shown in Table 1.

SECTOR	TOTAL ANNUAL CARBON EMISSIONS 2012 (MILLION TONNES CO_2)
Iron and Steel[1]	22.8
Chemicals	18.4
Oil Refining	**16.3**
Food and Drink	9.5
Cement[2]	7.5
Pulp and Paper	3.3
Glass	2.2
Ceramic	1.3

Table 1: Energy-intensive Industry total direct and indirect carbon emissions in 2012 (data sources include CCA data, EU ETS and NAEI)

[1] For the iron and steel sector, the reference year used is 2013. This was chosen due to the large production increase from the re-commissioning of SSI Teesside steelworks in 2012.

[2] For the cement sector, the 2012 actual production levels where adversely affected by the recession. Therefore we have assumed production of 10 million tonnes (rather than the actual production in 2012) and normalised emissions to this production level.

The companies operating within the oil refining sector are predominantly owned by international businesses headquartered outside of the UK. It is the view of industry that competition for investment from facilities in countries where labour and energy costs are lower than in the UK means that funding for the development of new plants or improvements to existing plants in the UK can be difficult to obtain. Competition in the sector is high, margins are small and on-going maintenance and investments costs are high. Demand for finished products is declining in the UK and competition is global, with UK refineries competing with refineries both in Europe and further afield.

The UK oil refining sector has recently experienced three refinery closures and a reduction through mothballing of primary distillation capacity. The sector will continue to face challenges from demand destruction for transport fossil fuels. The threat of further refinery closures remains, with the potential for increased imports to make up any shortfall developing in this event, which would result in further carbon leakage to refineries in other parts of the world.

1.4 Enablers and Barriers for Decarbonisation in the Oil Refining Sector

In this report, we look at 'enablers', 'barriers' and 'technical options' for decarbonisation of the oil refining sector. There is some overlap between barriers and enablers, as they sometimes offer two perspectives on the same issue. Based on our research, the main enablers for decarbonisation for the oil refining sector include:

- Cost savings from energy savings (threat of increasing energy costs)
- Government actions that encourage investments in decarbonisation
- Management focus, corporate targets, long-term energy strategies and willingness of top management to make climate change a priority
- Regulatory compliance
- Increased energy efficiency through improved energy monitoring and process control systems
- Government recognition of the strategic importance of the oil refining sector
- Enhanced collaboration between industry, government, trade associations and academia.

The main barriers to decarbonisation have been identified as:

- Unfavourable market conditions, demand destruction, negative cash flow and uncertainty
- Short-term approach and lack of focus on decarbonisation resulting from organisational structure and management focus
- Regulatory compliance
- High and increasing energy costs
- High competition levels preventing collaboration on decarbonisation projects
- Long payback periods for advanced technologies
- Specific shortage of key skilled staff
- Carbon Capture and Storage (CCS) has a number of barriers
- Long lifespan of refineries
- Risk of production disruption
- Disruptive tested and reliable technologies not available

1.5 Analysis of Decarbonisation Potential in the Oil Refining Sector

A 'pathway' represents a particular selection and deployment of options from 2012 to 2050 chosen to achieve reductions falling into a specific carbon reduction band relative to a reference trend in which no options are deployed. Two further pathways with specific definitions were also created, assessing (i) what would happen if no particular additional interventions were taken to accelerate decarbonisation (business as usual, BAU) or (ii) the maximum possible technical potential for decarbonisation in the sector (Max Tech). These pathways include deployment of options comprising (i) incremental improvements to existing technology, (ii) upgrades to utilise the best available technology, and (iii) the application of significant process changes using 'disruptive' technologies that have the potential to become commercially viable in the medium term.

The pathways created in the current trends scenario, the central of three scenarios used in this study, are shown below in Figure 1.[3]

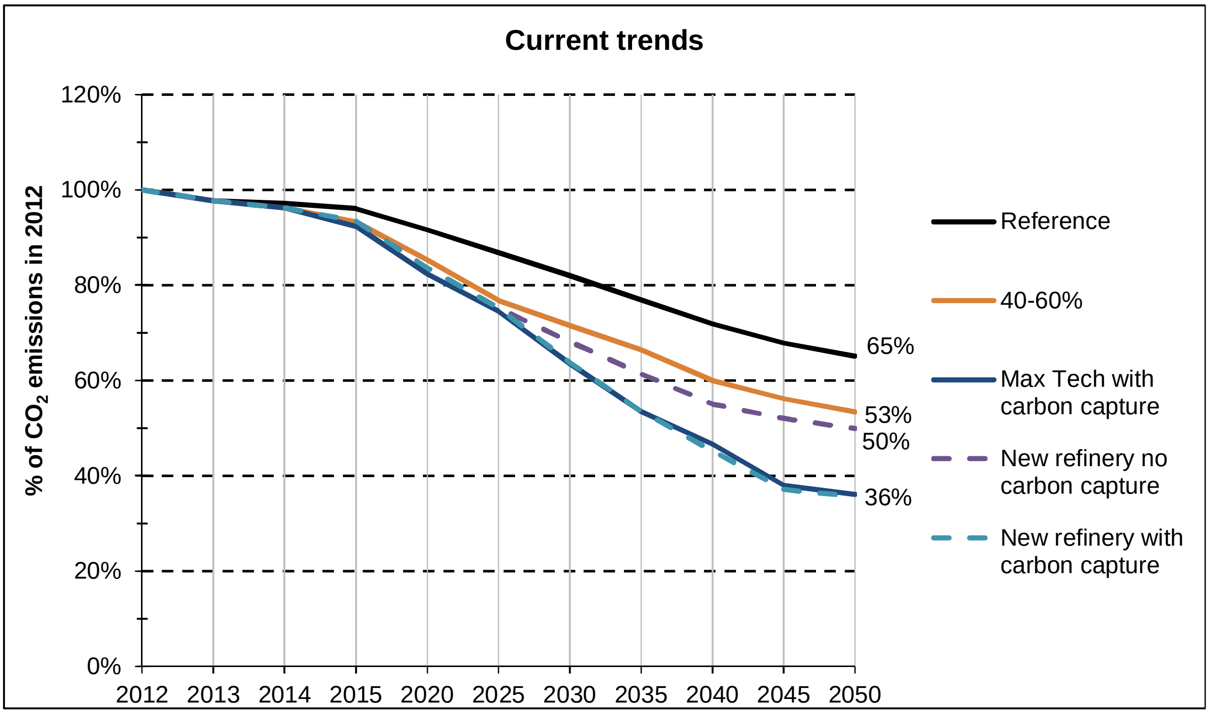

Figure 1: Pathways to decarbonisation of the oil refining sector, current trends scenario

Analysis of the costs of the pathways used order of magnitude estimates to add up the capital cost of each pathway. As an indication, the net present capital cost for the pathways, discounted at 3.5%, falls within an estimated range of £200 million[4] to £500 million[5]. There is a large degree of uncertainty attached to the cost analysis, especially for options which are still in the research and development stage. Also, costs of operation, energy use, research, development, demonstration, civil works, modifications to plant and costs to other stakeholders are significant for some options, but not included here. The costs presented are for the study period and are adjusted to exclude residual value after 2050, thus a proportion of the costs of high capex items deployed close to 2050 is excluded. Great care must be taken in how these costs are interpreted. While implementation of some of the options within the pathways may reduce energy costs due to increased efficiency, the scale of the investments associated with the pathways must be considered by stakeholders when planning the next steps in the sector.

[3] Sensitivity analysis includes illustrative pathways showing the impact on decarbonisation of a new refinery with or without carbon capture
[4] For the BAU pathway in the current trends scenario
[5] For the Max Tech pathway in the current trends scenario

1.6 Conclusions and Key Technology Groups

The following conclusions have been drawn from the evidence and analysis:

Strategy, Leadership and Organisation

It is important that the oil refining sector, the government and other stakeholders recognise the strategic and long-term importance of the sector to the UK in the context of decarbonisation, energy efficiency and general competitiveness for the sector.

Business Case Barriers

The research, development and demonstration (RD&D) and commercial deployment of major technologies requires significant upfront capital, which is often not available internally due to competition with UK and overseas projects with higher business priority. The long investment cycles in the industry combined with ageing UK plants and the view of high operating costs in the UK makes it harder for UK sites to compete for limited investment funds. In addition oil refining is low margin which reduces the ability to invest. External funding is often not available on terms that meet internal investment criteria.

Future Energy Costs, Energy Supply Security, Market Structure and Competition

The sector is characterised by high competition levels limiting collaboration on energy efficiency. Three refineries have closed between 2009 and 2014 (UKPIA, 2014) and a number of refineries have reduced crude throughput by mothballing distillation capacity due to reducing margins in the sector. Energy efficiency projects are viewed as a competitive advantage and thus refiners do not share best practice information.

Industrial Energy Policy Context

Regulatory compliance is a driver of energy efficiency investments. However, oil refiners are unclear how they will survive past the medium-term regulatory compliance requirements already set out by government for improving environmental performance.

Research, Development and Demonstration

The research, development and demonstration of the new technologies required to deliver decarbonisation is difficult to achieve with current approaches in the sector. This includes early RD&D activity but also, crucially, progressing technology to successful commercial demonstration so that it is de-risked for future deployment. Technologies should be selected through a collaborative process. Companies may not have the time and expertise to identify if and how different options may be of benefit to them and so may not progress the RD&D activity needed.

People and Skills

New staff resources with specialised skills and knowledge in energy and heat engineering are increasingly needed by the UK oil refining sector. Currently, key responsibilities of energy teams include ensuring compliance with existing regulation which diverts attention and effort from identification and implementation of energy efficiency activities.

The key technology groups that, in this investigation, make the largest contributions to sector decarbonisation or energy efficiency are as follows:

Fuel and Feedstock Availability (Including Biomass)

Biomass may make a small contribution to reducing emissions in the oil refining sector, substituting for natural gas. The availability of low-carbon fuels is a potential issue for sector decarbonisation. This availability issue can be between uses within the sector (biomass as a fuel) or with other external uses (e.g. the use of waste plastics for electricity generation). The challenges are to understand where the greatest decarbonisation potential can be achieved with a limited resource, as well as to maximise the availability of the resource. There is significant added value to use biomass for heat and power (via CHP technology) compared to power generation only, and this is recognised in government electricity market support policy.

Energy Efficiency and Heat Recovery

Energy efficiency and heat recovery technologies are generally well-established, of low technical risk and can provide operational cost savings as well as reducing emissions. There is a need to improve the availability of human and financial resources to allow the potential of this option to be fully realised.

Clustering

Improving site or sector integration could enable use of CO_2 and recovered heat from oil refineries. Clustering also allows infrastructure investment to benefit from economies of scale in serving multiple sites, as well as spreading investment risk. It is recognised that relocating an oil refinery is highly unlikely due to the scale of operations and size of sites, but clustering of other industries around refining sites could still represent an opportunity to reduce emissions. Stronger encouragement for increased clustering could mitigate barriers.

Carbon Capture

Refineries could be considered a sufficient scale to justify their own CO_2 pipeline and storage infrastructure however collaboration with external sectors would support the establishment of the networks, along with the availability of sources of funding appropriate to this type of shared infrastructure. There is also a need to demonstrate the technology.

Next Steps

This roadmap report is intended to provide an evidence-based foundation upon which future policy can be implemented and actions delivered. The report has been compiled with the aim that is has credibility with industrial, academic and other stakeholders and is recognised by government as a useful contribution when considering future policy.

2. INTRODUCTION, INCLUDING METHODOLOGY

2.1 Project Aims and Research Questions

2.1.1 Introduction

Changes in the international economy, coupled with the need to decarbonise, mean that UK businesses face increased competition as well as new opportunities. The government wants to enable UK businesses to compete and grow while moving to a low-carbon economy. The UK requires a low-carbon economy but currently includes industries that consume significant amounts of energy. These energy-intensive industries have an essential role to play in delivering the UK's transition to a low-carbon economy, as well contributing to economic growth and rebalancing the economy.

Overall, industry is responsible for nearly a quarter of the UK's total emissions (DECC, 2011)[6]. By 2050, the government expects industry to have delivered a proportionate share of emissions cuts, achieving reductions of up to 70% from 2009 levels (DECC, 2011). Nonetheless, the government recognises the risk of 'carbon leakage' and 'investment leakage' arising from the need to decarbonise and is committed to ensuring that energy-intensive industries are able to remain competitive during the transition to a low-carbon economy.

The Department of Energy and Climate Change (DECC) and the Department of Business, Innovation and Skills (BIS) have set up a joint project focusing on the eight industrial sectors which use the greatest amount of energy[7]. The project aims to improve the understanding of technical options available to sectors to reduce carbon emissions and increase energy efficiency while remaining competitive. This includes include investigating the costs involved, the related business environment, and how investment decisions are made in sector firms. This will provide the industry and government with a better understanding of the technical and economic abatement potential, set in the relevant business context, with the aim to agree measures that both the government and these industries can take to reduce emissions while maintaining sector competitiveness.

The project scope covers both direct emissions from sites within the sector and indirect emissions from the use of electricity at the sites but generated off site

The industrial sectors evaluated in this project are listed in Table 2.

Cement	Glass
Ceramics	Iron and Steel
Chemicals	**Oil Refining**
Food and Drink	Pulp and Paper

Table 2: Industrial sectors evaluated in this project

[6] It has also been estimated that 70% of industrial energy use is for heat generation (Source: Energy Consumption in the UK 2014: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk)
[7] The 'non-metallic minerals' sector has been divided into three sectors: glass, ceramics and cement.

2.1.2 Aims of the Project

The DECC 2011 Carbon Plan outlined the UK's plans to reduce greenhouse gas emissions and make the transition to a low-carbon economy while maintaining energy security and minimising negative economic impacts. This project aims to improve evidence on decarbonisation and energy efficiency for eight energy-intensive industry sectors, with oil refining sector the subject of this report.

The project consortium of Parsons Brinckerhoff and DNV GL was appointed by DECC and BIS in 2013 to work with stakeholders, including the UK manufacturers' organisations (i.e. trade associations), to establish a shared evidence base to support decarbonisation. The roadmap process consisted of three main phases:

i. Information and evidence gathering on existing technical options and potential breakthrough technologies, together with research to identify the social and business barriers and enablers to decarbonisation
ii. Development of sector decarbonisation pathways
iii. Conclusions and identification of potential next steps

A series of questions were posed by DECC and BIS as part of the project. These 'principal questions' guided the research undertaken and the conclusions of this report. The questions and the report section in which they are addressed are stated below:

4. What are the current emissions from each sector and how is energy used? - section 3.3
5. For each sector, what is the business environment, what are the business strategies of companies, and how does it impact on decisions to invest in decarbonisation? - section 3.4
6. How might the baseline level of energy and emissions in the sectors change over the period to 2050? - section 4.3
7. What is the potential to reduce emissions in these sectors beyond the baseline over the period to 2050? - section 4.4
8. What emissions pathways might each sector follow over the period to 2050 under different scenarios? - section 4.4
9. What next steps into the future might be required by industry, the government and others to overcome the barriers in order to achieve the pathways in each sector? - section 5

2.1.3 What is a Roadmap?

A 'roadmap', in the context of this research, is a mechanism to visualise future paths, the relationship between them and the required actions to achieve a certain goal. A technology roadmap is a plan that matches short-term and long-term goals with specific technology solutions to help meet those goals. Roadmaps for achieving policy objectives go beyond technology solutions into broader consideration of strategic planning, market demands, supplier capabilities, and regulatory and competitive information.

The roadmaps developed by this project investigate decarbonisation in various UK industries, including how much carbon abatement potential currently exists, what technologies will need to be implemented in order to extend that potential, and how businesses will be affected. The roadmap aims to present existing and new evidence, analysis and conclusions as a 'consensual blueprint' to inform subsequent action with respect to issues such as future energy and manufacturing industrial strategy and policy, decarbonisation and energy efficiency business investments, research and development, and skills. The roadmaps consist of three components: evidence, pathways analysis and conclusions, as illustrated in Table 3. Each component is necessary to address the principal questions, and is briefly defined below.

INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAP TO 2050			
SOURCES OF EVIDENCE	**INTERMEDIATE OUTPUTS**	**PATHWAYS**	**STRATEGIC CONCLUSIONS AND EXAMPLE ACTIONS**
Literature	Validated emission data	Analysis of evidence to construct decarbonisation and energy efficiency pathways	Analysis of evidence and pathways to develop strategic conclusions and possible next steps to: • Overcome barriers and strengthen enablers • Implement pathways
Publicly available emissions data	Decarbonisation options and associated data		
Interviews, a site visit, written responses, meetings and a workshop with stakeholders	Energy efficiency options and associated data		
Government policy and analytical teams, trade associations, academics as part of engagement with the sector team	Barriers and enablers to decarbonisation and energy efficiency options and investment		

Table 3: Input and output for a decarbonisation and energy efficiency roadmap to 2050

The views of contributing organisations

These reports were commissioned by DECC and BIS, and jointly authored by Parsons Brinckerhoff and DNV GL. The project was progressed using a collaborative process and while important contributions were provided by the sector, it should not be assumed that participating organisations (i.e. government, trade associations and their members and academic institutions) endorse all of the report's data, analysis and conclusions.

The findings from the interviews and workshops represent the opinions and perceptions of particular industrial stakeholders, and may not therefore be representative of the entire sector. We have tried to include alternative findings or viewpoints, but this has not always been possible within the constraints of the project. This needs to be taken into account when reading this report.

2.2 Overall Methodology

The overall methodology is illustrated in Figure 2 and shows the different stages of the project. As can be seen, the stakeholders are engaged throughout the process that follows the main phases of the project: evidence gathering, modelling/pathway development and finally drawing out the conclusions and potential next steps. A detailed description of the methodology can be found in appendix A.

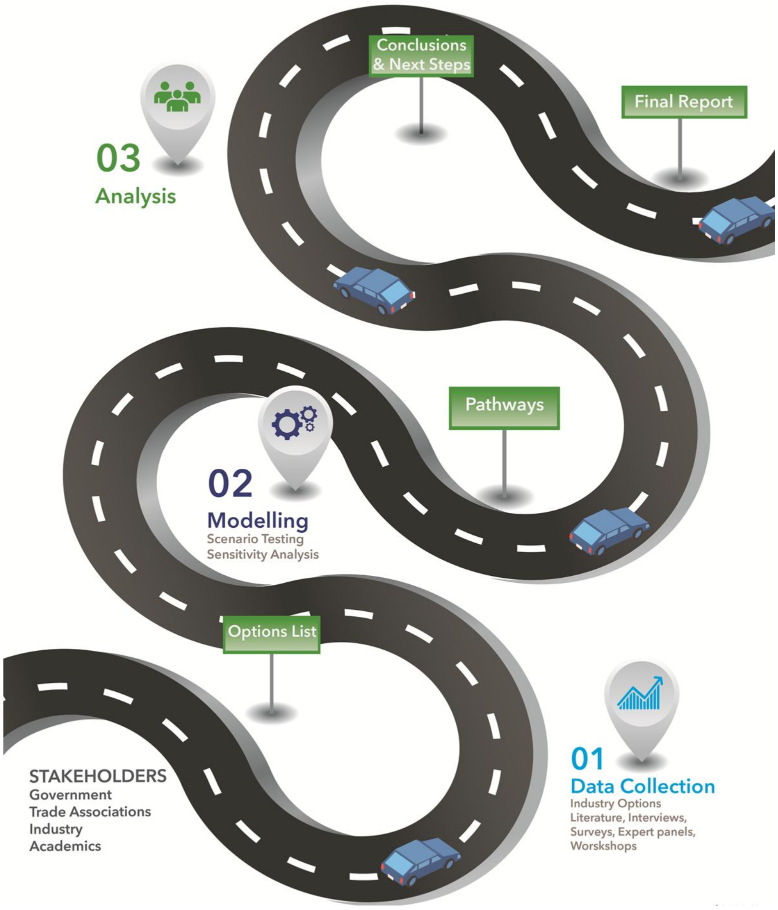

Figure 2: Roadmap Methodology

Evidence was gathered for covering technical, and social and business aspects from literature reviews, interviews, written responses, a site visit and a workshop with relevant stakeholders. These different sources of information allowed evidence triangulation to improve the overall research. The data was then used to develop a consolidated list of barriers and enablers for decarbonisation, and a register of technical options for the industry. This was subsequently used to develop a set of decarbonisation pathways to evaluate the decarbonisation potential of the UK oil refining sector and the main technical options required within each pathway.

Key to the overall roadmap methodology was engagement with all stakeholders, including with business and trade association representatives, academics and civil servants, to contribute to the evidence, validate its quality and interpret the analysis. We have worked closely with UKPIA (UK Petroleum Industry Association), DECC and BIS to identify and involve the most appropriate people from the oil refining sector, relevant academics and other stakeholders, such as representatives from the financial sector.

2.2.1 Findings

Evidence Gathering

The data focused on technical, and social and business information, aiming to acquire evidence on:

- Decarbonisation options (i.e. technologies)

- Barriers and enablers to decarbonisation and energy efficiency
- Background to the sector
- Current state of the sector and possible future changes within the sector
- Business environment and markets
- Potential next steps

Such evidence was required to either answer the principal questions directly and/or to inform the development of pathways for 2050. Four methods of research were used in order to gather as much evidence as possible (and to triangulate the information) within a short timescale. These methods were:

- **Literature review:** A short focussed review of over 42 documents all published after 2000 (with minor exceptions) was completed. The documents were either related to energy efficiency and decarbonisation of the sector or to energy-intensive industries in general. This was not a thorough literature review or rapid evidence assessment (REA) but a desktop research exercise deemed sufficient by the project team[8] in its breadth and depth to capture the evidence required for the purpose of this project. The literature review was not intended to be exhaustive and aimed to capture key documentation that applied to the UK. This included the sector structure, recent history and context including consumption, demand patterns and emissions, the business environment, organisational and decision-making structures and the impacts of UK policy and regulation. Further details are provided in appendix A.
- **Interviews:** In liaison with UKPIA, DECC and BIS, seven oil refining companies were invited to participate in the social and business interviews. The purpose of the interviews was to obtain further details on the different subsectors within the oil refining sector and gain a deeper understanding of the principal questions, including details of decision-making processes and how companies make investment decisions, how advanced technologies are financed, what a company's strategic priorities are and where climate change sits within this. The social and business team were unable to interview any of the refineries, as refineries declined to participate due to reservations regarding Competition Law. They did, however, complete two interviews with the trade association and a retired oil refining specialist from university. The interviewees were interviewed using an 'interview protocol' template, developed in liaison with DECC and BIS. This template was used to ensure consistency across interviews, fill gaps in the literature review, identify key success stories and extract key barriers to investment in low-carbon technologies. The interview protocol can be found in appendix A. Interviewees were selected to maximise coverage across sub-sectors and emissions and also take into account company headquarters location, production processes and company size.
- **Written responses:** There were limited written responses by four different respondents, ranging from refineries, to academics and the trade association.
- **Site visit:** In order to overcome the barriers to conducting the interviews, the project team completed one site visit in order to fill the information gaps. The site visit was also used to review potential technological options for decarbonisation to support the literature review findings.
- **Workshop:** One workshop was held, attendees for which were identified in consultation with UKPIA, DECC and BIS. The sector had one workshop. The first activity of the workshop was focused on reviewing potential technological options (that were identified from literature and interviews) for decarbonisation and the proposed pathways towards decarbonisation of the sector. It included identifying adoption rate, applicability, improvement potential, ease of implementation, capex, ROI, saving potential and timeline for the different options. This was done through two breakout sessions;

[8] DECC, BIS and the consultants of PB and DNV GL.

one focused on collecting more data and the other one on timelines under different scenarios. The second activity involved group discussions on enablers and barriers, and how to overcome them. The aim of this workshop was to prioritise the enablers and barriers and to consider how to overcome the latter. This was done by each of the four tables indicating their top five enablers and barriers, and in a separate session identifying if there were any missing enablers or barriers from the information gathered to date. This helped build confidence in the final list of enablers and barriers. The workshop participants included the relevant trade associations, large companies with the aim of achieving representation of key companies or subsectors and academics with expert knowledge of the sector, PB and DNV GL consultants, DECC and BIS project managers and senior civil servants. The average size of a workshop was 40 people.

Note:

- That for the purposes of anonymity all interviews, site visits and written responses have been combined together in the analysis and are referred to as industry sources and the role of the person interviewed or the company name has not been indicated to ensure anonymity.
- That the sector has no subsectors or sub-categories therefore the sources are representative of the sector. This has allowed generalisation during the rest of the report including the following areas: decision-making, barriers, conclusions.

By using a range of information sources, the evidence could be triangulated to improve the overall research. Themes that were identified during the literature review were subsequently used as a focus or a starting point during the interviews, a site visit and the workshop. The data from the literature was corroborated by comparing it with evidence from the interviews, written responses, a site visit and the workshop. Likewise, information gaps identified during the interviews, the site visit and the workshop were, where possible populated using literature data or written responses. In addition, UKPIA collected data from its members that further helped to fill gaps and triangulate multiple data sources. It should be noted that the evidence-gathering exercise was subject to several limitations based upon the scale of activities that could be conducted within the time and resources available. Interview samples were gathered through purposive and snowball sampling techniques in collaboration with trade associations, DECC and BIS experts. But due to time, sampling and resource constraints the samples may be limited in terms of their numbers and/or diversity. Where possible we have attempted to triangulate the findings to counter any bias in the sample, but in some areas this has not been possible. Some caution should therefore be used in interpreting the findings. The literature review, while not intended to be exhaustive, aimed to capture key documentation that applied to the UK. The criteria for identifying and selecting literature is detailed in Appendix A.

The different sources of evidence together with the associated outputs are shown in Figure 3.

Figure 3: Evidence gathering process[9]

The different sources of evidence were used to develop a consolidated list of barriers to and enablers for decarbonisation and energy efficiency, and a register of technical options for the oil refining sector. Evidence on adoption rate, applicability, improvement potential, ease of implementation, capex, ROI and saving potential of all options (where available) was collected, together with information on strengths, weaknesses, opportunities and threats (SWOT). A SWOT analysis is a different lens to examine the enablers and barriers and reinforce conclusions and linkages between evidence sources. It identifies how internal strengths mitigate external threats and can be used to create new opportunities, and how new opportunities can help overcome weaknesses. By clustering the various possibilities, we identified key stories from the SWOT analysis which enabled us to describe the business and market story in which companies operate. Further information on the SWOT analysis is provided in appendix B. The SWOT analysis was used to further understand and validate the initial findings from the literature review and provided the basis for workshop, site visit and interview discussions, and further helped to qualify the interview and workshop outcomes. Enablers and barriers were prioritised as a result of the outcomes and analysis of the evidence-gathering process and workshop scores.

This information was used to inform the development of a set of pathways to illustrate the decarbonisation potential of the oil refining sector in the UK. The summary and outcomes of this analysis are discussed in Section 4.6.

The evidence gathering process was supported by moderate levels of engagement with a wide range of stakeholders including industry members, trade association representatives, academics and staff of DECC and BIS.

The evidence gathering exercise (see appendix A for details) was subject to inherent limitations based upon the scale of activities and sample sizes that could be conducted within the time and resources available. The oil refining companies targeted for interview included the operators of refineries that account for almost 100% of carbon emissions produced by UK refineries, and included UK decision-makers and technical specialists

[9] In addition to interviews, a site visit was also carried out for the refining sector

from the sector. However, as stated above, the social and business team were unable to interview any of the refineries, and only completed two interviews with the trade association and a retired oil refining specialist from university. These interviews were conducted to provide greater depth and insight to the issues faced by companies. Information gaps were filled with a site visit, written responses and discussions at the workshop.

The identification of relevant information was approached from a ‘global’ and UK viewpoint. The global outlook examined dominating technologies and process types, global production, CO_2 emissions (in the EU27), and the global outlook to 2050, including the implications for pulp and paper producers and consumers. The UK outlook examined the sector structure, recent history and context including consumption, demand patterns, emissions, the business environment, organisational and decision-making structures and the impacts of UK policy and regulation.

Options examined were classified into 20 categories (see appendix C). Most of these categories are applicable to the whole refinery and include: advanced control and improved monitoring; CCS (carbon capture and storage); flaring; fuel switching; lighting; maintenance; motors, pumps, compressors and fans; new refinery as replacement; process heaters and furnaces; storage tanks; and waste heat and energy recovery. Other categories are more process-specific and include: crude unit upgrades; on-site renewables; FCC design improvements; hydrogen recovery and optimisation; HCK design improvements; biomass; CHP; steam use optimisation (boiler retrofit and utilities); and VDU design improvements.

Evidence Analysis

The first stage in the analysis was to assess the strength of the evidence for the identification of the enablers and barriers. This was based on the source and strength of the evidence, and whether the findings were validated by more than one information source. The evidence was also analysed and interpreted using a variety of analytical techniques. Elements of the Porter’s five forces analysis, SWOT analysis and system analysis were used to conduct the analysis of the business environment, and the barriers and enablers (section 3.4); while concepts from storytelling and root cause analysis were used during the interviews with stakeholders. These different techniques are discussed in appendix B.

The options register of the technology options for decarbonisation was developed based on the literature review, interviews, written responses, the site visit and the workshop, and additional information provided by UKPIA and its members. The strengths, weaknesses, enablers and barriers of each option were taken into account to refine the options register, which was then used to build up the different pathways in the pathway model.

A second stage in the analysis was the classification of technological options and an assessment of their readiness.

Limitations of these Findings

The scope of the study did not cover a full assessment of the overall innovation chain or of present landscape of policies and actors. Direct and indirect impacting policies, gaps in the current policy portfolio, and how future actions would fit into that portfolio (e.g. whether they would supplement or supplant existing policies) are not assessed in the report in any detail.

2.2.2 Pathways

The pathways analysis is an illustration of how the oil refining industry could potentially decarbonise from the base year 2012 to 2050. Together the set of pathways developed in the study help give a view of the range of technology mixes that the sector could deploy over coming decades. Each pathway consists of different technology options that are implemented over time at different levels. Each technology option included a number of key input parameters including carbon dioxide saving, cost, fuel use change, applicability, current adoption (in the base year), and deployment (both rate and extent). A 'pathway' represents a particular selection and deployment of options from 2014[10] to 2050 chosen to achieve reductions falling into a specific decarbonisation band.

In this project, up to five pathways were developed, three of which were created to explore possible ways to deliver carbon dioxide emissions to different decarbonisation bands by 2050, as shown below:

- 20-40% CO_2 reduction pathway relative to the base year
- 40-60% CO_2 reduction pathway relative to the base year
- 60-80% CO_2 reduction pathway relative to the base year

Two further pathways - with specific definitions - were also created, assessing (i) what would happen if no particular additional interventions were taken to accelerate decarbonisation (business as usual, BAU) or (ii) the maximum possible technical potential for decarbonisation in the sector (Max Tech)[11].

The BAU pathway consisted of the continued roll-out of technologies that are presently being deployed across the sector as each plant or site reaches the appropriate point to implement the technology. For the oil refining industry, next to the general Max Tech pathway, two alternative pathways (sensitivities) have been created in which a new refinery is built using BAT (best available technology) as replacement to an old plant new refinery pathway without CCS and new refinery pathway with CCS.

Pathways were developed in an iterative manual process and not through a mathematical optimisation process. This was done to facilitate the exploration of uncertain relationships that would be difficult to express analytically. This process started with data collected in the evidence gathering phase regarding the different decarbonisation options, current production levels and the current use of energy or CO_2 emissions of the sector. This data was then enriched through discussion with the sector team and in the first workshop. Logic reasoning (largely driven by option interaction), sector knowledge and technical expertise were applied when selecting technical options for the different pathways. These pathways were discussed by the sector team, modelled, and finally tested by the stakeholders participating in the second workshop. This feedback was then taken into account and final pathways were developed. All quantitative data and references are detailed in the options register and relevant worksheets of the model. The pathway model is available through DECC and BIS and the methodology is summarised in appendix A.

Scenario Testing

The different pathways developed have been tested under different scenarios (i.e. there are three different scenarios for each pathway). A scenario is a specific set of conditions that could directly or indirectly affect the ability of the sector to decarbonise. Examples of these are: future decarbonisation of the grid, future growth of the sector, future energy costs, and future cost of carbon. Since we do not know what the future will look like, using scenarios is a way to test the robustness of the different pathways.

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[10] Model anticipates deployment from 2014 (assuming 2012 and 2013 are too early).
[11] Definitions are provided in the glossary.

For each pathway, the following three scenarios were tested (a detailed description of these scenarios is provided in appendix A):

- **Current trends**: This would represent a future world very similar to our world today with low continuing decline in domestic refinery activity.
- **Challenging world**: This would represent a future world with a more challenging economic climate and where decarbonisation is not a priority.
- **Collaborative growth**: This would represent a future world with a positive economic climate and where there is collaboration across the globe to decarbonise.

In order to produce pathways for the same decarbonisation bands under the different scenarios, the deployment rate of the options varied according to the principals set out in the scenarios. For example, in order to achieve a specific decarbonisation band in 2050 in the collaborative growth scenario, options were typically deployed at a faster rate and to a higher degree as compared to the current trends scenario (provided this was considered to be consistent with the conditions set out in the scenarios).

Key Assumptions and Limitations

The pathway model was developed and used to estimate the impact on emissions and costs of alternative technology mixes and macro-economic scenarios. Modelled estimates of decarbonisation over the period (2014 to 2050) are presented as percentage reductions in emissions meaning the percentage difference between emissions in 2050 and emissions in the base year (2012). CO_2 emissions reductions and costs are reported compared to a future in which there was no further take up of decarbonisation options (referred to as the reference trend).

The model inputs and option deployments are based on literature review, interviews and stakeholder input at workshops and sector meetings. Parsons Brinckerhoff and DNV GL sector leads used these sources to inform judgements for these key parameters. Key input values (e.g. decarbonisation factors for options) are adapted from literature or directly from stakeholder views. If data values were still missing then values were estimated based on consultant team judgements. Decarbonisation inputs and pathways were reviewed and challenged at the workshop. The uncertainties in this process are large given this level of judgement, however, they are not quantified. A range of sensitivity analysis was carried out, including the development of alternative versions of the Max Tech pathway and also testing of different availabilities of biomass.

Deployment of options at five-year intervals is generally restricted to 25% steps unless otherwise indicated. For example, an option cannot be incrementally deployed by 25% over ten years, but has to deploy over five years and flat-line over the other five years.

In this report, when we report carbon dioxide – this represents CO_2 equivalent. However, other GHGs were not the focus of the study which centred on both decarbonisation and improving energy efficiency in processes, combustion and indirect emissions from electricity used on site but generated off site. Also, technical options assessed in this work result primarily in CO_2 emissions reduction and improved energy efficiency. In general, emissions of other GHGs, relative to those of CO_2, are very low.

Assumptions in relation to the maximum technical pathway

Max Tech pathway: A combination of carbon abatement options and savings that is both highly ambitious but also reasonably foreseeable. It is designed to investigate what might be technically possible when other barriers are set to one side. Options selected in Max Tech take into account barriers to deployment but are not excluded based on these grounds. Where there is a choice between one option or another, the easier or cheaper option is chosen or two alternative Max Tech pathways are developed.

The following assumptions apply:

1. Technology Readiness Level (TRL): process or technology at least demonstrated at a pilot scale today, even if that is in a different sector.
2. Other disruptive technology options that could make a significant difference but that are not mature enough for inclusion in the pathways are covered in the commentary.
3. Cost is not a constraint: it has been assumed that there are strong and growing financial incentives to decarbonise which mean that the cost of doing so is not generally a barrier.
4. Option deployment rate: the sector team followed the roadmap method process to develop and test option deployments in all pathways, including Max Tech. Hence, in each sector, rates at which the options can be deployed were considered as 'highly ambitious but also reasonably foreseeable'.
5. Biomass: maximum penetration of biogenic material as fuel or feedstock assuming unlimited availability. Carbon intensity and sensitivities are included in each sector.
6. Carbon Capture (CC): All sectors have made individual (sector) assessments of the maximum possible potential by 2050 based on what is 'highly ambitious but also reasonably foreseeable'. This assessment included the most suitable CO_2 capture technology or technologies for application in the sector, the existing location of the sites relative to each other and anticipated future CC infrastructure, the space constraints on sites, the potential viability of relocation, the scale of the potential CO_2 captured and potential viability of both CO_2 utilisation and CO_2 storage of the captured CO_2.
7. Electricity Grid: three decarbonisation grid trends were applied through the scenario analysis.

Option Interaction Calculation

The pathway model incorporated two methods of evaluating potential interaction of options. The first method reflected the assumption that all options interacted maximally, and the second method reflected the assumption that the options did not interact. Neither of these cases was likely to be representative of reality; however the actual pathway trend would lie between the two. The two methods therefore provided a theoretical bound on the uncertainty of this type of interaction in results that was introduced by the choice of a top down modelling approach. Figures calculated based on the assumption of maximum interaction are presented exclusively in the report unless otherwise stated.

Cumulative Emissions

An important aspect of an emission pathway is the total emission resulting from it. The pathways presented in this report are not designed or compared on the basis of cumulative emissions over the course to 2050. Only end-targets are assessed e.g., it is possible for a pathway of lower 2050 emission to have larger cumulative emissions, and thus a greater impact on the global climate system. The exception to this is in the cost analysis section where total CO_2 abated under each pathway – as calculated by the model – is quoted.

Scope of Emissions Considered

Only emissions from production or manufacturing sites were included in scope (from combustion of fuels, process emissions and indirect emissions from imported electricity). Consumed and embedded emissions were outside the scope of this project.

Complexity of the Model

The model provided a simplified top down representation of the sector to which decarbonisation options were applied. It does not include any optimisation algorithm to automatically identify a least cost or optimal pathway.

Material Efficiency

Demand reduction through material efficiency was outside the scope of the quantitative analysis. It is included in the conclusions as material efficiency opportunities are considered to be significant in terms of the long-term reduction of industrial emissions: see for example Allwood et al. (2012) and the ongoing work of the UK INDEMAND Centre.

Base Year (2012)

The Climate Change Act established a legally binding target to reduce the UK's greenhouse gas emissions by at least 80% below base year (1990) levels by 2050. DECC's 2011 Carbon Plan set out how the UK will achieve decarbonisation within the framework of the carbon budgets and policy objectives: to make the transition to a low-carbon economy while maintaining energy security and minimising costs to consumers. The Carbon Plan proposed that decarbonising the UK economy "could require a reduction in overall industry emissions of up to 70% by 2050" (against 2009 emissions).

In this project for the analytical work, we have set 2012 as the base year. This is the most recent dataset available to the project, and was considered to be a suitable date to assess how sectors (as they currently are) can reduce emissions to 2050. This separates the illustrative pathways exercise from national targets, which are based on 1990 emissions.

2.2.3 Conclusions and next steps

The conclusions and potential next steps are drawn from the outcomes of the pathways modelling, the scenario testing and the potential actions to overcome barriers and enhance enablers that were identified together with stakeholders. The strategic conclusions can include high-level and/or longer term issues, or more specific, discrete example actions which can lead to tangible benefits. The potential next steps are presented in the context of eight strategic conclusions (or themes) and six or seven technology groups. The strategic conclusions or themes are:

- Strategy, leadership and organisation
- Business case barriers
- Future energy costs, energy supply security, market structure and competition
- Industrial energy policy context
- Life-cycle accounting
- Value chain collaboration
- Research, development and demonstration
- People and skills

The main technology groups as presented in section 5 are:

- Electricity grid decarbonisation
- Electrification of heat
- Fuel and feedstock availability (including biomass)
- Energy efficiency and heat recovery
- Clustering
- Carbon capture
- Sector-specific technologies

3. FINDINGS

3.1 Key Points

For the UK the CO_2 emissions in 2012 from Oil Refining production totalled 16.3 million tonnes of CO_2 for a primary oil demand of 67.07 million tonnes (Dukes, 2014). Direct emissions originate largely from combustion of hydrocarbons (mostly gases) in boilers and furnaces, hydrogen production, and catalyst regeneration. Other CO_2 emissions (some in the form of hydrocarbons) arise from sulphur recovery units (SRUs), storage tanks and other process equipment, pressure relief valves (PRV) and emergency shut-downs. Indirect emissions are related to electricity use or production, and to steam generation or import. The fuel use in the sector is dominated by refinery fuel gas (50.1%), followed by catalyst coke (25.7%), natural gas (17.3%) and fuel oil (6.9%) (UKPIA, 2014).

It was reported that before carbon-related legislation was introduced, the UK oil refining sector was already evolving towards a lower carbon energy strategy. Energy efficiency is perceived as important, but decarbonisation is generally not a priority in the current investment climate due to different causes, including:

- Declining industry - the sector is facing consolidation
- The majority of the sector is facing negative margins
- Demand destruction – resulting in over-capacity in the refining sector, and continuing low margins
- Shifting demand - major changes to product demand shifting from gasoline and heavy fuel oil to diesel and jet fuel
- Significant investment required to meet legislative requirements estimated by IHS Purvin and Gertz (2013) to be close to £11.5 billion of which £5.5 billion is capex, poses a serious challenge to future refining margins

At the time of writing the oil refining sector in the UK had six major operational refineries (UKPIA, 2014), as illustrated in Figure 4 below.

Figure 4: Map of UK refineries (UKPIA, 2014)

In 2012, there were eight operating major refineries in the UK (shown in Figure 4): Petroplus Coryton, Essar Stanlow, Esso Fawley, Murco Milford Haven, PetroIneos Grangemouth, Phillips 66 Humber, Total Lindsey and Valero Pembroke and one specialised bitumen refinery, the Eastham Refinery, which is owned by a Nynas/Shell joint venture and operated by Nynas AB. These major refineries accounted for over 99% of sector emissions in 2012, and are all owned by international companies (UKPIA, 2014). Three refineries have closed between 2009 and 2014 shown in Figure 4 in light grey and BP and Shell no longer operate in the UK but have sold their assets to other companies.

The industry view is that competition in the sector is high, as margins are small and on-going maintenance and investments costs are high. Demand for finished products is declining in the UK and competition is global, with UK refineries competing with refineries both in Europe and further afield.

Decarbonisation is not a priority in the current investment environment but two business drivers contribute to decarbonisation: the need to reduce energy costs and the cyclic investment in new equipment. Major refinery plants are designed to last 30 years or more, with new plants taking between four and five years to build (UKPIA, 2014). The majority of refineries have been expanded or upgraded to meet new fuel specifications rather than rebuilt.

The main enablers for decarbonisation for the oil refining sector are:

- Cost savings from energy savings (threat of increasing energy costs)
- Government actions that encourage investments in decarbonisation
- Management focus, corporate targets, long-term energy strategies and willingness of top management to make climate change a priority
- Regulatory compliance
- Increased energy efficiency through improved energy monitoring and process control systems
- Government recognition of the strategic importance of the oil refining sector
- Enhanced collaboration between industry, government, trade associations and academia.

The main barriers to decarbonisation are:

- Unfavourable market conditions, demand destruction, negative cash flow and uncertainty
- Short-term approach and lack of focus on decarbonisation resulting from organisational structure and management focus
- Regulatory compliance
- High and increasing energy costs
- High competition levels preventing collaboration on decarbonisation projects
- Long payback periods for advanced technologies
- Specific shortage of key skilled staff
- CCS has a number of barriers
- Long lifespan of refineries
- Risk of production disruption
- Disruptive tested and reliable technologies not available

The UK oil refining sector has recently experienced three refinery closures and a reduction through mothballing of primary distillation capacity. The view of the industry sources is that the sector will continue to face challenges from demand destruction for transport fossil fuels. The threat of further refinery closures remains, with the potential for increased imports to make up any shortfall developing in this event, which could result in further carbon leakage to refineries in other parts of the world. Future production for the UK oil refining sector is projected to decline, regardless of the scenario applied: -1.04% annual decline for the current trends, -0.83% for the challenging world and -1.31% for the collaborative growth scenario.

The energy saving opportunities for the oil refining sector found from the literature review, site visits and the workshop can be classified into 20 categories. Most of these categories are applicable to the whole refinery and include: advanced control and improved monitoring; CCS; flaring; fuel switching; lighting; maintenance; motors, pumps, compressors and fans; new refinery as replacement; process heaters and furnaces; storage tanks; and waste heat and energy recovery. Other categories are more process-specific and include: crude unit upgrades; on-site renewables; FCC design improvements; hydrogen recovery and optimisation; HCK design improvements; biomass; CHP; steam use optimisation (boiler retrofit and utilities); and VDU design improvements. A detailed overview of these energy saving opportunities is provided in appendix C.

3.2 Oil Refining Processes

3.2.1 Oil Production

The UK refinery throughput peaked in the early and late 1970's and again (although lower) in the early and late 1990's, and has been in decline since. Total Primary Oil Demand (TPOD) has followed this refinery throughput closely in the past, but after a short drop in demand in 1984 (the year of the miners' strike), demand has been higher than the throughput, reaching a maximum of nearly 120,000 Kilo Tonnes oil equivalent (ktoe) in the late 1990's. From 2006 onwards, throughput and demand have been aligning again (Dukes, 2014).

Both refinery throughput and primary oil demand show a decrease over a 40 years period, starting at ca. 100,000 ktoe in 1970 and ending up at ca. 60,000 ktoe, showing a 40% reduction (Dukes, 2014). These trends are shown in Figure 5.

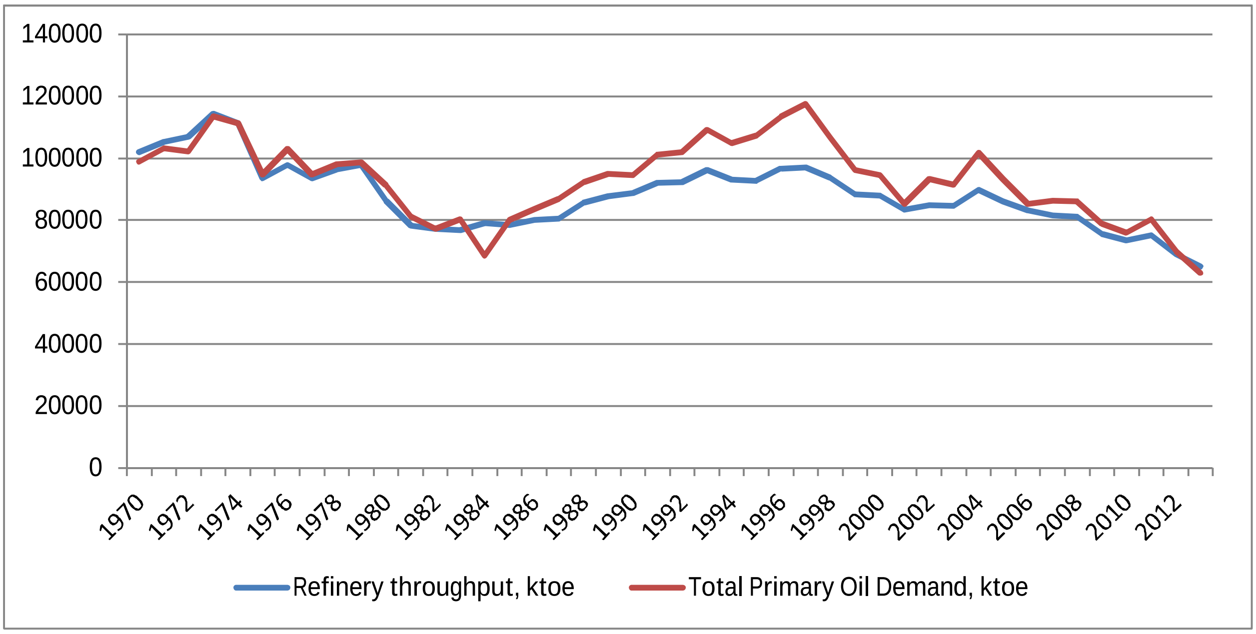

Figure 5: UK petroleum production and consumption 1970-2013 (in ktoe) (Dukes, 2014)

Many of the UK refineries came on stream in the late 1950s and early 1960s, reflecting the post-war demand for petroleum products. Since that time, refineries have evolved to meet the growing demand for more complex and more environmentally friendly fuels. The market has demanded an ever increasing proportion of lighter products and a decreasing proportion of heavier materials (e.g. fuel oils). There has also been a dieselfication of the car industry over the last 20 years which has shifted demand considerably towards diesel from motor gasoline and away from what UK refineries were set up to produce. As a result, refineries have gradually become more complex, incorporating an array of processes to 'reshape' the supply of refined products to meet the market demand (CONCAWE, 2012). Resulting from that, no two refineries are identical: the common factors in refineries are crude distillation and upgrading units, but different routes are used for extracting maximum value from each barrel of crude oil processed (UKPIA, 2014).

3.2.2 Oil Refining Processes

Crude oil contains a mixture of substances containing carbon and hydrogen (mostly hydrocarbons) and varies enormously in quality and sulphur content depending on the origin of the oil. It therefore has to be refined to manufacture products which are both useful and of consistent quality (UKPIA, 2013). Crude oil can be refined to liquid petroleum gas (LPG), petrol, diesel, jet fuel, gas oil, heating oil and residues such as bitumen. Refining also provides the feedstock for lubricants and petrochemicals, but these are covered in the chemical sector roadmap and are hence out of scope of this roadmap. The type of crude oil processed will determine the mix of refinery products and UK refineries process a range of crude oils. A barrel of North Sea crude oil will typically yield 3% LPG, 37% petrol, 25% diesel, 20% kerosene (jet fuel and heating oil) and 12% fuel oil (UKPIA, 2014).

Figure 6 illustrates the typical refinery processing units. In general, the refinery operations can be broken down into five main processes: distillation, conversion, reforming, desulphurisation and blending of different streams (UKPIA, 2014).

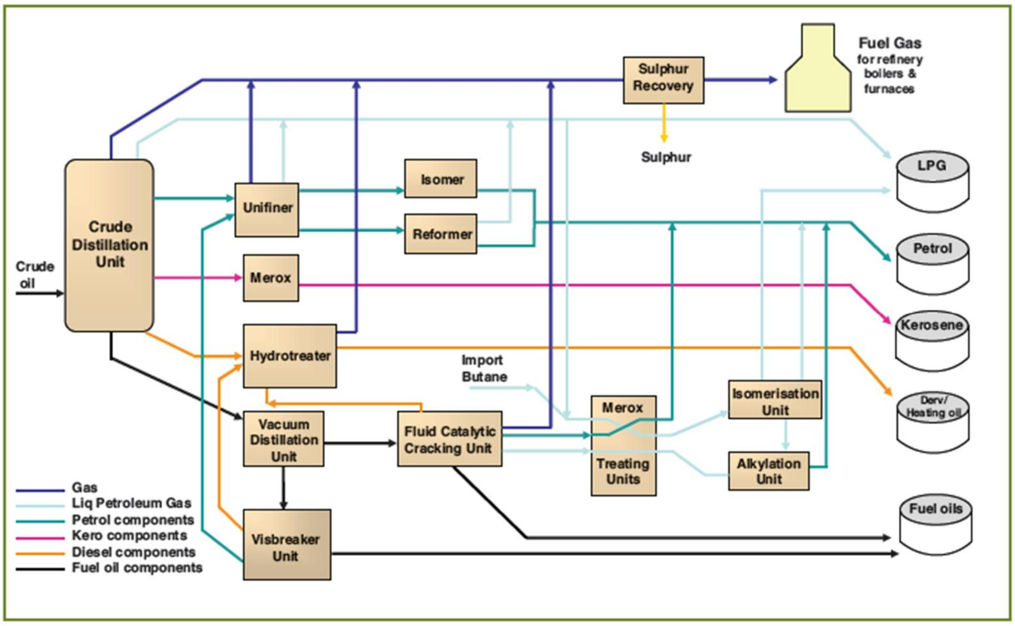

Figure 6: Typical refinery processing units (UKPIA, 2014)

To separate crude oil into different refinery streams, a crude **distillation** unit (CDU) is used as the starting point for all refinery options. Crude oil is fed into the bottom of a fractioning column and boiled at 380°C. The lighter fractions are vaporised and rise up the column, where they are cooled by a downward flow of liquid and condense at different points. Fractions with different boiling points can hence be drawn off at different levels in the column, breaking the oil down into more useful components. Fractions obtained here - ranging from lighter gases such as propane and butane to heavier diesel and gas oil - are then sent on to other refinery units for further processing. At the bottom of the column, a liquid residue remains, which requires further processing to turn it into more valuable, lighter products. This residue is first sent to the VDU, working under reduced pressure and allowing distillation at lower temperatures. The streams from CDU and VDU are then processed further by the remaining refinery units to provide high quality products and comply with all relevant legislation (UKPIA, 2014). **Conversion** units (e.g. FCC): cracking of heavy gasoil takes place in a reactor on a powder-like catalyst producing both lighter products and a coke-like material (CONCAWE, 2012)) are used to treat streams from the VDU to turn heavy components into lighter transport fuels (UKPIA, 2014). **Reforming** units are used to upgrade the octane of the petrol components produced in the CDU: this improves the quality of these streams and adjusts the yields to meet market demand (UKPIA, 2014). After conversion and reforming, **desulphurisation** units are used to reduce the sulphur in the streams to the required level. This allows products to meet today's tighter fuel specifications and provides refineries with additional flexibility to process higher sulphur crude oils (UKPIA, 2014). Finally, the fuel oil components from the different units are **blended** to produce the final products, to meet current legislation and specifications (UKPIA, 2014).

Petroleum gases are taken directly from the CDU and the FCC, and compressed to produce LPG without further processing. **Petrol** streams from the CDU and VDU are cleaned in the unifiner, stripping out the unwanted sulphur and nitrogen compounds (e.g. sulphide and ammonia). The streams are then sent to the reformer and isomer units to raise the octane number by modifying the petrol molecular structure. The large amounts of hydrogen that are formed here are recycled for use in the desulphurisation (hydrotreater) units. **Jet fuel and kerosene** streams from the CDU and VDU are cleaned in the merox unit, using a caustic wash and additives to remove sulphur compounds and inhibit gum formation. **Diesel (Derv) and heating oil** streams are processed in the hydrotreater, removing sulphur and other unwanted compounds, using hydrogen as a catalyst. The **lighter fuel oil** streams from the VDU are processed in the FCC: resulting LPG and petrol components are then cleaned in a merox unit, and some of the petroleum gases (propane and butane) are converted in an isomerisation or alkylation unit into high-octane petrol blending components. The **heavier fuel oil** residues are processed in a visbreaker, using high temperatures to reduce viscosity (UKPIA, 2014).

Hydrogen is used to remove impurities (such as sulphur or nitrogen) and to saturate aromatics and olefins for the production of high quality diesel. Traditionally refineries have generated hydrogen in the catalytic reformer (dehydrogenating linear and cyclic paraffins to aromatic molecules to increase the octane rating of virgin naphtha), but the increased need for more and cleaner light products has increased the demand for hydrogen beyond the production of catalytic reformers. Refineries have therefore gradually resorted to dedicated **hydrogen production**. The most widely used process is methane steam reforming. Some refineries use partial oxidation (POX) of heavy residues to produce syngas with subsequent conversion to hydrogen and CO_2 by the CO shift reaction (CONCAWE, 2013).

3.2.3 Technologies for Delivering Heat and Power

Fuel is consumed in process furnaces that directly provide heat to the process units and in utility boilers or other devices (such as gas turbines) that generate electricity and steam for use in pumps, compressors, heat exchangers, etc. Process heaters generate the largest proportion of the total energy requirement, the actual share depending on the configuration and original design of the refinery (CONCAWE, 2011).

Refineries require high amounts of electric power and steam: these are mostly internally generated, although many sites import at least some power. Power and steam export is becoming increasingly common, as more and more refineries become equipped with highly efficient **CHP** plants, taking advantage of the fact that they can make use of relatively low-pressure steam from back-pressure turbines. Refineries have often replaced simple steam boilers by gas turbines, using their excess refinery gas or imported natural gas to directly produce electric power. More electricity and medium-pressure steam are produced by passing the high-pressure exhaust gases through a conventional turbine (combined cycle) or by using them to supply high-temperature process heat. Such CHP systems can increase thermal efficiency up to 80% (CONCAWE, 2011).

Coke produced during cracking of the oil feed is burned to generate heat of reaction. In the FCC, **surplus heat** can be used to generate steam and electricity. In the continuous coker, a lot of surplus heat is available (equivalent to 25.7% of the total energy use at the refinery), and the coke is partially burned with steam and air producing a 'lowJoule gas' (CONCAWE, 2011).

The type of equipment and the form of energy used for heating depends on the required temperature level and the required thermal duty. The main heating equipment is the **fired heater**, burning liquid or gaseous fuel and providing process heat for temperatures of 250-500°C. Many refining stages, however, do not require such high temperatures, and can be heated using **steam**, applied in many ways at different pressures and temperatures: high-pressure steam (40-100 bar) to drive turbines for large rotating machines (such as compressors and electricity generating turbines), medium-pressure steam (10-40 bar) for fractionation and separation of light hydrocarbon mixtures, and lower-pressure steam (< 10 bar) for many other applications (such as continuous heating and frost protection of piping). Pipe and process heating can - under specific conditions - also be delivered by **electricity** via an intermediate thermal fluid. Electricity is also used for pumps, compressors, instrumentation, lighting, etc. (CONCAWE, 2012).

A key element of refinery design is heat recovery and integration. Feedstock needs to be heated and refining products need to be cooled down before storage. The surplus heat available in hot streams can be transferred to cold streams through heat exchangers. Another way of heat recovery is to transfer heat from the hot streams to water to generate steam. Heat recovery can be both within a process unit and between different units, optimising the use of available heat flows and temperature levels (CONCAWE, 2012).

3.3 Current Emissions and Energy Use – Principal Question 1

This section covers the findings in response to Principal Question 1: 'What are the current emissions from each sector and how is energy used?' It focuses on technologies that are currently used in the sector, the emissions associated with the activities, the heat and power demand of Oil Refining plants and the fuels that are used to deliver this energy and the lifespan of equipment and key timings for replacement or rebuild.

3.3.1 Evolution of Emissions Reduction

According to the guidelines for monitoring and reporting of greenhouse gas emissions from installations included in the European Union Emissions Trading System (EU ETS), the monitoring from greenhouse gas emissions from oil refineries shall include all emissions from combustion and production processes as occurring in refineries (IVL, 2005). The EU Transaction Log[12] (EUTL) reports verified EU ETS CO_2 emissions from the UK, and these emissions are shown in Figure 7 from 2002, with total emissions of 19.7 million tonnes of CO_2, to 2011 with 18.2 million tonnes of CO_2. In 2012, total emissions decreased further to 16.3 million tonnes of CO_2, resulting in a reduction of 17% over the ten years period (Ricardo AEA, 2010).

[12] The boundary of the oil refining sector is the production of primary products (ethane, LPG, naphtha, gasoline, distillate, etc.). Where these streams are further modified (e.g. naphtha in a cracker), this operation is part of the chemical sector, regardless of whether this operation is performed on the same site or a different site. For an integrated site with shared facilities, the utility consumption should hence be divided pro-rata between the refining and the petrochemicals units, so that each includes its own energy consumption as if it were a stand-alone facility. Unfortunately, information available in the public domain and in EUTL does not support analysis of CO_2 emissions on this basis. Three UK sites have significant integration between refinery, utilities, petrochemicals and other sites.

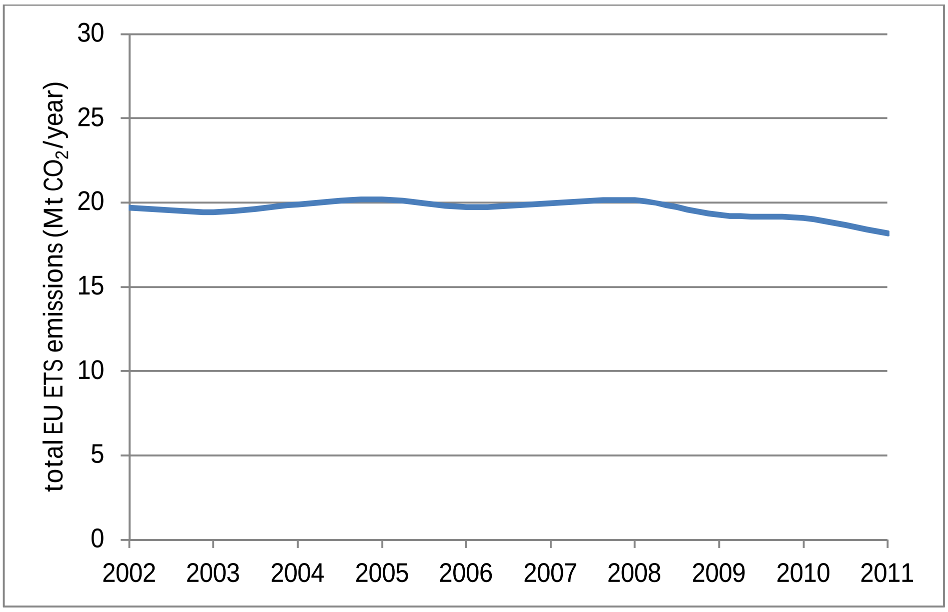

Figure 7: Trends and forecast of greenhouse gas emissions in the UK industry (Ricardo AEA, 2010)

3.3.2 Emissions

In 2012, UK refineries collectively emitted some 16.3 million tonnes of CO_2, corresponding to just over 240 kg of CO_2 per tonne of crude processed. At the time of writing the report these emissions are expected to decrease to 14.9 million tonnes in 2020 (Purvin and Gertz, 2013), due to reduction in demand for finished oil products and are expected to continue to decrease (IEA oil demand scenarios converted to CO_2 emissions).

To achieve the high quality standards of oil products, energy is required for physical separation, for key chemical reactions such as cracking of heavy molecules and for the production of hydrogen. EU refineries consume on average 6.5-7% of the calorific value of their crude intake, although values highly depend on the actual complexity of each particular refinery (CONCAWE, 2011). CO_2 emissions from oil refineries are affected by many sources: the complexity of the refinery (number of different processes), process-related fuels that have to be burned, the quality of refining products (e.g. low sulphur fuels) and the quality of crudes and other raw materials used in the refining process.

The obvious link between energy consumption and CO_2 emissions is the carbon content of the fuel burnt. **Combustion of hydrocarbons** - in boilers, process heaters, turbines, engines, flares, catalytic and thermal oxidisers, coke calcining kilns and incinerators - is responsible for the majority of refinery CO_2 emissions. The second source of emissions is the **hydrogen production**, emitting both 'combustion' CO_2 (to supply the heat of reaction) and 'chemical' CO_2 (from decarbonisation of the hydrocarbon feedstock). Total emissions from hydrogen production are in the range of 10 tonnes CO_2 per tonne of hydrogen produced, depending on the actual feedstock used, representing about 10% of total EU refinery emissions (CONCAWE, 2011). **Burning catalyst coke** - which is produced during cracking processes (FCC regenerator stack) and burned to generate heat of reaction - is a third important source of CO_2 emissions. Because nearly pure carbon is being burned, the concentration of CO_2 in the flue gases is relatively high (up to 20%) (CONCAWE, 2011). **Other CO_2 emissions** arise (often indirectly as hydrocarbon emissions) from SRUs, storage tanks, leaks from fuel gas systems and other process equipment, PRVs, emergency shut-downs (ESD); together with **indirect emissions** from electricity usage or production and steam generation or import.

In addition to the combustion-related sources (like process heaters and boilers), there are certain processes (such as FCC, hydrogen production and sulphur recovery) with significant process emissions of CO_2. Asphalt blowing and flaring also contribute to the overall CO_2 emissions at the refinery. Figure 8 provides a breakdown of the US emissions projected for different parts of the oil refineries (US EPA, 2010). The refineries in the US have a similar layout to the UK, so the figure is useful to imply the UK emission sources.

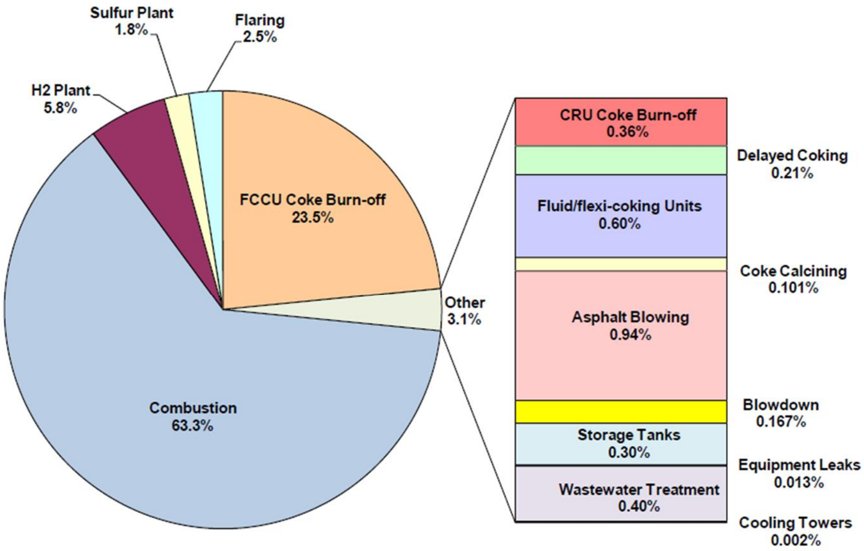

Figure 8: Contribution of different CO2 emission sources in US oil refineries (US EPA, 2010)

Table 4 shows typical properties of the various refinery sources of $CO_{2,}$ The data is taken from a US source but this is also representative of UK refineries as technology choices are similar.

Emission sources	CO_2 (% v/v)
Gas fired process and utility furnaces	3-6
Oil fired process and utility furnaces	7-12
FCC regenerator stack	8-12
Hydrogen via steam reforming	40-50
Hydrogen via residue gasification (POX)	95-99
SRU incinerator	2-7

Table 4: Typical properties of refinery CO_2 emission sources (CONCAWE, 2011)

All CO_2 containing streams are only at or close to atmospheric pressure. When originating from flue gases, they have a low CO_2 concentration. Hydrogen plants produce the streams with the highest CO_2 content when using solvent absorption, whereas pressure swing absorption (PSA) delivers a less concentrated off-gas containing some hydrogen and unconverted hydrocarbons, normally recycled as fuel to the process heater (CONCAWE, 2011). The concentration of CO_2 in flue gases is an important consideration for carbon capture projects as this dictates the most efficient methods and sources for CO_2 reduction.

3.3.3 Heat and Power Demand

Most (if not all) refinery operations involve heating and cooling, which require a net energy input. Cracking large molecules into smaller ones is an endothermic process, i.e. requires energy. Moreover, the increasing manufacturing of extra hydrogen - to comply with market demand - is a particularly energy-intensive operation. Refining also involves fluid transportation (such as pumping of liquids and compression of gases) within the process units, and for ancillary operation (such as product blending and storage, water treatment, etc.). Also, small amount of energy are required for lighting, space heating, etc. (CONCAWE, 2012).

EU refineries consume nearly 50 million toe of total energy per year, an equivalent of 7% of their crude oil intake. The remaining 93% of the energy content of the crude oil processed is hence available in the refined products (CONCAWE, 2012). Energy consumption of a refinery depends of course on the size of the refinery, but a major influencing factor is the refinery configuration, i.e. the combination of processes operated which determines which crude oils can be processed and the type, yield and quality of the refined products manufactured. The more conversion of heavy streams into light products is carried out and the cleaner the finished products, the higher the specific energy consumption (SEC) will be.

Because refineries are all so different in size and complexity, simplistic metrics such as energy consumption per unit of throughput or products do not provide a realistic view on the actual energy efficiency. Therefore, Solomon Associates (SA) have developed their Energy Intensity Index (EII®) which takes into account physical differences between refineries to focus on energy performance. This EII® benchmarks the overall energy performance of oil refineries. A value of 100 corresponds to a standard reference refinery, with decreasing values reflecting higher levels of energy performance. Most European refineries participate in this benchmark scheme, and know their ranking relative to their geographical peer refineries, although the exact scoring of each refinery is kept confidential (SNIFFER, 2011).

Figure 9 shows the evolution of the total energy consumption of a consistent group of EU refineries (top red curve) and their combined EII® (bottom blue curve). Although the total energy consumption per tonne net input has increased over the past 18 years, efficiency has still improved by 10% over that same period (CONCAWE, 2012). A higher energy consumption does not automatically mean that refineries are performing badly: differences are due to the complexity of refineries. More complex refineries are needed to meet the demand for lighter or more complex refining products, and the energy consumption is therefore rather an indicator of what refineries do instead of how efficiently they do it.

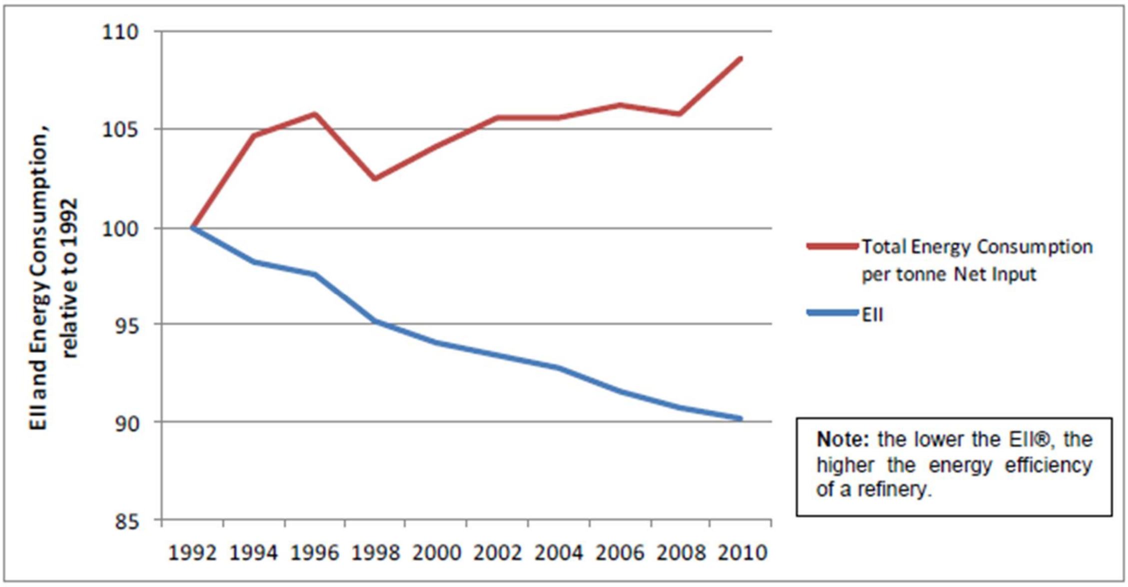

Figure 9: EU refineries energy consumption and efficiency trends 1992-2010 (CONCAWE, 2012)

Note that the EII® is not designed to determine CO_2 performance of a refinery but the energy efficiency.

3.3.4 Fuels Used

The main fuels used in UK refineries in 2012 were refinery fuel gas 47.3%, petroleum coke 24.8%, natural gas 21.3% and fuel oil 6.7% (UKPIA, 2014). In comparison, according to the US Energy Information Administration (US EIA, 2014), the main fuels consumed in US refineries are natural gas (64.5%), still gas i.e.

any form or mixture of gases produced in refineries (16.5%), steam (9.3%), catalyst coke (6.1%) and electricity (3.3%). The 2012 fuel mix for the UK Oil Refining Sector is shown in Figure 10 and represents approximately 50% of the costs for a refinery.

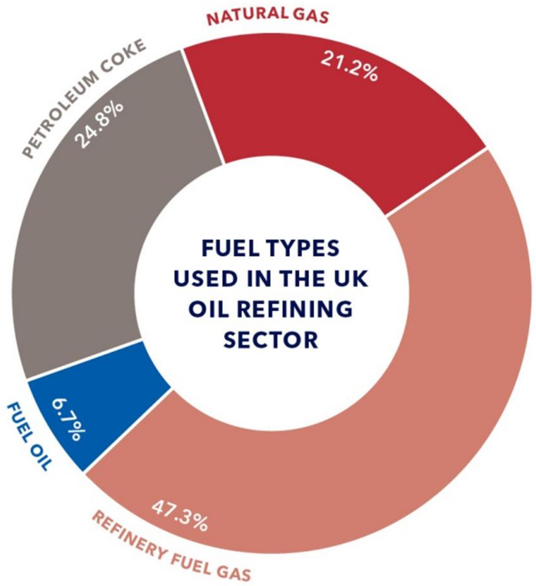

Figure 10: 2012 distribution of fuel type use in the UK oil refining industry (UKPIA, 2014)

Many refinery processes produce light hydrocarbons, either deliberately in conversion processes or as side reaction, resulting in a gaseous residue stream. This mixture is an attractive fuel with mostly no practical alternative usage. It is known as **refinery fuel gas** and is by far the largest component of refinery fuel. Furthermore, the coke-like material that is deposited on the catalyst particles in the FCC is routed to the regenerator where the coke is burnt. The hot catalyst is returned to the reactor where it provides the heat for the endothermic cracking reaction and supply heat for product separation: coke is hence not only a by-product but also the fuel for the process. **FCC coke** represents a significant fraction of refinery fuel. When heavy feeds are processed, **surplus heat** is produced and exported to other process units. To cover the rest of their energy needs, refineries used to apply **heavy fuel oil**. But due to pollutant emissions regulations (mainly SO_x), this heavy fuel oil has been often displaced by **natural gas**. Gas, either self-produced[13] or imported, is the main fuel in the majority of EU refineries today, accounting for nearly 65% of the total refinery fuel. FCC and calciner coke represent about 14% of the total, and the balance (21%) is provided by various liquid fuels (CONCAWE, 2012).

Refineries also use heat (mostly steam for indirect heating purposes) and electricity, which is a typical scenario for **cogeneration of heat and power**: most UK refineries have already applied this for a long time. **Steam** is traditionally generated in (usually natural) gas-fired turbines, producing high-pressure steam (which is more efficient): this steam is then routed through back-pressure turbines driving electric generators and extracted at lower pressures and temperatures for use as process heat. **Electricity** can also be produced via condensing turbines (only used to a limited extent since it is less efficient). Additional steam is generated by recovering heat in process units (CONCAWE, 2012).

[13] A number of refinery processes produce light hydrocarbon gases (mainly methane and ethane) that generally do not have any practical commercial outlets and must therefore be burnt in the refinery.

3.3.5 Lifespan of Equipment and Key Timings

If EU refineries are to continue supplying the EU market as they do today, major adaptations are required. The industry has already heavily invested since the beginning of 2000, essentially to meet Auto-Oil specifications for road transport and de-sulphurise heating oil (CONCAWE, 2008).

Although much can be achieved by operational measures, stepwise improvements in energy efficiency tend to require physical changes, which in turn require investment. Investments may be geared to processes in either existing or new plants, or to utilities systems.

Oil refineries typically have maintenance turn-around cycles every 6 years, where the refinery is shutdown for an extended period (approximately 6 to 8 weeks) and undergo maintenance and inspection work to extend the life of the refinery. The turn-around are also used as opportunities to install new equipment and make improvements at a refinery.

There are very few newly built plants in the UK. The majority of the plants have equipment from different time periods. As a consequence there are no publicly available key dates for when major equipment will be replaced. Often equipment have been refurbished or rebuilt, making it difficult to exactly determine the age. CHPs and turbines have a typical life span of 10-20 years (with a major refurbishment during this period). Vacuum pumps can also easily reach 25 years life whereas smaller utilities (compressed air, HVAC, lighting) have typical lifetimes of 10-15 years before replacement or major upgrade. ESP filters in exhaust systems can last for several decades (BREF, 2003).

A refinery does not only consist of processing units: crude oil jetty and receipt tankage are required as well as storage for intermediate production, blending and finished sales tankage, water treatment, laboratories, and maintenance and administration facilities. The whole refinery site requires a very large area, typically more than 200 hectares for a mid-sized refinery. Given land and planning permission, it would cost around £4-5 billion to construct one today, making it very unlikely that these vital assets will be replaced under the current economic environment (UKPIA, 2013).

3.4 Business Environment - Principal Question 2

This section provides an assessment of the range of questions under Principal Question 2: 'For each sector, what is the business environment, what are the business strategies of companies, and how do these have an impact on decisions to invest in decarbonisation?'

Note that for the purposes of anonymity all interviews, site visits and written responses have been combined together in the analysis and are referred to as industry sources and the role of the person interviewed or the company name has not been indicated to ensure anonymity.

3.4.1 Market Structure

The UK refining sector is a significant contributor to the UK economy, supporting around 26,400 jobs and contributing annually around £2.3 billion (Purvin and Gertz, 2013). The sector is of key strategic importance in supply of petroleum products, which provide over 30% of primary energy requirements. Although the IEA believes demand for oil products will decline by 2030 and perhaps more so by 2050, oil will remain a major part of the EU energy mix through to 2050 and beyond. The UK refinery capacity is the fourth largest refining capacity in Europe after, Italy, France and Germany. In comparison to their European counterparts, UK refineries tend to be larger and more complex. The oil refining sector in the UK is a declining industry, due to demand destruction linked to changes in transportation fuels. The views of industry sources are that refinery revenues are growing slower than the economy, as the majority of refineries are experiencing negative margins, due to high operational costs and an oversupply of heavier fuels. The UK oil refineries are experiencing unfavourable market conditions, with refineries competing against each other for investment by international majors. The ownership structures of existing refineries, impacts UK refineries ability to access finance as multi-national companies with operations in Asia and the Middle East may prioritise investments upstream or other investment opportunities elsewhere. There has been consolidation from nine to six refineries over the period 2008-2014.

Oil refineries have high capital intensity and high revenue volatility due to higher crude oil prices, and lower demand for petrol (IBIS, Breeze 2014). As a result of excess capacity and falling demand, many refineries are changing their production to diesel as the new primary fuel. The main products and services produced by the sector include diesel, fuel oil, gas oil, jet fuel, LPG, Petrol, refinery gas, and other petroleum based products. UK oil refinery revenues were £37.8 billion in 2013 (IBIS World, 2014).

UK Refinery operators face considerable investment challenge for the foreseeable future as demand for road transport falls, due to improved vehicle energy efficiency and substitution of petroleum products by renewable energy technologies (primarily biofuels and electric vehicles) and changes in the product supply/demand balance. According to Purvin and Gertz, UK refineries would need to invest £1.5 to £2.3 billion over the next 20 years in order to remain competitive (2013). Revenues are expected to shrink by 4.5% in 2013-14, which reflects the closure of the Coryton refinery in May 2012 and flat demand in the UK. The falling oil production in the North Sea will also mean that refineries will need to look to imported crude oil in order to continue operations (IBIS, Breeze 2014). As described in the table below regarding annual growth going forward, the sector is expected to have negative growth in sales revenue of -0.6% between 2014 and 2019 (IBIS, Breeze 2014). This is because the downstream oil market in the UK is going through a process of change characterised by weak overall petroleum demand, growth in the aviation sector, increasing numbers of diesel vehicles and a reduction in the use of oil for power generation. Other pressures that may be highlighted, including a mixed global legislative environment. Oil refinery owners are looking to assess their continued involvement in downstream UK fuel markets focusing their efforts more on upstream operations and exiting petrol retailing to focus on more profitable parts of the supply chain (IBIS, Breeze 2014).

IBIS Breeze 2014	Annual Growth in Sales Revenue 09-14	Annual Growth in Sales Revenue 14-19
Petroleum refinery	-3.3%	-0.6%

Table 5: Projected annual growth for oil refining sector (IBIS, Breeze 2014)

Globally, the refining industry faces further restructuring and a potential oversupply of light products and an increase in diesel (IEA 2014). Most refinery growth comes from non OECD countries, half from Asia, but production plans are being scaled back due to over-capacity (IEA 2014). According to the IEA, “to bring utilisation rates to levels of 2006-2008 (when margins were good), nearly 5 mb/d of capacity would have to be eliminated through plant closures, delays or cancellations globally.” For the UK refineries, strong competition from the European Union (EU) and moderately high exposure to non-EU firms exists (EUROPIA 2011). Carbon leakage risk in the EU ETS is significant for UK refiners (Vivid Economics 2014). Additionally, the review is that the sector is heavily regulated and all information sources identified the investment burden in order to meet regulatory compliance in 2025 a challenge. Purvin and Gertz stated that “no industry would bear such an investment burden for no return. It would be highly likely that, when faced with such a large mandatory capital expenditure requirement that provides no ROI, UK refiners could be forced to close more UK refineries.” An industry source stated: “there is a major investment challenge for regulatory compliance bringing us to 2025 to 2030.” One industry source and participants of the workshop discussed the fact that the future of the UK transport sector, especially the potential for the further electrification of vehicles, will have a further negative impact on the sector.

3.4.2 Business Strategies

As oil refiners are currently experiencing unfavourable market conditions, current business strategies are focused on survival.

There are limited funds to invest in the range of projects that are required to ensure the refineries continue to operate and meet regulatory obligations. There is evidence from industry sources that energy efficiency projects are being considered as a cost saving measure, but that the focus is on minimising overall costs and increasing throughputs.

Another important factor influencing the business strategies of the UK is the ownership structure. As all are multi-national companies, business strategies are set by headquarters and have to compete with other investments elsewhere in the company. The industry sources view is that energy costs, overall regulatory, and labour costs are higher in the UK than in Europe or elsewhere, and as such competiveness is an issue for the sector in terms of gaining funding for UK based investments in general terms. Although, Total stated it is actively seeking to continue to invest in Europe and the UK by producing less, more efficiently (Total, 2013).

> One industry source stated that: “Larger capex projects get ranked across the world against investments in other sectors such as petrochemicals or upstream production.”
>
> Another industry source stated: “There is limited discretionary investment by the oil majors in UK refineries results from the need for, and greater returns obtained from, large scale projects in Oil and Gas Exploration and Production.”

Decarbonisation Strategies

Corporate Level Reporting

The maturity of carbon-related strategies varies and there are corporate level objectives and targets, and associated sustainability reporting within the sector. Three of the companies publicly report carbon emissions and targets. None of the current company strategies look further than 2025 in terms of decarbonisation targets.

Companies without a target either have an environmental performance report with greenhouse gas emissions included or a more generic social responsibility statement, but no disclosure of carbon emissions.

The level of transparency of reporting on greenhouse gas emissions in the sector and the robustness of the reporting is weak. This may not be surprising given the competitive nature of the sector. Thus, based on the public reporting of the refineries included in this research, the majority do not have decarbonisation or detailed energy efficiency strategies or targets. More information is needed to understand whether this is a true reflection of related activities.

Project findings

Based on the information gathered as part of this project, some of the companies stated that they have corporate strategies to reduce greenhouse gas emissions and/or supporting energy efficiency strategies.

For example, one industry source stated it has a three phase GHG emissions strategy. This is focused on improving energy efficiency in the short term; implementing current proven emissions reduction technologies in the medium term; and developing innovative radical technologies in the long term. For this industry source, climate change initiatives include implementing best available technologies, reducing flaring, and improving energy efficiency through the use of cogeneration CHP facilities.

Another example, is that one industry source has a global energy management system (EnMS) which it stated has helped it to improve its energy efficiency by 10 percent over the last 10 years.

50% of refinery operating cost is refinery fuel (Ricardo AEA, 2013). Thus, energy efficiency can be a cost saving exercise and as equipment needs replacing energy efficiency is one consideration for new equipment. As stated previously, such projects have to compete for funding across their organisation. Refiners are also focused on meeting their upcoming regulatory obligations on reducing NOX, SOX, and other air emissions. All information sources indicated that the cost of meeting these obligations, may lead to further consolidation in the sector (Purvin and Gertz 2012).

Overall, the factors outlined above are thought to be limiting the sector's focus on decarbonisation and energy efficiency. The number of companies starting to change their business models by investing in renewables or biofuels is increasing, but this is still a small portion of their overall business and revenue.

3.4.3 Decision-Making Processes

As discussed previously, given the current unfavourable market conditions, in general the refineries' ability to finance and invest in decarbonisation and energy efficiency technologies is limited, refinery managers currently have minimal discretionary spend and decision-making is focused on minimising costs, optimisation and margin improvement.

In the oil refining sector the vast majority of the refiners operating in the UK are headquartered overseas. One industry source stated that UK refinery managers may not have the authority to make investment decisions or may not have their projects approved if ROI is significantly better in other countries, in the upstream sector, or in other sectors.

Energy efficiency projects, as with all of its capital investment projects, are usually only undertaken if they are economically viable and satisfy internal investment criteria, return rates, and payback periods, which can be as short as six months. The short payback times are imposed due to low refinery margins, restricted capital funds and the need to focus on operational related investment.

The investments in energy efficiency are likely to be incremental in nature and another industry source indicated that another factor is the scale of capex required and that new step change technologies are needed to further reduce energy use and carbon emissions that require significant capital investments. Those companies who have EnMS in place or who have corporate level carbon strategies and targets are more likely to invest in advanced decarbonisation technologies.

One initiative that supports energy efficiency was mentioned. This was that, as part of BAU, every two years the SA EII® assessment is undertaken, which examines refiner's energy efficiency and industry sources indicated that they used this assessment as a driver to improve energy efficiency investment decisions across the company's assets.

> An industry source highlighted the differences in returns across global companies businesses by stating: "A barrier to implementation is multi-national oil companies focus on getting crude oil and natural gas, replacing reserves, returns on investment (Upstream profit after tax 26%) Downstream (8% return on capital employed 2.5 billion) Chemicals (4%, 1 billion)."

Discussed and prioritised at the workshop:

Two tables out of four listed a lack of management focus due to companies' corporate structure and better returns in other parts of the business as one of the top five barriers to decarbonisation in the sector.

Supported by literature:

Ricardo AEA (2013) also found that: "a lack of resources, both in terms of time and capital, and closely related, lack of prioritisation" is limiting refineries ability to invest in decarbonisation.

3.4.4 Financing Investments

The oil refining sector is defined by high capital intensity, which requires significant access to funds in order to pay for items such as equipment upgrades, regulatory obligations, refinery fuel, and employees' wages. When financing investments, these are planned ahead of time and larger investments are linked to refinery shut downs to minimise the impact on production.

Due to the high capital intensity of the sector, the European Commission found that "the EU refining industry needs continuous access to funds in order to carry out operational improvements in line with regulatory requirements imposed on the industry (fuel quality, industrial emissions, CO_2 emissions etc.). EU refiners have however been having difficulties accessing funds lately (not least, due to the unfavourable current and future market expectations mentioned previously)."

Ricardo AEA and three industry sources stated that advanced technologies such as CHP and CCS have long pay back periods, whereas decision makers in oil refineries often require shorter payback periods, given current margins, as low as six months in order for a project to go ahead. Ricardo AEA adds investments that have a negative impact or potential risk on production will have more stringent economic criteria compared to investments that are more closely linked to the core business (2013).

One industry source also added that hurdle rates or rates of return are high for capital expenditure projects, and indicated that rates of 15 to 20% or higher or payback periods of less than12 months may be required for cost reduction projects. Energy efficiency projects are usually not singled out and thus are usually linked to equipment upgrades and implementing best available technologies, potentially limiting energy efficiency technologies to incremental technologies rather than more advanced disruptive technologies. In summary, the decline in the oil refining sector, increased competition, and significant investment required to meet regulatory compliance in the sector is limiting the sector's ability to finance energy efficiency investments. One interviewee indicated that "there has been some joint venture and third party investment in CHP, but most companies self-fund energy efficiency technologies." Thus, given their current margins significant investments in decarbonisation may not be feasible.

In addition, Purvin and Gertz (2013) estimated that increasing costs of regulatory compliance is around £11.4 billion, and an industry source and one table at the workshop identified that enhancing corporate capital allowance schemes, which allows the cost of investments for specific energy efficiency, air quality, and emissions abatement to have tax allowances as a potential solution to assist in increasing funds for investing in advanced energy efficiency technologies.

Across the information sources, CCS was identified as a key long-term decarbonisation option, but the investment required is significant and remains a key barrier to widespread adoption. Many advanced technologies, such as CCS should be implemented simultaneously when a refinery is upgraded or rebuilt, but given the current business environment, this opportunity is rare. Moreover, as energy efficiency is seen as a competitive advantage and is widely felt in the sector, and collaboration on pilot or demonstration projects in the UK for CCS is perceived to be limited.

3.4.5 Enablers and Barriers

One of the outcomes of the analysis of the sector is a list of the most prevalent enablers and barriers for decarbonisation. The barriers and enablers have been identified through a number of different research methods, namely literature review, additional industry sources and workshops. Triangulating data has been of utmost importance. Seen below are details of the enablers and barriers that have not only been triangulated with regards to research methods, but were also selected at the workshops as the most important enablers and barriers.

Table 6 and Table 7 below indicate the most prevalent enablers and barriers across literature and interviews, and workshop discussions. Although the number of times an enabler or barrier was referenced or highlighted could provide some guidance as to the strength of sentiment towards a particular enabler or barrier, the discussions during workshops and industry sources provided a greater understanding as to the detail and context behind each barrier and enabler.

- There were 42 documents reviewed as part of the literature review. The number in the literature column below represents the prevalence in occurrence of the enabler or barrier; or in other words the number of sources that discuss it.
- The social and business team were unable to interview any of the refineries, as refineries declined to participate due to reservations regarding Competition Law. There were limited written responses by four different respondents, ranging from refineries, to academics to the trade association, and no quotes will be directly attributed to anyone involved. The number in the industry source column below represents the prevalence in occurrence of the enabler or barrier; or in other words the number of industry sources that discussed it.
- The workshop column shows the prevalence in occurrence of the enabler or barrier; or in other words the number of groups that considered and discussed it at the workshop.
- The numbers on the left-hand side do not present a ranking but provide an easy point of reference to the order of analysis.

These enablers and barriers are illustrated throughout the text with supporting quotes and citations from workshop and literature. Further depth and interpretation is provided in the following paragraphs.”

Top Enablers

#	Category	Enablers	Primary Source	Prevalence of occurrence		
				Literature	Industry sources	Workshop
1	Market	Cost savings from energy savings (threat of increasing energy costs)	Literature	8	5	4
2	Regulation and Policy	Government actions that encourage investments in decarbonisation	Industry Sources	3	8	4
3	Organisation	Management focus, corporate targets, long-term energy strategies and willingness of top management to make climate change a priority	Industry Sources	2	6	3
4	Regulation and Policy	Regulatory compliance	Industry Sources	3	3	2
5	Production and Operational	Increased energy efficiency through improved energy monitoring and process control systems	Literature and Industry Sources	3	3	0
6	Strategy	Government recognition of the strategic importance of the oil refining sector	Industry Sources and Workshop	0	1	1
7	Value chain	Enhanced collaboration between industry, government, trade associations, and academia	Industry Sources	0	2	1

Table 6: Top Enablers

The first enabler – **cost savings from energy savings (threat of increasing energy costs) -** was identified by a range of literature (Ricardo AEA, 2013; EUROPIA, 2011; IPIECA; CONCAWE, 2008; CONCAWE, 2012; Total, 2013, Valero, 2003; Worrell et al., 2009; and Neelis, Worrell, and Masanet, 2008) and was a key theme from industry sources and at the workshop. The costs of refinery fuel is a high and variable cost for refineries which means that it is beneficial to have robust EnMS, and improve energy efficiency, for example when upgrading process equipment.

This was also discussed as a barrier if energy prices for refinery fuel become too high and impact on competiveness.

Cost savings from energy savings, especially given the threat of increasing energy prices, was a key theme across all information sources.

Eight literature sources support this enabler. The overall finding from the literature can be summarised by the following two sources: EUROPIA (2011) found that*: "Refinery fuel is about 50% of refining cash costs, which drives efficient use of energy in refining and the EU ETS with further incentivise economic efficiency measures."*

CONCAWE (2008) identified that: *"Energy efficiency improvement, a constant theme for many years in refineries still presents opportunities and these will undoubtedly be grasped especially in the current 'expensive energy' environment."*

Supported by six industry sources, the most material two are identified below, and the workshop:

An industry source stated: "Energy costs represent a substantial operating expense for our refining operations. Successfully improving energy efficiency is therefore a major driver for cost reduction and industrial competitiveness and as such is of high importance to us."

The second enabler – **government actions that encourage investments in decarbonisation** – was identified by eight industry sources and workshop and supported by the literature (EUROPIA, 2011; Ricardo AEA, 2013; and UKPIA). The actions discussed that could encourage investments varied and included: developing a predictable policy and legislative framework, creating a long-term stable regulatory and fiscal environment for CHP and CCS, implementation of a level playing field with other regions (was an opinion of interviewees), reducing overall cumulative regulatory costs in refineries, use of targeted corporate level capital allowance schemes, creation of a carbon tax on refinery imports, creation of a carbon price support mechanism to help incentivise investments in low-carbon electricity, and elimination of specific subsidies in order to support an array of technologies.

Overall, the opinion of industry sources was that Government can take a variety of actions to support oil refineries in investing in decarbonisation most importantly by creating a level playing field, a stable regulatory and fiscal environment, and reducing overall regulatory costs for refineries.

One industry source stated: "Key enablers of energy efficiency and carbon reduction projects include: implementation of a level playing field with competing regions (both in terms of relevant policies and overall cumulative regulatory burden); elimination of technology specific subsidies and; a stable and predictable policy and legislative framework."

A second source stated: "The introduction of a suitable policy as part of a stable, long-term regulatory and fiscal environment for CHP could act as an enabler for further investment in this effective, proven energy efficient technology."

Supported by literature:

EUROPIA (2011) found that: "*The continued need for oil products to 2050 indicates that it is in the EU's interest to implement policy and legislation that maintains the viability of the EU domestic refining sector throughout the transition to a competitive low-carbon economy."*

A key priority at the workshop:

All four tables listed government actions to encourage investment in decarbonisation as one of their top five enablers. One table specifically indicated that having more support for community use of waste heat for district heating would beneficial for decarbonisation.

The third enabler – **Management focus, corporate targets, long-term energy strategies and willingness of top management to make climate change a priority** – was a key theme. During the workshop, there was discussion on the SA EII® refinery tool and participants from industry stated that managers in their operations use this to drive continuous improvements in energy efficiency across their assets alongside other improvements. Management prioritisation is a key enabler but that, in general, the sector is focused on business survival, rather than energy efficiency and decarbonisation which are also discussed in the barriers section.

Management focus- A key enabler identified by all information sources:

One industry source stated: "Energy costs represent a substantial operating expense for their refining facilities. Successfully improving energy efficiency is therefore a major driver for cost reduction and industrial competitiveness and as such is of high importance to the company. The company has a clear strategy and well developed approaches to improve energy efficiency, which have been successful in achieving significant reductions."

Three out of four tables listed management focus as one of their top five enablers.

The fourth enabler – **regulatory compliance**– was a key theme across all information sources – if further improving energy efficiencies or promoting decarbonisation was a regulatory requirement. Care should be taken in interpretation of this point because regulatory compliance for decarbonisation and energy efficiency was seen as both a barrier and an enabler. Purvin and Gertz (2013) concluded that the cost impacts from existing legislation would impose a serious challenge to future refining margins and as such potentially have unintended consequences on competiveness. This is also discussed in the barriers section.

Regulatory compliance as an enabler for decarbonisation:

House of Commons Energy and Climate Change Committee 2013 found that: *"There is considerable investment in the refining industry, although much of it is primarily directed at compliance with legislative and regulatory requirements."*

Milosevic and Cowart (2002) found that: *"Stringent environmental limits being imposed on the quality of fuels that refineries can burn is increasing the cost of refinery marginal fuels, which prompts an additional incentive to save energy."*

One industry source stated: "Regulatory compliance is a driver."

A second source identified: "Legislative compliance is an enabler to a point. There is a tension between this being an enabler and barrier. Move operations elsewhere if compliance burden too high."

At the workshop two out of four tables listed regulatory compliance as one of their top five enablers.

The fifth enabler – **increased energy efficiency through improved energy monitoring and process control –** was identified by the literature (Ricardo AEA, 2010; Milosevic and Cowart, 2002; Worrell et al., 2009) and was reinforced by discussions with industry sources. In the pathways, process and control improvements are a medium-term option for decarbonising the oil refinery sector. Many refineries already have these systems in place, for continued operational improvement.

Increasing energy efficiency via continued process and operational controls as an enabler:

Ricardo AEA (2010) found that: "*There are a number of actions that can be carried out to bring UK refineries up to the efficiencies of top EU refineries of the Benelux and Scandinavian countries. These actions are estimated to improve energy efficiency across the board in refinery operations by 20%. These include: improving the use of energy monitoring and process control systems, elimination of flaring, improved operation of process and elimination of steam leaks, improved condensate recovery, improved integration and operation of preheaters for process fired heaters and improved operation of process fired heaters are actions with mostly short lead times."*

Supported by industry sources:

One industry source stated: *"Invested a total of $330 million to help improve energy efficiency, reduce flaring and decrease GHG emissions."*

A third stated: *"There is a lot that refineries can do to improve energy efficiency such as improving energy monitoring and process controls, but that requires management focus and resources."*

The sixth enabler – **government recognition of the strategic importance of the oil refining sector** – was identified by one industry source to help oil refineries overcome the uncertainty about the future of their refineries in the UK.

Government recognition of the strategic importance of the oil refining sector- an enabler identified by the workshop and one industry source:

One industry source stated: *"Government objectives for refining are not clear. What refinery structure should there be*?"

One industry source stated that *"Uncertainty is the biggest barrier. Up to 2025 there is a short-term uncertainty due to very low margins."*

The seventh enabler – **enhanced collaboration between industry, government, trade associations, and academia** – was identified by two industry sources and at the workshop. Competition was seen as a key barrier to collaboration on research and development across the information sources. Moreover, the high capex costs and risks involved in piloting new technologies such as CCS was identified as a barrier to their deployment. Multi-stakeholder research projects can overcome this barrier by reducing the financial risk for each player and thus support the investment and deployment of new decarbonisation technologies.

Top Barriers

#	Category	Barriers	Primary Source	Prevalence of occurrence		
				Literature	Industry sources	Workshop
1	Market	Unfavourable market conditions, demand destruction, negative cash flow and uncertainty	Industry Sources	5	6	4
2	Organisation	Short-term management approach and less focus on decarbonisation, due to companies' structure	Industry Sources	2	9	2
3	Market	Regulatory compliance	Literature	4	3	3
4	Market	High and increasing energy costs	Literature	4	2	2
5	Market	High competition levels preventing collaboration on decarbonisation projects	Industry Sources	3	5	1
6	Investment and Finance	Long payback periods for advanced technologies	Industry Sources	1	3	1
7	Organisation	Staff shortage	Industry Sources	1	6	0
8	Technology	CCS has a number of barriers	Industry Sources	3	6	0
9	Operational	Long lifespan of refineries	Industry Sources	1	2	1
10	Organisation	Risk of production disruption	Workshop	1	1	1
11	Technology	Disruptive tested and reliable technologies not available	Workshop	1	1	1

Table 7: Top Barriers

The first barrier – **unfavourable market conditions, demand destruction, negative cash flow and uncertainty decarbonisation** – was the single most important topic discussed and identified across all information sources as the key barrier to decarbonisation in the refining sector. All of the information sources reaffirm the opinion that oil refineries are currently experiencing demand destruction as the sector is in decline. This limits their ability to invest in decarbonisation or energy efficiency technologies as they have limited funds to do so. Moreover, the uncertainty regarding demand destruction and the future of the oil refining sector in the UK may limit management's willingness to invest in technologies that have longer payback periods.

Unfavourable market conditions: the number one barrier to decarbonisation in the refining sector in the UK

This barrier was supported by five literature sources, and can be summarised by the following source:

CONCAWE (2008) found that: "*In the last decade the oil product market in Europe has undergone very significant changes. This will continue through the coming decade and towards the 2020 time horizon considered in this study. The changes stem both from the evolution of demand, particularly with that of road fuels but also the relentless increase in the proportion of diesel and jet fuel, and from product quality changes brought about chiefly by environmental legislation across the spectrum of fuel grades. Slow rate of growth of total demand'*

One industry source stated: "*Economics is a key barrier…... Up to 2025 there is short-term uncertainty with very low margins. The focus is on survival. In the medium term there is a major investment challenge for regulatory compliance bringing us to 2025 to 2030. Between 2030 and 2050 there is the challenge of demand destruction. It is a very uncertain world with refining*."

The second barrier – **short-term management approach and lack of focus on decarbonisation, due to companies' structure** – was a key theme across all information sources and was identified by nine industry sources. Multi-national companies with operations in the UK and elsewhere compete for investment internally. UK refinery managers may not be able to make investment decisions or may not the authority to have their projects approved. In addition, the lack of focus on decarbonisation in the form of overall strategy or targets as discussed in the decision-making section is also a barrier.

A lack of management focus on decarbonisation- a key barrier

Ricardo AEA (2013) found that one of the key risks was: *"Lack of resources, both in terms of time and capital; and, closely related, lack of prioritization."*

Neelis, Worrell and Masanet (2008) found that: *"Even when energy is a significant cost, many companies still lack a strong commitment to improve energy management… Companies without a clear program in place, opportunities for improvement may be known, but may not be promoted or implemented because of organizational barriers."*

Supported by industry sources:

One industry source stated: "*Management focus, resources, and funds are needed for refineries to prioritise basic energy efficiency improvements."*

Another source discussed: "*Larger capex projects get ranked across the world or investments in other sectors such as petrochemicals or upstream production. All the companies compete with investment opportunities elsewhere and compete with investment requirements under current business strategies*."

The third barrier – **regulatory compliance** – was identified by the literature (House of Commons and Climate Change Committee, 2013; Milosevic and Cowart, 2002; UK PIA, 2014; Purvin and Gertz, 2013). This was supported by industry sources and participants at the workshop. This was discussed as an enabler but had further emphasis as a barrier in terms of the opinions of participants that cost of regulatory compliance is increasing and is high in the UK that impacts competiveness and opinion that there is an unlevel playing field in comparison to competitors abroad.

Regulatory compliance- industry sources:

One industry source stated: "*In the medium term there is a major investment challenge for regulatory compliance bringing us to 2025 to 2030."*

Another industry source stated: "*Upcoming cost of legislation will drive us out of business*."

Three out of four tables listed investment challenges linked to regulatory compliance as one of their top five barriers.

The fourth barrier – **high and increasing energy costs** – was identified by the literature (Neelis, Worrell and Masanet, 2008; Ricardo AEA, 2013; EUROPIA, 2011; and CONCAWE, 2012) and supported by two industry sources and two tables at the workshop identified it as one of their top five barriers. It is the opinion of industry sources that high and increasing energy costs act as a barrier as it can impact competiveness by minimising margins and therefore a company's ability to invest in energy efficiency technologies.

A recent publication of Agora – Energiewende (2014), however, illustrates that the comparison of electricity wholesale prices between Sectors and countries is a difficult task. Moreover, a recent communication from the European Commission on energy prices and costs in Europe shows that UK electricity prices for industry are very similar to the average EU-27 prices (see Figure 11), although certain countries (like Bulgaria and Finland) show significantly lower prices (European Commission, 2014).

This has also been discussed as an enabler.

High and increasing energy costs- a squeeze on margins

CONCAWE (2012) found that: "The consumption of energy within EU refineries plays a crucial role in determining refinery operating costs and emissions and has therefore long been a focus of attention by refinery operators."

According to Vivid Economics (2014), "*Carbon leakage risk in the EU ETS is potentially significant for carbon- and trade-intensive sectors under high carbon prices; a number of measures can tackle leakage but no perfect solution exists."*

"While numerous European companies have complained of market distortion due to regulatory favouritism for Germany's energy-intensive industries, caution must be exercised when attempting to directly compare industrial end-use prices between countries and sectors. Because firms in different regions and Sectors vary considerably in the extent to which they pay wholesale market prices and/or receive tax exemptions and levy reductions, comparing prices between Sectors and countries is a difficult task. The heterogeneity of the situation is not fully and transparently captured by European statistics." (Agora – Energiewende, 2014)

Supported by industry sources:

One industry source stated: "*Energy efficiency is always considered for 'kit' replacement as energy costs are the second most important cost after feedstock.*"

The fifth barrier – **high competition levels preventing collaboration on decarbonisation projects** – was identified by five industry sources and supported by literature (Vivid Economics, 2014; EUROPIA, 2011; and

European Commission, 2012) and the workshop. Competition was also seen as limiting collaboration amongst refineries preventing large-scale demonstration projects from being implemented.

Competition - key barriers to collaboration on decarbonisation

One industry source stated: "*Competition Law constraints are keenly felt and observed by the UK refiners especially those with American based principals*."

Another industry source found that: "*Competition between the two refineries prevented collaboration on CHP."*

The sixth barrier – **long payback period for advanced technologies** – was identified by industry sources and supported by the literature (Ricardo AEA 2013) and workshop. Given current unfavourable market conditions, investors and internal decision makers demand quick payback in some cases as short as six months, limiting the energy efficiency technologies implemented to incremental technologies rather than disruptive technologies which have longer paybacks of six to seven years.

Disparity between payback of advanced technologies and internal decision-making ROI criteria: a key theme from industry sources

One industry source found: "*For capex projects- all projects have a threshold that they have to meet for the payback period; it can be as low as six months to warrant investment."*

A second industry source stated: "*Energy efficiency projects, as with all capital investment projects, are typically only undertaken if they are economically viable and satisfy internal investment criteria and return rates."*

Supported by the literature and discussions at the workshop:

Ricardo AEA (2013) found that: "*Continuity of production is of primary importance to firms. This is one of the reasons that energy efficiency technologies tend to have more stringent economic criteria compared to investments that are more closely related to the core business."*

The seventh barrier –**staff skills shortage** – was identified by five industry sources and supported by Ricardo AEA (2013). Refineries are experiencing an ageing workforce with many staff opting for early retirement. As the sector continues to consolidate and margins continue to be low, refiners are forced to reduce staff numbers to manage labour costs, which may also have a knock on effect of being under-resourced and thus less able to prioritise energy efficiency and decarbonisation projects. New technologies such as CCS also require engineers with skills in these technologies in order to successfully implement them.

Shortage of staff due to an ageing workforce and sector consolidation a key theme raised by industry sources and across all sectors

An industry source stated that: "*There is a distinct shortage of instrument and electrical engineers for process safety work and offshore*."

A second industry source identified: "*Human resources might be limiting the rate at which the UK refining industry can progress activities to improve operations… as a result of mergers and reorganisations in the industry there has been a general decline in the number of employees. Many employees in the sector also take advantage of early retirement, causing the demographics of the industry to generally be recognised as having limited skilled human resources. A possible skills shortage could possibly limit the scope and delay the schedule of any energy efficiency projects.* "

Another industry source indicated: "*Skills are becoming an issue because of the age profile of refinery engineering staff. But in terms of skills for implementing CCS some of the concerns would be shared with other sectors.*"

Supported by literature:

Ricardo AEA (2013) found that a lack of focus on decarbonisation was compounded by the risks of "*lack of awareness, heterogeneity, concern for job security, shortage of staff …"*

The eighth barrier – **CCS has a number of barriers** – was identified by industry sources and supported by literature. Participants at the workshop discussed challenges of CCS during the breakout sessions on the pathways.

The key barriers linked to CCS include: increased operational complexity and risks, applications not proven at scale, lack of availability of space, plant integration risks (hidden costs of additional downtime, alternative product supplies, technology lock-in etc.), high levels of uncertainty regarding costs; health, safety and environmental considerations, staff familiarity and expertise, effects on product quality, challenge of capturing emissions in sites which have multiple, heterogeneous small CO_2 streams, a lack of commercial incentives to implement CCS (which has significant up-front and ongoing variable costs), lack of CO_2 transport and storage infrastructure, limited experience of operational full chain CCS projects with industrial sources, and scale of investment is required and remains a potential barrier to widespread deployment of CCS.

CCS has significant barriers that must be overcome - a key theme across industry sources and literature:

CONCAWE (2008) found that*: "Some refineries may develop CCS projects based on a combination of favourable local circumstances. In the next 15 years this will be the exception rather than the rule….Although refineries are fairly large CO_2 emitters as an entire site, these emissions come from a number of discrete sources, often spread over a large area and with different gas compositions. This makes efficient capture more complex and expensive than is the case for single-source sites such as power stations."*

CONCAWE (2011) concludes that: *"One important conclusion is that the volumes and unit locations for CO_2 production in refineries are not conducive to CCS projects in individual refineries and will require alliances with other large CO_2 producers, particularly the power industry, in order to be commercially justified."*

Total (2013) found that: *"Research is on-going to further reduce the high costs of capture and an assessment of regional and global carbon storage capacity still needs to be undertaken. We believe that the immediate priority is to replace coal with natural gas wherever possible and to supplement fossil fuels by developing new energies.***"**

One industry source stated: "*Research and money are required for CCS... A national effort would be needed but there is no incentive for government to enhance collaboration."*

The ninth barrier – **long lifespan of refineries –** was identified by Vivid Economics (2014), two industry sources, and was prioritised by one out of four tables at the workshop. The long lifespan of refineries and the longer investment cycles required, together with the fact that oil refining is a declining sector in the UK, make it unlikely that there will be any new builds, limiting the energy efficiency technologies and techniques that can be applied.

Long lifespan of equipment and investment cycles: a barrier discussed at the workshop and by industry sources:

An industry source found that: "*Limited capability for making changes to operation. The nature, size, and time scale of investment projects require certainty of planning to give acceptable levels of financial risk.*"

Identified by the literature:

Vivid Economics (2014) found that: *"Improved energy efficiency techniques are more likely to be economical in the case of new build refineries but new builds are relatively rare."*

The tenth barrier – **risk of production disruption**– was identified by Ricardo AEA (2013), one industry source and was listed as one of the top barriers by one workshop table out of four. The view was that given unfavourable market conditions, intense competition, and a focus on throughput, oil refiners are risk averse and are wary about implementing new technologies that may disrupt production, as they prefer to be the first follower rather than a leader.

A culture of risk aversion: a theme across the information sources

Ricardo AEA (2013) found that for energy efficiency projects: *"risk of production disruption is of primary importance to refiners when making investment decisions."*

One industry source stated: *"Most refiners would describe themselves as followers."*

One Table out of four listed risk aversion as one of its top barriers. This table discussed that there is a culture or risk aversion given the current unfavourable market conditions and fear of disrupting production. The table also discussed there was risk aversion in allowing outside suppliers of technology to implement new riskier technologies. It was discussed that oil refineries like to be the first follower not the leader in implementing new technologies.

The eleventh barrier – **disruptive tested and reliable technologies not available** – was identified by all information sources. Suppliers have limited access to refineries to try out new disruptive technologies. This is compounded by increased outsourcing of new technology developments and limited access of suppliers to refineries to test technologies.

Non-availability of technology a theme across information sources:

Ricardo AEA (2013) found that: "*The disruptive technologies for decarbonisation are not available acting as a barrier to implementation.*"

One industry source stated: **"***One of the top barriers includes availability and reliability of technology."*

One table out of four listed non-availability of technology as a top barrier. The table also noted that in the last 20-30 years there has been a shift from new technologies being developed in house to suppliers. Suppliers have less ready access to refineries to test it on capex the site. Technology providers do not have the scale or facility to test on their own sites.

The key findings are summarised in section 3.1.

3.5 Technologies to Reduce Carbon Emissions

Increasing energy efficiency offers both energy and CO_2 emission reductions. This is not a new pursuit in the oil refining sector, where fuel represents the single highest cost item, particularly at current price levels.

Energy efficiency improvements include a sustained focus on energy saving in everyday operation as well as investments in e.g. improved heat integration or energy efficient pumps and compressors. The "low-hanging fruits" have long been picked, though, and improvements in recent years have already involved complex and expensive schemes. A significant part of the efficiency improvements has been achieved by installing highly efficient CHP plants replacing simple steam boilers and imported electricity. Further opportunities exist but are increasingly difficult to achieve and less cost-effective (CONCAWE, 2008).

Some technologies are very specific to an individual process unit. For example, a hot gas expander is a technology only really applicable to the FCC process unit. Some categories of technologies are more applicable to certain process units. For example, all techniques that improve heat transfer have the highest value for process units where energy performance is dominated by achieved levels of heat recovery, which is particularly true for CDU. The three most important areas with the greatest contribution to carbon emissions in refining at the process unit level are distillation, heat recovery and fired heater energy performance. As these areas also have the biggest impact on refinery operating cost (energy consumption), many techniques to mitigate carbon emissions have been developed to address these (SNIFFER, 2011).

The energy saving opportunities for the oil refining sector found from the literature review, site visits and the workshop can be classified into 20 categories. Most of these categories are applicable to the whole refinery and include: advanced control and improved monitoring; CCS; flaring; fuel switching; lighting; maintenance; motors, pumps, compressors and fans; new refinery as replacement; process heaters and furnaces; storage tanks; and waste heat and energy recovery. Other categories are more process-specific and include: crude unit upgrades; on-site renewables; FCC design improvements; hydrogen recovery and optimisation; HCK design improvements; biomass; CHP; steam use optimisation (boiler retrofit and utilities); and VDU design improvements.

A summary of the key options used in the pathways are detailed below:

Carbon Capture

CCS is the collection of flue gas from CHP plants, hydrogen production plants and FCC flue gases, the three largest producers of CO_2 on a refinery.

New Refinery

This option is to replace a number of the older UK refineries with a fewer number of larger and more energy efficient refineries, strategically located to maintain supply of transport fuels to the inland market.

Waste Heat and Energy Recovery

This is a group of options to improve the performance of existing refinery equipment by increasing heat integration and waste heat recovery. This improvement comes from using best available technology for recovery.

Pumps, Compressors and Fans

This is a group of options to improve the performance of existing refinery equipment by replacing older less efficient equipment with more efficient designs and different technologies.

Process Heaters and Furnaces

This is a group of options to improve the performance of existing refinery equipment by replacing older less efficient equipment with more efficient designs and different technologies for monitoring and control.

Storage Tanks

This is a group of options to improve the efficiency of heavy oil storage heating by replacing older, less efficient equipment with more efficient designs and upgrading lagging and heating systems.

Combined Heat and Power

This is a single investment option to replace older steam raising equipment and electrical producing equipment with current State-of-the-Art Technology.

Utilities Optimisation

This is a group of options that require only low or medium capital investment. These are largely the current State-of-the-Art Technologies such as energy management, focus on maintenance, leak detection etc.

A detailed overview of these energy saving opportunities is provided in appendix C.

3.5.1 Biomass Carbon Intensity

Pathways including biomass reflect biomass carbon intensity (unless the biomass in the pathway is assumed to be waste biomass). The carbon intensities (below) are applied to two scenarios to help reflect and bound the uncertainties around biomass carbon availability: these are (i) unlimited availability (as deployed in the Max Tech pathway) or (ii) no availability.

In all cases, combustion emissions are assumed to be zero (in line with EU Renewable Energy Directive methodology), on the basis that all biomass used is from renewable sources and thus additional CO_2 is removed from the atmosphere equivalent to that emitted on combustion. This means that all biomass is assumed to be sourced from material that meets published sustainability criteria.

Given the wide variation in pre-combustion emissions, a carbon intensity (based on pre-combustion emissions) was derived from a low scenario from the DECC-commissioned Bioenergy Emissions and Counterfactual Model report (published 2014) for modelling purposes. An emission value of 20 kgCO2e/MWh(th) has been used for solid biomass use, and this has been modified to 25 kgCO2e/MWh(th) if the pathways includes pyrolysis, and 30 kgCO2e/MWh(th) if the pathways includes production of biogas.

3.5.2 Cost of Options

Limited information related to the capital cost of technologies was identified in this project as summarised in appendix C. In gathering capital cost-related data, literature or engagement with stakeholders, together with expert judgement, were used to establish an initial order of magnitude dataset for use in the cost analysis assessment. The degree of stakeholder engagement in relation to the cost dataset was lower than for the carbon reduction pathways. Operating costs such as energy use changes, energy costs and labour are not included in this analysis, although we recognise that operating costs will have a major impact on the decarbonisation pathways. For example, some options (e.g. carbon capture and electrification of firing) will greatly increase energy use and costs of a process plant.

Costs analysis was carried out for the pathways, which is presented in section 4. There is a large degree of uncertainty attached to the cost analysis, especially for options which are still in the research and development stage. As well as costs of operation and energy use, other significant costs not included in the analysis are research, development, demonstration, civil works, modifications to plant and costs to other stakeholders, which are significant for many options. Great care must be taken in how these costs are interpreted and it is recommended to check with trade associations.

4. PATHWAYS

4.1 Key Points

The pathways development and analysis shows that the maximum decarbonisation potential of the sector for the current trends scenario is a reduction to 5.9 Mt of CO_2 emitted in 2050 in the Max Tech pathway, which corresponds to a reduction in emissions of 64% compared with emissions in 2012. Significant reductions of 59% and 70% could be achieved under challenging world and collaborative growth scenarios respectively. The most significant reductions could be achieved by application of CCS.

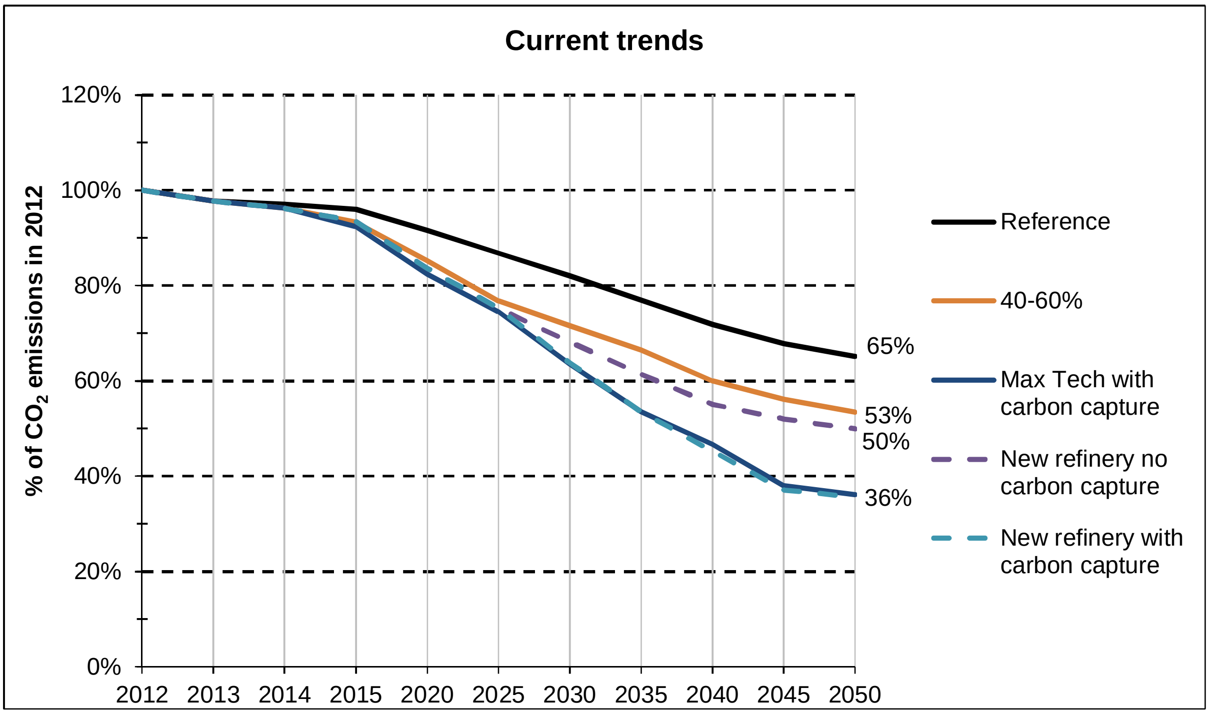

Figure 11: Performance of pathways for the current trends scenario

Figure 11 shows the range of decarbonisation pathways that are possible for the current trends scenario.

- BAU represents a pathway where existing trends in energy efficiency and decarbonisation continue. This reduction comes from a range of incremental and major options deployed to represent a continuation of current practice and policies.
- 40-60% CO_2 reduction pathway includes the same options as the BAU pathway but deployed faster and at a higher rate. Higher impact disruptive options such as CCS were not introduced. The figure shows only limited extra reductions are achieved in this pathway.
- Max Tech pathway includes all options, reaching the 40-60% CO_2 reduction band. The option with the largest potential to reduce carbon emissions is CCS.
- Two alternative pathways ('sensitivities') have been created in which a new refinery is built using Best Available Technology as replacement to an old plant. They are not treated as core pathways because the current and projected commercial context for the sector does not justify a new and efficient refinery rebuild option. The pathways are represented as dashed lines, the first being new refinery pathway without CCS, which extends reductions a little further than the 40-60% CO_2 reduction pathway, and second is the new refinery pathway with CCS, which follows the same trend

as the Max Tech pathway. The new refinery replaces 50% of the current capacity of the UK refineries.

In summary, the main technical categories of options deployed across the pathways to varying degrees, are:

- Incremental improvements extending known solutions, such as optimising process controls, improving maintenance, and plant retrofits.
- Major improvements reducing carbon emissions, including: design improvements, upgrading process units such as using Best Available Technologies (BAT), fuel switch (from fuel oil to natural gas), and new CHP on remaining sites.
- Disruptive technology shifts consisting of CCS and waste heat and energy recovery. Additionally, an alternative disruptive option includes a new refinery rebuild, using the most efficient European refinery as a benchmark (modelled with and without CCS).

4.2 Pathways and Scenarios – Introduction and Guide

The pathways development uses evidence gathered, as set out in Section 3, to create a set of decarbonisation 'pathways', which provide a quantitative component to the roadmap and help inform the strategic conclusions.

A pathway consists of decarbonisation options deployed over time from 2015 to 2050, as well as a reference emissions trend.. The analysis covers three: 'scenarios': with pathways developed under a central trend ('Current Trends' scenario) and alternative future outlooks ('Challenging World' and 'Collaborative Growth' scenarios).

A scenario is a specific set of conditions that could directly or indirectly affect the ability of the sector to decarbonise. Examples of these are: future decarbonisation of the grid, future growth of the sector, future energy costs, and future cost of carbon. Since we do not know what the future will look like, using scenarios is a way to test the robustness of the different pathways. A detailed description of these scenarios is provided in Appendix A.

The three scenarios were developed, covering a range of parameters. They characterised possible versions of the future by describing assumptions relating to international consensus; international economic context; resource availability and prices; international agreements on climate change; general technical innovation; attitude of end consumers to sustainability and energy efficiency; collaboration between sectors and organisations; and demographics (world outlook).

Quantitative parameters were also part of the scenarios, including production outlook (agreed sector-specific view) and Grid CO_2 factors (DECC supplied) which both impact decarbonisation (assuming production and carbon emissions have a linear directly proportional relationship). Other quantitative parameters within the scenarios governed forward price forecasts and technology deployment.

The purpose of the model that underpins this pathways analysis is to bring together the data captured from various sources and to broadly reflect, using a simple "top down" approach, how emissions might develop to 2050. The model is therefore capable of indicating magnitudes of emission savings that can be achieved, when various technology options are applied, and also how different deployment timings and high-level economic outlooks for a sector might change the results. A sector model was used to create pathways based on reference emissions and energy consumption in 2012. The model is not intended to give exact results and is not of sufficient detail to account for all mass/ energy/ carbon flows, losses and interactions in a sector (i.e. it is not "bottom up" and does not use automatic optimisation techniques).

The methodology is summarised in Figure 12

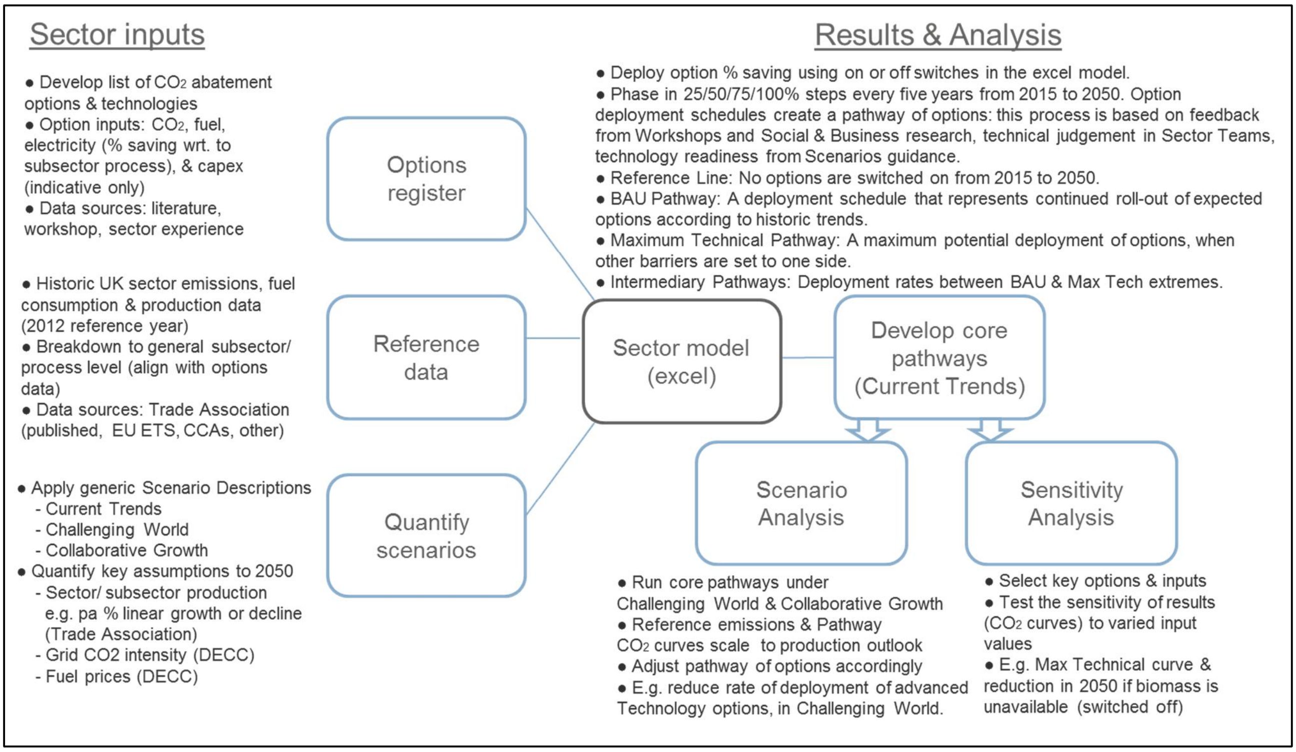

Figure 12: Summary of analysis methodology

This section of the report is structured to present the pathways in the current trends scenario (section 4.4), whilst also briefly describing how the pathways change when modelled under other scenarios. Table 8 illustrates this structure and acts as a guide to the section. Appendix D summarises the pathway analysis in the other two scenarios (challenging world and collaborative growth).

Pathway	Current Trends Scenario	Challenging World Scenario	Collaborative Growth Scenario
Reference Emissions Trend	*Scenario assumptions only linked to production outlook and grid decarbonisation No options deployed in the model*		
BAU	Builds on the reference line by deploying options from 2015 to 2050 in the model, to construct a BAU pathway. Run model under current trends.	Builds on BAU pathway current trends by adjusting option selections and deployment schedule, to reflect the scenario assumptions and technology constraints. Run model under challenging world.	Adjust BAU pathway current trends, i.e. option selections and deployment schedule, to reflect scenario assumptions and technology constraints. Run model under collaborative growth.
20-40%[14]	Builds on BAU for example by: deploying	Builds on 20-40% pathway current trends in	Adjust 20-40% pathway current trends in the

[14] Intermediary pathways may or may not be developed for a sector, depending on the carbon reductions of the BAU and Max Tech pathways.

	more advanced options, extending further across sector, deploying options earlier. Run under current trends.	the same way. Run under challenging world.	same way. Run under collaborative growth.
40-60%	Builds on 20-40% in the same way. Run under current trends.	Builds on 20-40% pathway current trends in the same way. Run under challenging world.	Adjust 20-40% pathway current trends in the same way. Run under collaborative growth.
60-80%	Builds on 40-60% in the same way. Run model under current trends.	Builds on 40-60% pathway current trends in the same way. Run under challenging world	Adjust 40-60% pathway current trends in the same way. Run under collaborative growth.
Max Tech	Configure a schedule of options from 2015 to 2050 that broadly represents a maximum rate and spread across the sector. Run model under current trends.	Adjust Max Tech pathway current trends in the same way. Run under challenging world.	Adjust Max Tech pathway current trends in the same way. Run under collaborative growth.

Table 8: Pathways and scenario matrix

Section 4.5 presents results from the sensitivity analysis, which aims to demonstrate the impact of key options and sensitivity of the pathways to e inputs. Section 4.6 presents the analysis of pathway costs. Section 4.7 summarises the enablers and barriers to the options and pathways developed in the modelling, taking account of information gathered from literature and stakeholders.

4.3 Baseline Evolution - Principal Question 3

This section provides assessment of the range of questions under Principal Question 3: 'How might the baseline level of energy and emissions in the sectors change over the period to 2050?'

The scenarios are based on the 2013 IEA World Energy Outlook Current Policies Scenario. This includes projections for EU-28 TPOD and total sales into consumption (TSC) for 2020, 2030 and 2035, based on data reported for 2011, along with compound average annual growth rates (CAAGRs) for the period 2011 to 2035. The latter have been used to project TPOD forward from 2035 to 2050 and the assumption made that UK TPOD will continue to represent around 12.4% of EU-28 demand. Refinery utilisation rates have been calculated taking into account closure of the Petroplus Coryton refinery in 2012 and the Murco Milford Haven refinery in 2014 and the mothballing of distillation capacity at the Exxon Mobil (Esso) Fawley and Essar Stanlow refineries in 2012 and 2013

Based on the above assumptions and together with UKPIA, we have developed the following growth estimates for the different future scenarios:

- Current Trends – 1.04% annual decline
- Challenging World – 0.81% annual decline
- Collaborative growth – 1.31% annual decline

The effect of the scenario assumptions in the modelling is shown by the reference trend. This is the top curve in Figure 13 (for the current trends scenario), showing the results if no individual options and only production changes and grid decarbonisation were applied. Under current trends, a reduction occurs in reference sector emissions from 2012 to 2050. These effects can be seen in the reference emissions line, sitting at the 65% level by 2050 compared to emissions in 2012.

The other two scenarios assume a decline in sector activity over the period from 2015 to 2050. Hence these assumptions also impact the reference trend and potential reductions.

4.4 Emission-Reduction Potential and Pathway Analysis – Principal Question 4 and 5

This section provides an assessment of the range of questions under Principal Questions 4 and 5:

- What is the potential to reduce emissions in these sectors beyond the baseline over the period to 2050?
- What emissions pathways might each sector follow over the period to 2050, under different scenarios?

For a detailed description of the pathways development and analysis, please see appendix A.

The list of barriers and enablers has informed the list of technical options that are being deployed in the different pathways. They also informed the deployment of the different technical options both with regards to time and degree of deployment. For example the enabler 'small incremental investments', led to a faster deployment of current State-of-the-Art technologies that had a low or low-medium investment requirement.

In addition to the growth or decline projections for the different scenarios the following electricity grid emission factors were used in the modelling:

- Current Trends: 100g CO_2 per kWh by 2030 and 26g CO_2 per kWh in 2050
- Challenging World: 200g CO_2 per kWh by 2030 and 150g CO_2 per kWh by 2050
- Collaborative growth: 50g CO_2 per kWh by 2030 and 25g CO_2 per kWh by 2050

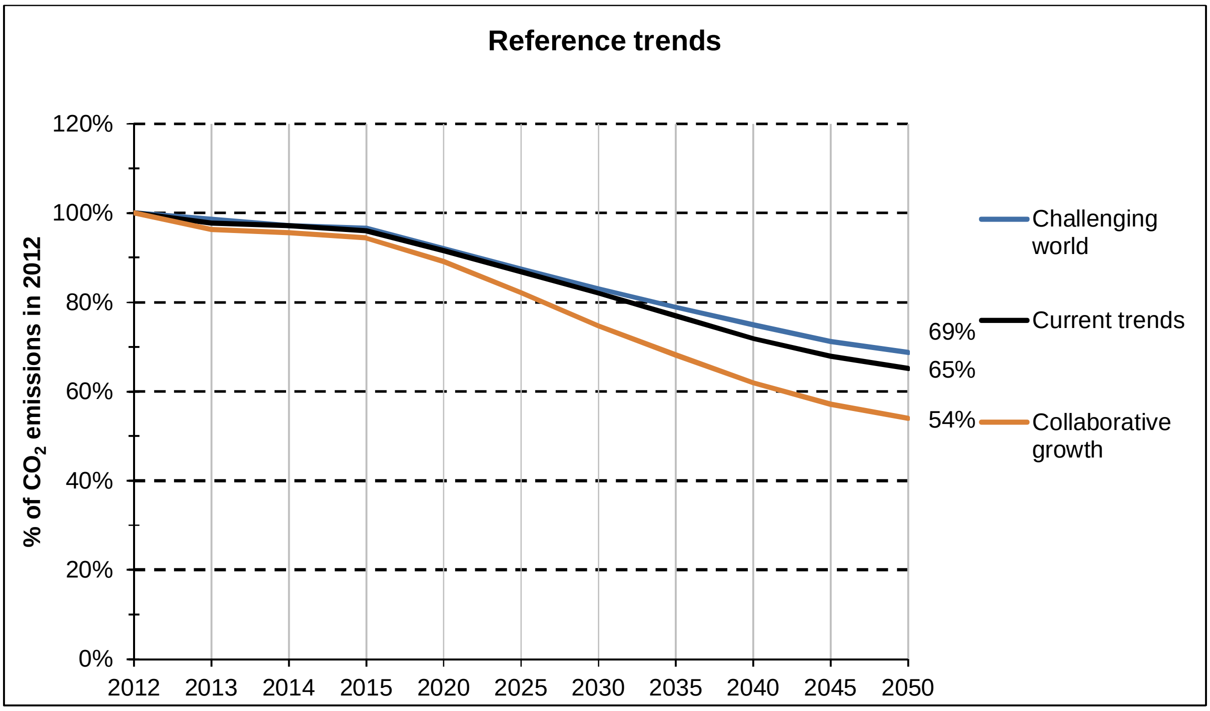

Figure 13: Reference trends for the different scenarios

For all of the pathways, to have the total CO_2 reduction, direct emissions and indirect emissions (from using electricity imported from the electricity grid) need to be accounted for. The growth or decline of the sector and the indirect emissions are illustrated by the reference trend. Figure 13 shows the reference trends for the different scenarios. The shape of the line is primarily linked to both growth or decline of the sector, and also to the different levels of decarbonisation of the electricity grid. Note electricity grid CO_2 emission factors have been applied to only the imported electricity, and not to the onsite generated electricity.

In the pathways development that follows, a range of options were then deployed in the model, to varying levels of application and at various timings, to produce the pathway reduction results. Note the option deployments input during the pathways modelling involved a degree of arbitrary choice, i.e. for which options to apply and when. The analysis is hence intended to provide illustrative pathways only, of the range and type of technology options that might be available from 2015 to 2050, and indications of the potential magnitudes of decarbonisation achievable.

4.4.1 Business as Usual Pathway

Pathway Summary

The guiding objective for the BAU pathway was to outline a set of decarbonisation and energy savings options that would be expected if current rates of efficiency improvement in the UK oil refining industry continued, and no significant intervention or outside support was provided to decarbonise the sector by 2050. Options requiring no policy intervention (compared to today) and only minor changes within the sector were chosen. We therefore selected the options [according to what criteria, referencing the options register data] and with input from UKPIA and DECC. This was presented at workshop for validation.

Deployment for the Current Trends Scenario

Figure 14 shows the option deployment for the BAU pathway under the current trends scenario. The first column lists the decarbonisation options on the left, each with an identifier that shows the subsector (process) to which the option applies in a typical refinery. The subsector (process) breakdown is as follows:

- All: Option applies to Total Refinery emissions
- CD: Option applies to Crude Distillation related emissions only
- Electricity: Option applies to Electricity related emissions only
- FCC: Option applies to Fluid Catalytic Cracking related emissions only
- H2: Option applies to Hydrogen Plant related emissions only
- HC: Option applies to HCK related emissions only
- NG: Option applies to Natural Gas (when direct firing) related emissions only
- Steam and Power: Option applies to Steam and Power Generation Plant (CHP) related emissions only
- Steam: Option applies to Steam Generation Plant related emissions only
- VDU: Option applies to Vacuum Distillation related emissions only

The second column categories the scale of investment of each option (incremental, major or disruptive). The third and fourth columns are the estimated adoption (ADOPT.) rate in 2012 and the applicability rate (APP.) assumption for the option. The applicability rate indicates to what level this option is applicable to the sector, or its relevant subsector. To the right of the applicability rate is the level of additional deployment of the option over time to 2050. The CO_2 reductions are estimated based on: the direct CO_2 reductions assumed for the option for its relevant process, the adoption rate, applicability rate and additional deployment.

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
All: Advanced Control and Improved Monitoring	85%	100%	0%	25%	25%	50%	75%	100%	100%	100%	100%
All: Carbon Capture and Storage (CCS) - Part 1	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
All: Carbon Capture and Storage (CCS) - Part 2	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
All: Flaring	43%	100%	0%	25%	50%	100%	100%	100%	100%	100%	100%
All: Fuel Switch	0%	100%	0%	25%	50%	100%	100%	100%	100%	100%	100%
All: Lighting	50%	100%	0%	25%	25%	25%	50%	50%	75%	75%	100%
All: Maintenance - Fouling control	80%	100%	0%	0%	25%	25%	50%	50%	75%	75%	75%
All: Motors, Pumps, Compressors, Fans	35%	100%	0%	25%	50%	50%	75%	75%	75%	75%	75%
All: New Refinery as replacement	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
All: Process Heaters and Furnaces	43%	80%	0%	25%	50%	50%	75%	75%	75%	75%	75%
All: Storage Tanks	10%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
All: Waste Heat and Energy recovery	0%	100%	0%	0%	0%	25%	25%	25%	25%	25%	25%
CD: Crude Unit Upgrades (BAT)	29%	80%	0%	0%	0%	25%	25%	50%	50%	75%	75%
Electricity: Onsite renewables e.g. Wind	0%	100%	0%	0%	0%	25%	25%	25%	50%	50%	50%
FCC: Design improvements (BAT)	50%	80%	0%	0%	25%	25%	25%	50%	50%	50%	50%
H2: Recovery / Optimisation	60%	100%	0%	0%	25%	25%	50%	50%	75%	75%	100%
HC: Design improvements (BAT)	0%	100%	0%	25%	25%	25%	50%	50%	75%	75%	75%
Natural Gas: Biomass (syngas etc)	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Steam & Power: CHP	79%	100%	0%	0%	0%	0%	50%	50%	100%	100%	100%
Steam: Boiler (Retrofit)	71%	100%	25%	25%	50%	75%	75%	75%	75%	75%	75%
Steam: Utilities Optimisation	75%	100%	25%	25%	50%	75%	100%	100%	100%	100%	100%
VDU: Design improvements (BAT)	29%	100%	0%	25%	25%	25%	50%	50%	75%	75%	75%

Figure 14: Option deployment for the BAU pathway

In this pathway, the principal options that contribute to the biggest emissions reductions in 2050 are (Figure 15):

- **Waste heat and energy recovery**: deployed in 2025 at 25% without further increase, accounts for 17% of the total emissions reduction from deployment of options in 2050.
- **Motors, pumps, compressors and fans**: deployed in 25% increments to 75% in 2030, accounts for 16% of the total emissions reduction from deployment of options in 2050.
- **Storage tanks**: deployed in 25% increments to 100% of potential in 2030, and accounts for 12% of the total emissions reduction from deployment of options in 2050.
- **Advanced control and improved monitoring**: deployed in 25% increments to 100% in 2035, accounts for 10% of the total emissions saving from deployment of options in 2050.
- **CHP**: deployed in 50% increments (only applicable at two UK sites, because the other refineries have already adopted CHP) to 100% in 2040, accounts for 9% of the total emissions saving from deployment of options in 2050.
- **Process heaters and furnaces**: deployed in 25% increments to 75% in 2030, accounts for 8% of the total emissions saving from deployment of options in 2050.
- **Lighting:** deployed from 2015 to reach 100% in 2050, accounts for 6% of the total emission saving from deployment of options in 2050.**Utilities optimisation**: deployed in 25% increments to 100% in 2030, accounts for 6% of the total emissions saving from deployment of options in 2050.

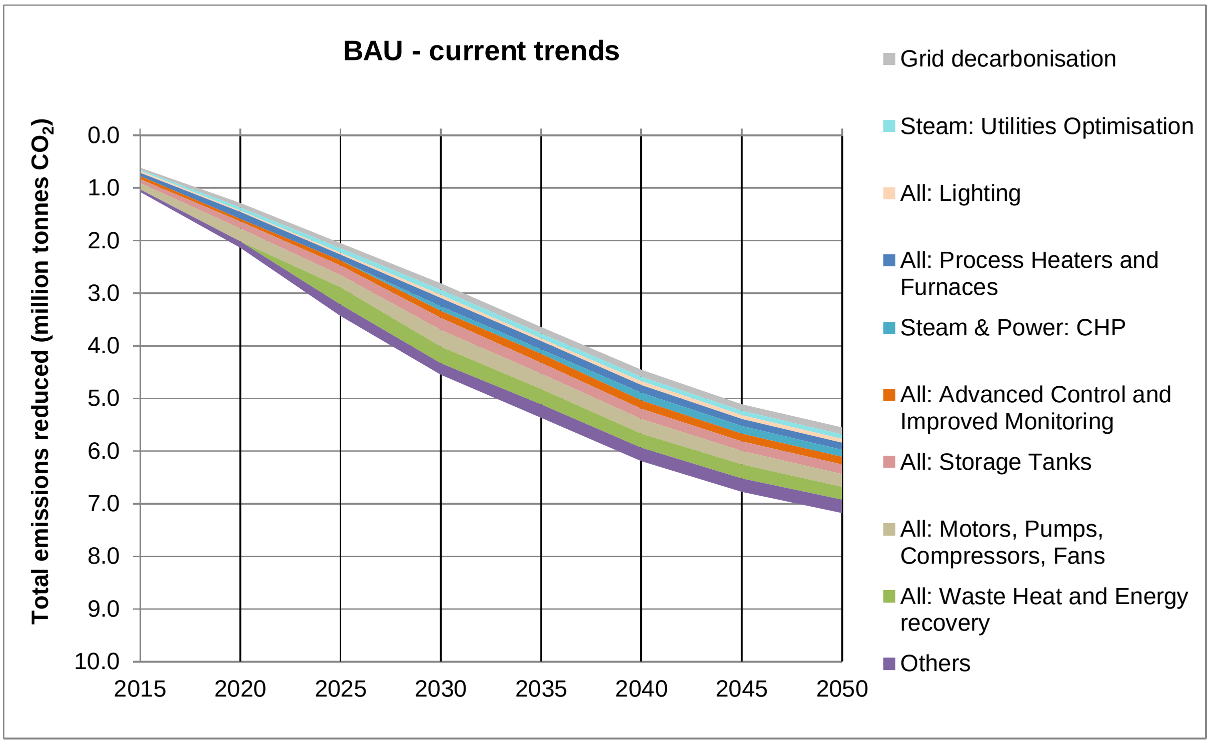

Figure 15: Contribution of principal options to the absolute emissions reduction throughout study period, for the BAU pathway, current trends scenario

For the current trends scenario, the options deployed in the BAU pathway give an overall reduction of 44% in 2050, compared to 2012. Most of this reduction comes from the fall in emissions in the reference trend, as assumed under the current trends scenario for sector – and the BAU pathway then delivers an added 8% reduction on top of this reference. This added reduction includes the emission abatement linked to the deployment of options and decarbonisation of the grid; although the contribution of the grid decarbonisation is negligible. This is because only one site currently imports electricity from the grid, whereas all others auto-generate using onsite power generation and CHP plant.

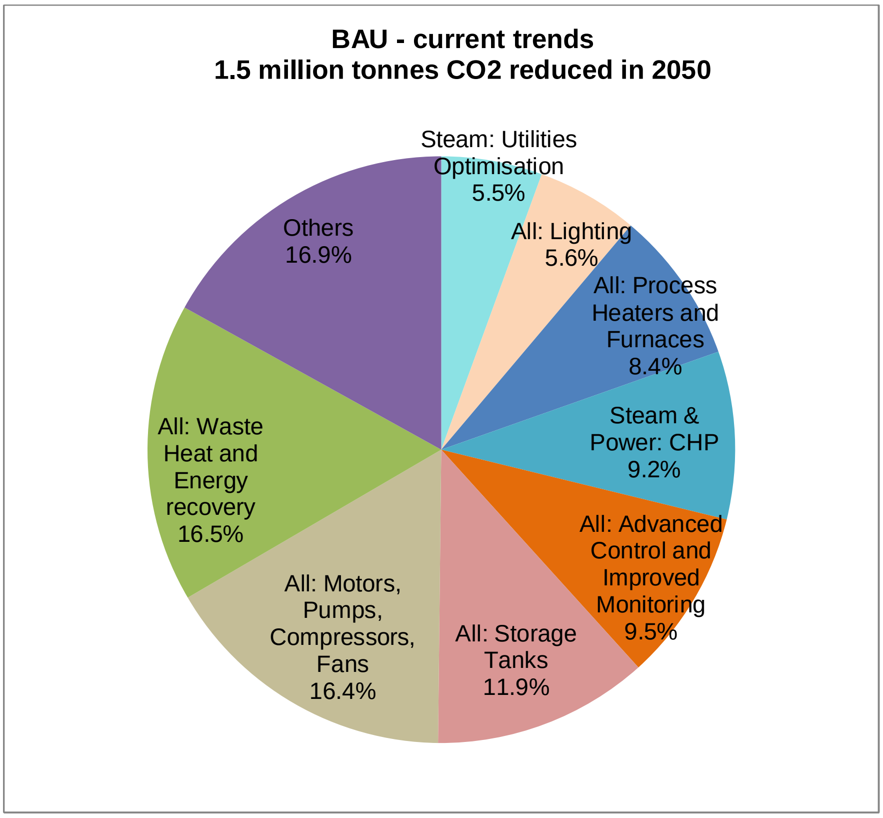

Figure 16: Breakdown of 2050 emissions reduction, for the BAU pathway, current trends scenario

The CO_2 saving contributions in 2050 revealed that most of the carbon savings in BAU came from a few key options (Figure 16): Waste heat and energy recovery; motors, pumps, compressors and fans; storage tanks; advanced control and improved monitoring; steam and power (CHP); process heaters and furnaces; lighting and utilities optimisation[15].

[15] Grid decarbonisation is not considered to be an option, but a variable in the different scenarios, and is therefore not shown in the pie charts of emissions reductions

Option Deployment for other Scenarios

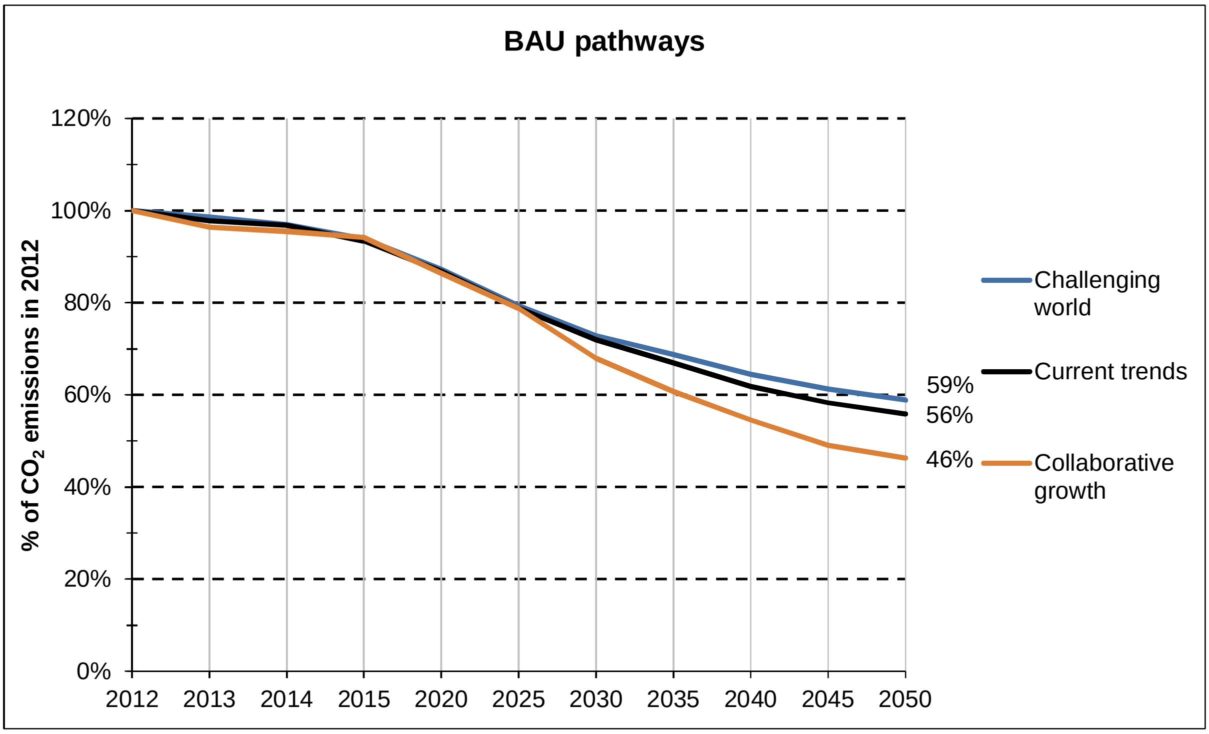

Figure 17: Business as Usual pathways for the different scenarios

Figure 17 shows the BAU pathways for the different scenarios. As can be seen the current trends scenario delivers an overall CO_2 reduction of 44%, the challenging world scenario delivers an overall CO_2 reduction of 41% and the collaborative growth scenario delivers an overall CO_2 reduction of 54%.

In the challenging world scenario, all options included under the current trends scenario were deployed at the same rate and reaching the same level by 2050. This is because, despite the wider economic challenges assumed under challenging world, the oil refining sector in fact declines less steeply, due to maintained demand for fossil fuels and petroleum products. It was therefore assumed that the business-as-usual measures applied under current trends remain the same in this scenario.

In the collaborative growth scenario, conversely, most of the options included under the current trends scenario were deployed later by 5-10 year but to the same level by 2050. Despite the more favourable technology readiness and low carbon development assumed under collaborative growth, the refining sector is assumed to decline at a steeper rate compared to other sectors. This would therefore imply slower and potentially less investment in decarbonisation measures.

Neither CCS nor Biomass technology options are deployed in the BAU pathways.

Detailed information on the modelled deployment of options for the challenging world and collaborative growth scenario is shown in appendix D.

4.4.2 40-60% CO_2 Reduction Pathway

Pathway Summary

A separate 40-60% CO_2 reduction pathway was modelled to show the effect of deploying all incremental and major options to their maximum potential, but still not using the higher impact disruptives (CCS, New

Refinery). The Waste heat and energy recovery option is extended to half of all refineries in this pathway, and is what mainly raises savings compared to BAU.

Deployment for the Current Trends Scenario

Figure 18 shows the Option Deployment for the 40-60% CO_2 reduction pathway under the current trends scenario. It builds on the BAU pathway by deploying all relevant options earlier, with full deployment of all increments by 2050 and most of the majors.

These options and their relative contributions to overall savings by the year 2050 are shown below in Figure 18.

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
All: Advanced Control and Improved Monitoring	85%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
All: Carbon Capture and Storage (CCS) - Part 1	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
All: Carbon Capture and Storage (CCS) - Part 2	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
All: Flaring	43%	100%	0%	25%	50%	100%	100%	100%	100%	100%	100%
All: Fuel Switch	0%	100%	0%	25%	50%	100%	100%	100%	100%	100%	100%
All: Lighting	50%	100%	25%	50%	75%	100%	100%	100%	100%	100%	100%
All: Maintenance - Fouling control	80%	100%	0%	25%	25%	50%	50%	75%	75%	100%	100%
All: Motors, Pumps, Compressors, Fans	35%	100%	0%	0%	25%	25%	50%	50%	75%	75%	100%
All: New Refinery as replacement	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
All: Process Heaters and Furnaces	43%	80%	0%	25%	25%	50%	50%	75%	75%	100%	100%
All: Storage Tanks	10%	100%	25%	50%	75%	100%	100%	100%	100%	100%	100%
All: Waste Heat and Energy recovery	0%	100%	0%	0%	0%	25%	25%	25%	50%	50%	50%
CD: Crude Unit Upgrades (BAT)	29%	80%	0%	0%	25%	50%	50%	75%	75%	100%	100%
Electricity: Onsite renewables e.g. Wind	0%	100%	0%	0%	25%	25%	25%	50%	50%	75%	75%
FCC: Design improvements (BAT)	50%	80%	0%	0%	25%	25%	25%	50%	50%	75%	75%
H2: Recovery / Optimisation	60%	100%	0%	0%	25%	25%	50%	50%	75%	75%	100%
HC: Design improvements (BAT)	0%	100%	0%	25%	25%	25%	50%	50%	75%	75%	100%
Natural Gas: Biomass (syngas etc)	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Steam & Power: CHP	79%	100%	0%	0%	100%	100%	100%	100%	100%	100%	100%
Steam: Boiler (Retrofit)	71%	100%	25%	25%	50%	75%	100%	100%	100%	100%	100%
Steam: Utilities Optimisation	75%	100%	25%	50%	75%	100%	100%	100%	100%	100%	100%
VDU: Design improvements (BAT)	29%	100%	0%	0%	25%	50%	75%	100%	100%	100%	100%

Figure 18: Option Deployment for the 40-60% CO_2 reduction pathway under Current Trends

In this pathway, the principal options that contribute to the biggest emissions reduction in 2050 are (Figure 19):

- **Waste heat and energy recovery**: deployed in 2025 at 25% and increasing to 50% deployment in 2040 and onwards, accounts for 27% of the total emissions saving from deployment of options in 2050.
- **Motors, pumps, compressors and fans**: deployed in 25% increments to 100% in 2050, accounts for 18% of the total emissions saving from deployment of options in 2050.
- **Storage tanks**: deployed in 25% increments to 100% of potential in 2025, accounts for 10% of the total emissions saving from deployment of options in 2050.
- **Process heaters and furnaces**: deployed in 25% increments to 100% in 2045, accounts for 9% of the total emissions saving from deployment of options in 2050.
- **Advanced control and improved monitoring**: deployed in 25% increments to 100% in 2030, accounts for 8% of the total emissions saving from deployment of options in 2050.

- **CHP**: is assumed to be deployed to the two remaining sites (100%) by 2020, and accounts for 8% of the total emissions saving from deployment of options in 2050.
- **Lighting**: deployed in 25% increments to 100% in 2025, accounts for 5% of the total emissions saving from deployment of options in 2050.
- **Steam utilities optimisation**: deployed in 25% increments to 100% in 2025, accounts for 5% of the total emissions saving from deployment of options in 2050.

Figure 19 shows the absolute emission savings from the principal options along the pathway.

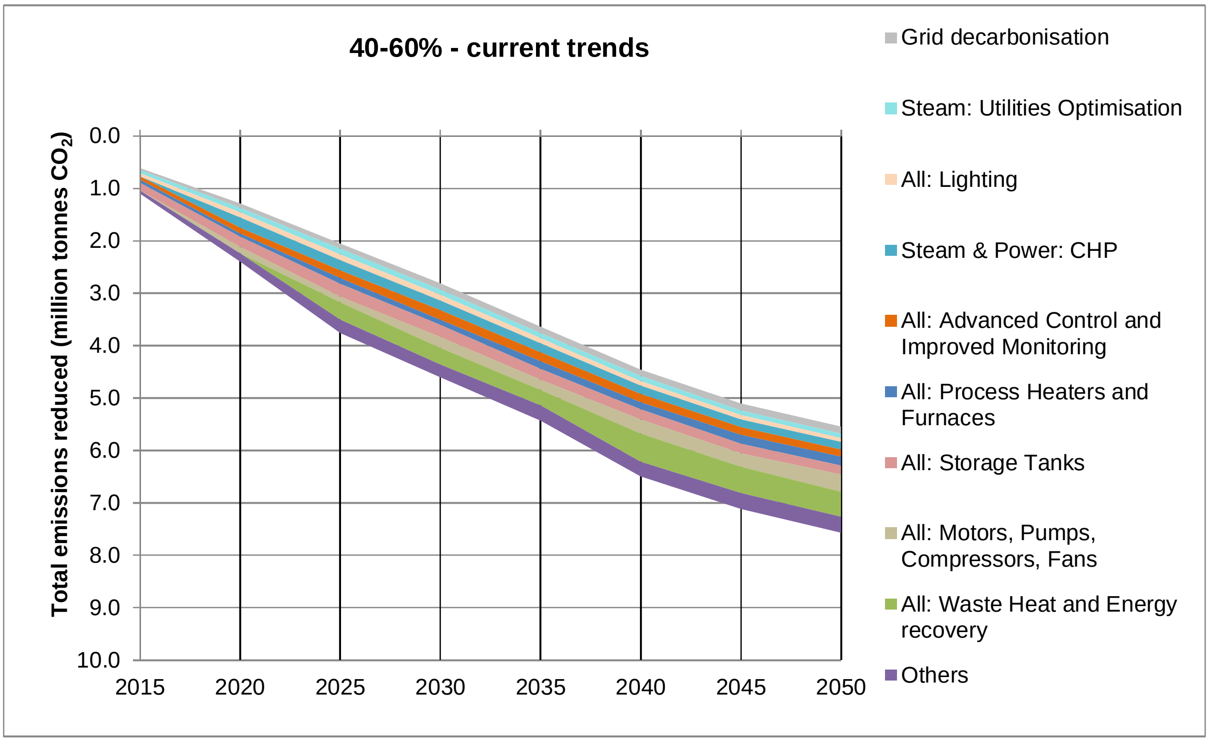

Figure 19: Contribution of principal options to the absolute emissions reduction throughout the study period for the 40-60% CO_2 reduction pathway, current trends scenario

For the current trends scenario, the options deployed in the 40-60% CO_2 reduction pathway give an overall reduction of 47% in 2050, compared to 2012. Most of the reduction again comes from the falling production (and hence reference emissions) assumed under the scenario, and the graph shows the remaining savings mainly consists of emissions reductions linked to the deployment of options (to direct emissions onsite), and a small contribution from decarbonisation of the grid (< 1%).

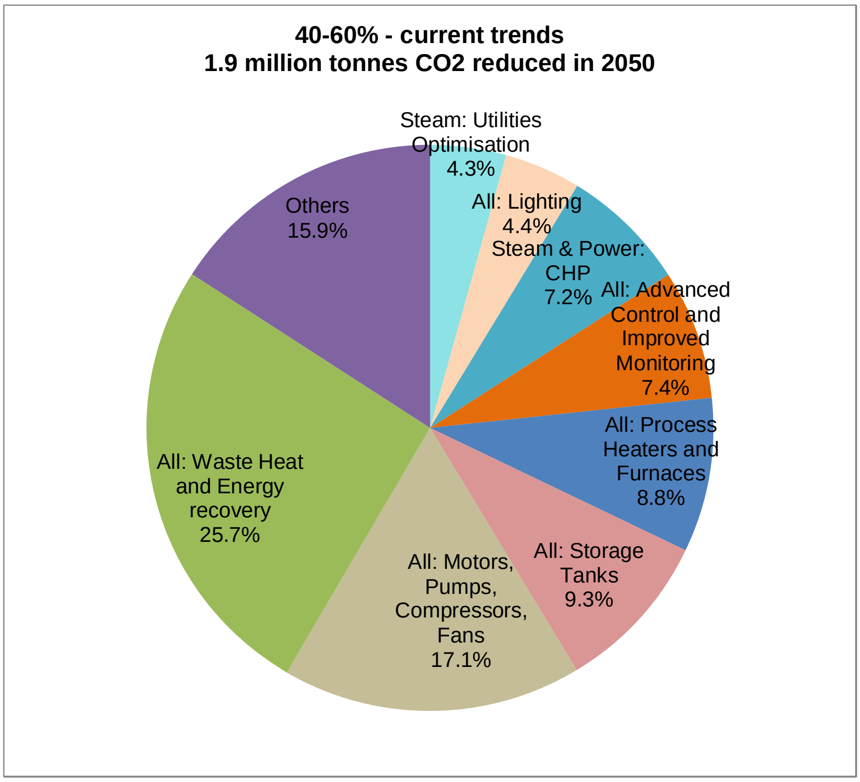

Figure 20: Breakdown of the 2050 emissions reduction for the 40-60% CO_2 reduction pathway under current trends

The CO_2 saving contributions in 2050 are shown to principally come from extending known solutions: Waste heat and energy recovery; new motors, pumps, compressors fans; storage tanks; process heaters and furnaces; advanced control and improved monitoring; CHP plant; lighting and utilities optimisation.

Option Deployment for Other Scenarios

In the challenging world scenario, all options included under the current trends scenario were deployed at the same rate and to the same degree, due to the reduced rate of decline of the sector (reference trend) compared to current trends.

In the collaborative growth scenario, all options occurring in the current trends scenario were deployed but shifted later by 5-10 years. This is due to the increased rate of decline of the sector compared to current trends.

The deployment of options in the challenging world and collaborative growth scenario is shown in appendix D.

4.4.3 Maximum Technical Pathway

Pathway Summary

As none of the Max Tech pathways achieve a CO_2 reduction of over 70%, it is not necessary to develop more intermediate pathways.

The Max Tech pathway for the current trends scenario includes all options (incremental, major and disruptive). The guiding principle for the Max Tech pathway is to select a combination of carbon abatement options and savings that is both highly ambitious but also reasonably foreseeable. It is designed to investigate what might be technically possible when other barriers are set to one side.

The Max Tech builds on the 40-60% CO_2 reduction pathway mainly by introducing CCS technology and extending it across a large part of the sector. There is also full deployment of Waste heat and energy recovery, and also a small level of biomass (as syngas) introduced as a substitute for natural gas.

Deployment for the Current Trends Scenario

Figure 21 shows the option deployment for the Max Tech pathway for the current trends scenario.

OPTION	ADOP.	APP.	DEPLOYMENT								
			2014	2015	2020	2025	2030	2035	2040	2045	2050
All: Advanced Control and Improved Monitoring	85%	100%	0%	75%	100%	100%	100%	100%	100%	100%	100%
All: Carbon Capture and Storage (CCS) - Part 1	0%	100%	0%	0%	0%	0%	25%	50%	50%	75%	75%
All: Carbon Capture and Storage (CCS) - Part 2	0%	100%	0%	0%	0%	0%	0%	0%	25%	50%	50%
All: Flaring	43%	100%	0%	25%	50%	100%	100%	100%	100%	100%	100%
All: Fuel Switch	0%	100%	0%	25%	50%	100%	100%	100%	100%	100%	100%
All: Lighting	50%	100%	25%	50%	75%	100%	100%	100%	100%	100%	100%
All: Maintenance - Fouling control	80%	100%	0%	25%	25%	50%	50%	75%	75%	100%	100%
All: Motors, Pumps, Compressors, Fans	35%	100%	0%	0%	25%	25%	50%	50%	75%	75%	100%
All: New Refinery as replacement	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
All: Process Heaters and Furnaces	43%	80%	0%	25%	25%	50%	50%	75%	75%	100%	100%
All: Storage Tanks	10%	100%	25%	50%	75%	100%	100%	100%	100%	100%	100%
All: Waste Heat and Energy recovery	0%	100%	0%	0%	25%	50%	75%	100%	100%	100%	100%
CD: Crude Unit Upgrades (BAT)	29%	80%	0%	0%	25%	50%	50%	75%	75%	100%	100%
Electricity: Onsite renewables e.g. Wind	0%	100%	0%	0%	25%	50%	50%	75%	75%	100%	100%
FCC: Design improvements (BAT)	50%	80%	0%	0%	25%	25%	25%	50%	50%	75%	75%
H2: Recovery / Optimisation	60%	100%	0%	0%	25%	25%	50%	50%	75%	75%	100%
HC: Design improvements (BAT)	0%	100%	0%	25%	25%	25%	50%	50%	75%	75%	100%
Natural Gas: Biomass (syngas etc)	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Steam & Power: CHP	79%	100%	0%	0%	100%	100%	100%	100%	100%	100%	100%
Steam: Boiler (Retrofit)	71%	100%	25%	25%	50%	75%	100%	100%	100%	100%	100%
Steam: Utilities Optimisation	75%	100%	25%	75%	100%	100%	100%	100%	100%	100%	100%
VDU: Design improvements (BAT)	29%	100%	0%	0%	25%	50%	75%	100%	100%	100%	100%

Figure 21: Option deployment for the Max Tech pathway

In this pathway, the principal options that contribute to the biggest emissions reduction in 2050 are (Figure 22):

- **Carbon Capture and Storage (CCS) – Part 1, applied to CHP and Hydrogen generation plant**: deployed in 2030 to 25% of all refineries and increasing to 75% deployment by 2050, accounts for 35% of the total emissions saving from deployment of options in 2050.
- **Carbon Capture and Storage (CCS) – Part 2, applied to FCC stack**: deployed in 2040 to 25% of all refineries and increasing to 50% deployment by 2050, accounts for 21% of the total emissions saving from deployment of options in 2050.
- **Waste heat and energy recovery**: deployed in 25% increments to 100% in 2035, accounts for 18% of the total emissions saving from deployment of options in 2050.
- **Motors, pumps, compressors and fans**: deployed in 25% increments to 100% in 2050, accounts for 6% of the total emissions saving from deployment of options in 2050.
- **Storage tanks**: deployed in 25% increments to 100% of potential in 2025, accounts for 3% of the total emissions saving from deployment of options in 2050.
- **Process heaters and furnaces**: deployed in 25% increments to 100% in 2045, accounts for 3% of the total emissions saving from deployment of options in 2050.

- **Advanced Control and improved monitoring**: deployed to 100% in 2020, accounts for 3% of the total emissions saving from deployment of options in 2050.
- **CHP**: deployed to the two remaining refineries (100%) in 2020, accounts for 3% of the total emissions saving from deployment of options in 2050.
- **Lighting**: deployed in 25% increments to 100% in 2025, accounts for 2% of the total emissions saving from deployment of options in 2050.
- **Utilities optimisation**: deployed in 25% increments to 100% in 2020, accounts for 2% of the total emissions saving from deployment of options in 2050.

Figure 22 shows the absolute emission savings from the principal options along the pathway.

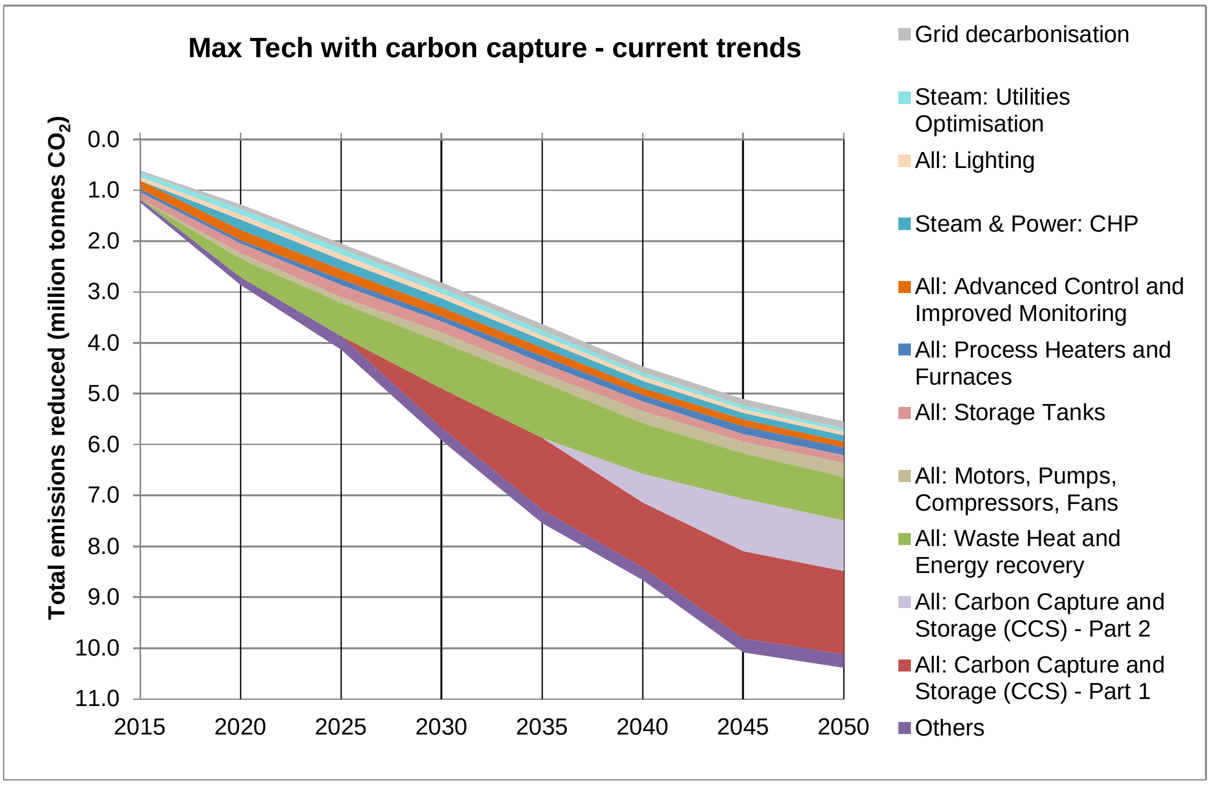

Figure 22: Contribution of principal options to the absolute emissions reduction throughout the study period for the Max Tech pathway, current trends scenario

For the current trends scenario, this pathway gives an overall reduction of 64% in 2050, compared to 2012. This includes the emission reductions primarily from the falling reference trend together with the deployment of options (direct emission savings onsite), and decarbonisation of the grid to only a small degree (< 1%).

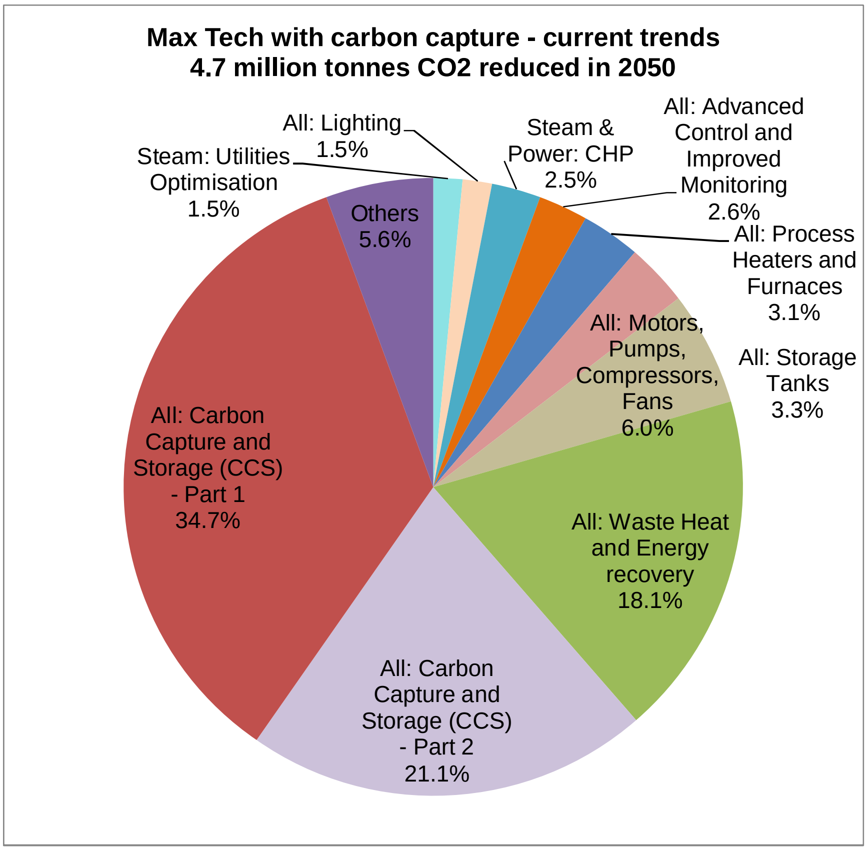

Figure 23: Breakdown of the 2050 emissions reduction for the Max Tech pathway under Current Trends

The CO_2 reduction contributions in 2050 revealed that the largest amount of decarbonisation in this pathway mainly come from Carbon Capture and Storage, in which the two relevant CCS options together contribute to 56% of the Max Tech reduction level in 2050. Waste heat and energy recovery retrofits also offer significant reduction.

Option Deployment for other Scenarios

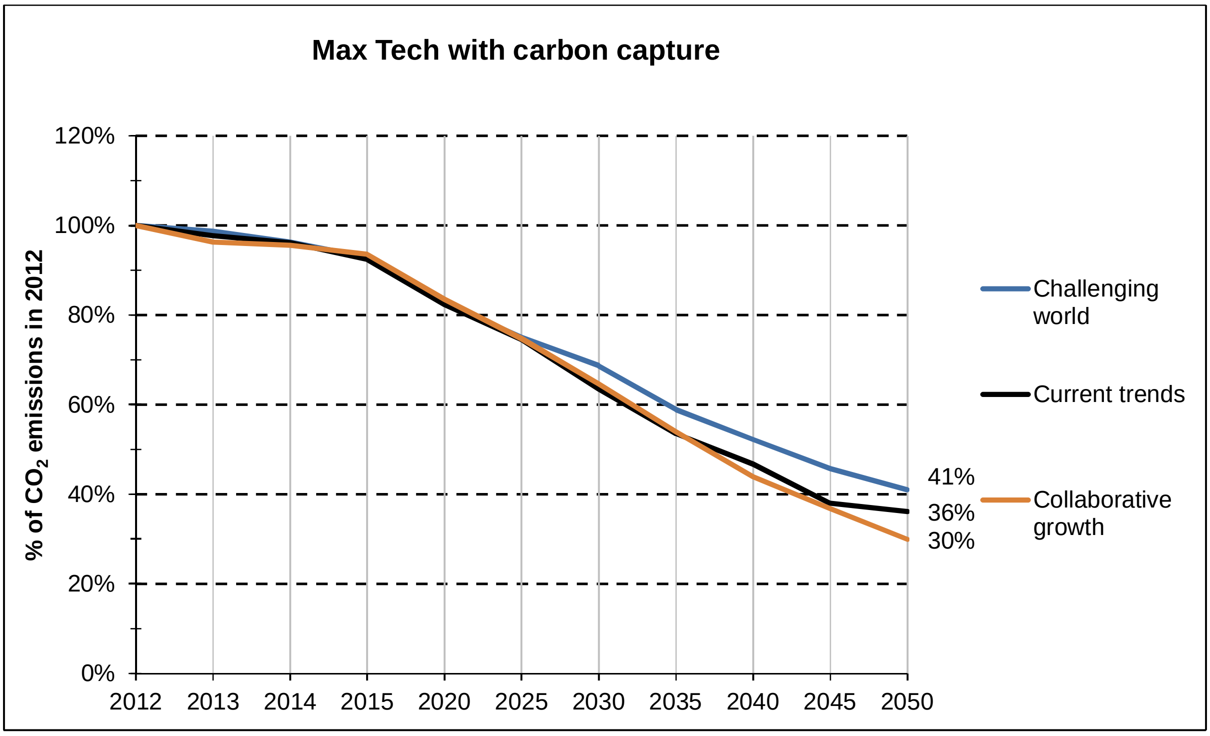

Figure 24: Max Tech pathways for the different scenarios

Figure 24 shows the Max Tech pathways for the different scenarios. As can be seen, the current trends scenario delivers a CO_2 reduction of 64%, the challenging world scenario delivers a CO_2 reduction of 59% and the collaborative growth scenario delivers 70%. The three pathway curves follow a similar trend, because the reference emissions (linked to sector outlook) decline in all three scenarios and also the option deployments are fairly consistent across all three scenarios.

For the challenging world scenario, all options introduced under current trends were also deployed at the same rate, except for CCS and biomass. This is because CCS technology and its wider commercialisation are assumed to develop more slowly under challenging world. CCS is introduced at a later point (2035) and only extended to 50% of refineries, and biomass still only makes a small impact delayed by five years.

In the collaborative growth scenario, the reference trend is assumed to decline at a faster rate for the refining sector compared to current trends – due to reducing demand for fossil fuels and petroleum products and associated constrained budgets in the sector. The deployment of all the options are therefore delayed by 5-10 years compared to current trends. The final deployment levels in 2050 are kept the same as in current trends, however, because it is assumed that the wider development and implementation of decarbonisation technology (including CCS) is improved.

The deployment of options for the challenging world and collaborative growth scenarios for this pathway is shown in appendix D.

4.5 Sensitivity analysis

Based on the Max Tech pathways analysis above, it is clear that the CCS option alone delivered most of the decarbonisation, yielding up to 17% more reduction compared to the shallower band pathway (40-60% CO_2 reduction pathway).

The options register also contains the option of building a new refinery to replace an old, less efficient plant. This option was not deployed in any of the pathways described above (BAU, 40-60% CO_2 reduction pathway, Max Tech) because a new refinery investment in the UK is not seen as reasonably foreseeable, as evidenced by the scenario outlooks for the sector.

To test the impact of CCS modelling results, whilst also assessing increased deployment of other best available technologies, two alternative (Max Tech) pathways were run with the following options inputs:

- New refinery option replacing 50% of old UK refinery plants from 2040, with no CCS deployed at all throughout the pathway, and all other options deployed at the maximum rate.
- New refinery option replacing 50% of old UK refinery plants from 2040, also with CCS integrated in the new technology. No CCS is applied (as retrofit) to other remaining plants. All other options are deployed at the maximum rate.

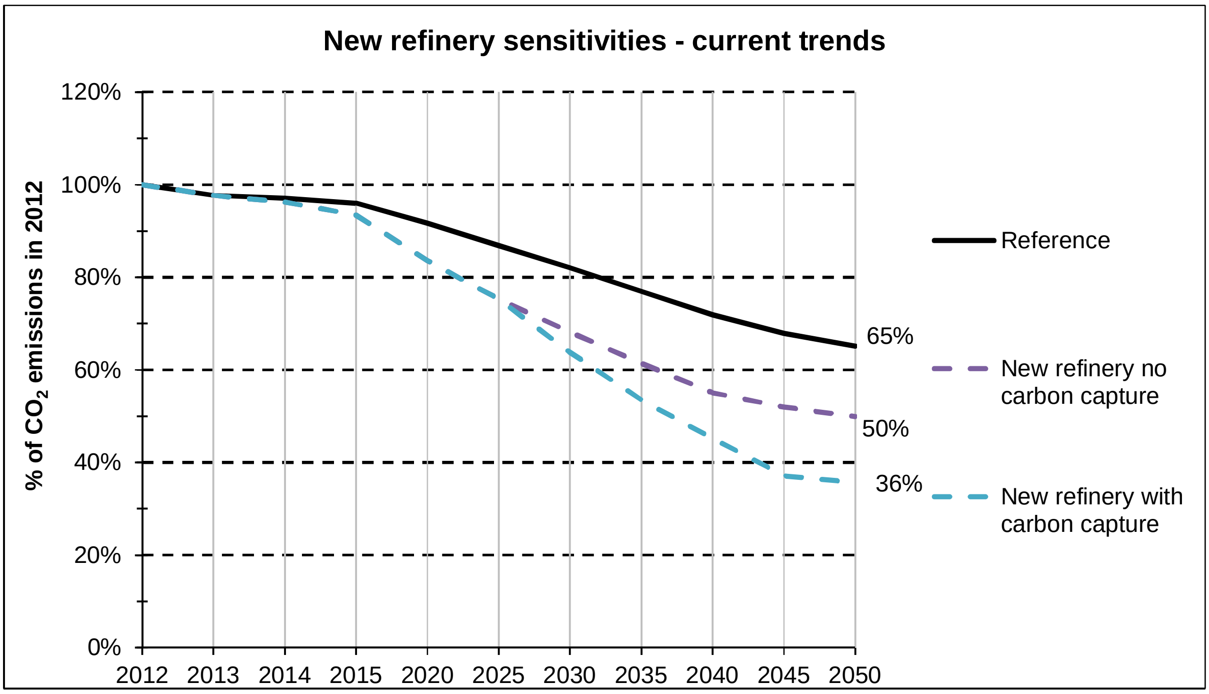

Figure 25: Alternative pathways for impact of new refinery (with and without CCS), under the current trends scenario

The pathway results are shown by the dashed lines in Figure 25 above and Figure 11 earlier, for the current trends scenario, and in appendix D for the other two scenarios. The new refinery pathway without CCS reaches 50% reduction, which is a 50% reduction on 2012 levels. This reduction is only ca. 3% better than the BAU pathway, both in current trends and the other two scenarios. The new refinery pathway with CCS follows the same trend as the Max Tech pathway, in all three scenarios, reaching the same end point at 64% reduction in 2050 (under current trends).

This demonstrates the significant impact of the CCS option in the model, and shows it is the only technology considered in the analysis to deliver the 'step change' in emissions. The results also show that the new refinery option can lead to further reduction if no CCS becomes available, but not by a significant margin.

A further sensitivity was modelled to test the impact of no biomass, due to lack of resource availability. The pathways were modelled with no deployment and savings contribution of the biomass option (syngas production through gasification of biomass, and its use as fuel gas in power or CHP plant). The Max Tech pathway resulted in the same final point (64% reduction) in 2050. This shows the negligible impact of biomass assumed in the pathways, because of (i) relatively low CO_2 reduction input for this option, since biomass is only assumed to substitute a small proportion of natural gas (and recycled-gases) combusted onsite in refineries; and (ii) it was only deployed to 25% by 2050, in the core Max Technical pathway.

4.6 Pathway Costs

4.6.1 Introduction

Estimates of the costs of new technologies or capital improvements with a time horizon to 2050 is fraught with difficulties. Any long-term forecasts should be treated with caution. The cost analysis presented in this report is intended to provide a high level estimate of the total capital cost of each pathway to the UK as a whole, in a form which is consistent with the government's approach to assessing the relative capital costs of alternative decarbonisation options from a social perspective (DECC, 2014). It is based on an analysis of 'order of magnitude' option capital costs. The purpose of developing and presenting this cost analysis is to provide an indication of the capital costs for the pathways, which could form a basis for further work.

In gathering capital cost-related data, literature and/or engagement with stakeholders were used to establish an initial dataset for use in the cost analysis assessment. Operating costs such as energy use changes, energy costs and labour are not included in this analysis, although we recognise that operating costs resulting from the decarbonisation pathways will have a major impact on any economic assessment. For example, some options (e.g. carbon capture and electrification of firing) greatly increase energy use and/or operating costs of a process plant.

4.6.2 Calculation of Pathway Costs

The pathway costs and carbon dioxide savings are measured with respect to the reference trend, i.e. they are calculated as the difference between costs and emissions under the decarbonisation pathway and those under the reference trend. This means the costs represent the additional capital costs for the pathway compared to a future in which there was no deployment of options. The pathway costs have been assembled from the estimated costs of the combination of decarbonisation and energy efficiency options, in accordance with each carbon reduction pathway including the selected deployment rates of each option. The methodology for calculating the total discounted capital costs which produce the CO_2 reductions for each pathway can be summarised as follows:

1. Capital costs of deployment for each decarbonisation and energy efficiency option are calculated based on the order of magnitude capital costs to deploy that option at one site (or installation or unit of equipment). This is then deployed to the applicable number of sites (or installations or units of equipment) for the (sub)sector in the pathway as defined by the model.
2. Capital costs reflect the additional cost of delivering the carbon dioxide and/or energy reduction options compared to continuing production without deploying the options. For a number of major investment options, including replacement of life-expired assets with BAT (for a list of options in this category see appendix C), only a proportion of the cost is assumed to be attributed to carbon dioxide emission or energy reduction, as a significant factor for the investment in this case would be to replace retiring production capacity and to recognise that options may be implemented for reasons other than decarbonisation or energy efficiency. In the absence of detailed information this proportion (attributed to the capital cost calculation in this analysis) is assumed to be 50%. For all other technology options the entire capital cost (i.e. 100%) is attributed to energy or carbon reduction. Capital costs are applied at the year of each deployment step (as modelled in the carbon reduction pathways), and adjusted in cases where the asset life defined in the option register would extend beyond 2050 to reflect their residual value on a linear depreciation basis.
3. The annual capital expenditure of each pathway is calculated from the capital cost and deployment of each of the options selected. Capital costs are presented in present day value (i.e. 2015) and

assumed to remain constant throughout the period. The discount rate for costs has been chosen to be 3.5% to value the costs from a social perspective and in accordance with standard HM Treasury methodology for this type of assessment. In other words, all proposed capital expenditure on the various pathways are adjusted for the time value of money, so costs (which occur at different points in time) are expressed on a common basis in terms of their 'net present value' using the discount rate of 3.5%. The effect of this standard methodology is to reduce the apparent cost of large investments that are deployed in the pathways later in the study period.

The following specific assumptions apply:

i. Asset replacement is assumed to take place at the end of life of an existing asset. No allowance has been made for loss of production during the shutdown period associated with the implementation of major or disruptive technology options. Similarly no allowance has been made for loss of EU ETS allowances or civil works associated with a major shutdowns and plant rebuilds. Although costs may be incurred in a case where a plant is written off before the end of its life, this has not been taken into account in this analysis.
ii. It has been assumed that minor incremental improvements would be implemented in the shadow of other rebuild or maintenance work so that no additional costs for shutdown would be incurred.
iii. No allowance has been made for the costs of innovation and it is assumed that the costs of development of breakthrough technologies would be funded separately and not be charged to subsequent capital investments. Technology licensing costs are assumed to be included in the capital costs.
iv. No carbon price or other policy costs are included in the calculations.
v. Changes in other operating costs including labour, maintenance or consumables associated with the deployment of options have not been included (although it is noted these will be significant for many options).
vi. For carbon capture and storage technologies, gas clean up and compression costs have not been fully accounted for, and transport and storage have not been included in the cost analysis.
vii. This analysis covers capital costs for carbon reduction: changes to energy use and energy costs (as a result of deployment of the options) has not been quantitatively included although it will be significant for many options.

4.6.3 Limitations

The project methodology for cost data collection and validation did not deliver a complete dataset for the capital cost of options, and where data was available, it was qualified at low confidence levels. Further, estimates based on expert judgement have been made where data gaps remained. Also, the degree of stakeholder engagement in relation to this cost analysis was lower than for the carbon reduction pathways.

All costs in the data input tables are subject to wide variation, for example between sites and sub-sectors and for technology options that have not been demonstrated at commercial scale. Hence, the cost data represent 'order of magnitude' estimates that require extensive further development and validation prior to any further use, including with sector stakeholders.

Moreover, the assumptions and constraints on confidence levels limit the valid uses for the results of this cost analysis, therefore the following applies to use of this analysis:

- The values are a starting point to help assess relative benefits of different technologies over the long term.
- The cost analysis results should not be used in isolation to compare decarbonisation technologies or decide on priorities for their development: additional techno-economic analysis should be carried out on individual options or groups of options.

- The cost analysis is part of a process of research and exploration and is being shared in a transparent way to support the development of broader strategy. The results are effectively provisional order of magnitude estimates which need to be developed further on the basis of thorough research before they can be used to inform decisions.

4.6.4 Cost Analysis Results

The results of the cost analysis of decarbonisation for the various pathways within the current trends scenario are summarised in Table 9 below.

Results can be used for relative comparison between pathways in a sector. No cost moderation process between the eight sectors has been carried out and therefore in the absence of further data validation and analysis comparison between sectors is not recommended.

The carbon dioxide emission abatement offered by each pathway has been totalled for each year to present a **cumulative** carbon abatement figure for the period from 2013-2050 compared to the reference pathway.

Although this analysis of discounted capital cost does not include energy costs, it should be noted that energy cost changes will be subject to the uncertainties of future energy cost projections and the significant divergence between energy costs applicable to the different levels of energy consumption. A high-level qualitative assessment of the impact of energy use and cost is presented in the table below.

Pathway	Total Discounted Capital Cost 2014-2050 (million £)[16]	Cumulative CO_2 Abated 2014-2050 (million tonnes CO_2)[17]	Projected Impact on Fuel or Energy use and Fuel or Energy cost
BAU	200	45	This pathway includes deployment of options that increase overall energy efficiency. In the study period 2014-2050, this pathway would result in a reduction in energy used. The projected value of this saving will depend on the energy cost forecasts adopted.
40-60%	300	53	This pathway includes deployment of options that increase overall energy efficiency. A saving in fuel costs is projected, the scale of which would depend on the fuel cost forecast adopted.
Max Tech	500	102	The carbon reduction in this pathway is dominated by carbon capture coupled with efficiency improvements. The carbon capture would increase energy use and cost. The scale of the increased cost would depend on the fuel cost forecast adopted.

Table 9: Summary costs and impacts of decarbonisation for the pathways

[16] Model output rounded to 1 significant figure to reflect 'order of magnitude' input data
[17] Model output rounded to nearest million tonnes of CO_2

4.7 Implications of Barriers and Enablers

From the pathways described above, there are a number of options that will need to make significant contributions to decarbonisation under some or all of the pathways and scenarios. These are:

- Carbon Capture and Storage
- New Refinery
- Waste Heat and Energy Recovery
- Motors, Pumps, Compressors. and Fans
- Process Heaters and Furnaces
- Storage Tanks
- CHP
- Utilities Optimisation
- Biomass

From the evidence gathered during the project (from literature, industry sources and workshop as described in section 3) there are a number of barriers and enablers associated with these options. These are summarised below.

4.7.1 Carbon Capture

This option relates to the use of CCS, for the collection of flue gas from CHP plants, hydrogen production plants and FCC flue gases, the three largest producers of CO_2 on a refinery. This option brings the largest emissions reduction assuming that the technology can be scaled up and there is appropriate infrastructure available for the storage of the CO_2.

CCS has a number of barriers identified by the literature, workshop, and industry sources. The key barriers linked to CCS include: perceived increased operational complexity and risks, applications not proven at scale, lack of availability of space, plant integration risks (hidden costs of additional downtime, alternative product supplies, technology lock-in etc.), high levels of uncertainty regarding costs; health, safety and environmental considerations, staff familiarity and expertise, effects on product quality, challenge of capturing emissions in sites which have multiple, heterogeneous small CO_2 streams, a lack of commercial incentives to implement CCS (which has significant up-front and ongoing variable costs), lack of CO_2 transport and storage infrastructure, limited experience of operational full chain CCS projects with industrial sources, and scale and significant investment is required and remains a potential barrier to widespread deployment of CCS.

Multi-stakeholder collaboration on CCS was seen as a potential way of overcoming the high capex costs, by sharing the costs across multiple stakeholders. Moreover, potential change in regulations and planning permissions and integration of refineries with other industries or ‘clustering’ was discussed as other enablers. Clustering around sites near the North Sea was considered a possible opportunity for further research, as it is geographically viable for CCS.

This option would be linked to the enablers and barriers below; the likelihood is that it would require considerable capital investment.

The option impacts all scenarios for Max Tech.

Enablers	Multi-stakeholder collaboration on a CCS pilot site. Regulations and planning permissions Clustering

Barriers	Uncertainty about return on capital Sources of financing Regulatory uncertainty Operational complexity

4.7.2 New Refinery

This option is to replace a number of the older UK refineries with a fewer number of larger and more energy efficient refineries, strategically located to maintain supply of transport fuels to the inland market.

The option is considered highly improbable due to excessive cost of building and the complexity of funding a significant project in the UK due to overcapacity; this would represent one of the largest barriers. This option would be linked to the barriers below.

Refinery replacement would allow the best technology to be adopted and improve efficiency in one step change.

This option only impacts the Max Tech (sensitivity) pathway.

Barriers	Uncertainty about return on capital Sources of financing and investment Regulatory uncertainty Unfavourable market conditions Competition rules

4.7.3 Waste Heat and Energy Recovery

This is a group of options to improve the performance of existing refinery equipment by increasing heat integration and waste heat recovery. This improvement comes from using best available technology for recovery. They have been grouped together for the purposes of this section as they have similar barriers and enablers.

This is an investment that can be spread out over time and is likely to fall into the category that will require funding from company headquarters.

This option would be linked to the enablers and barriers below. This option would impact all pathways.

Barriers	Uncertainty about return on capital Regulatory uncertainty Operational complexity Unfavourable market conditions People to apply the technology

4.7.4 Pumps, Compressors and Fans

This is a group of options to improve the performance of existing refinery equipment by replacing older less efficient equipment with more efficient designs and different technologies. They have been grouped together for the purposes of this section as they have similar barriers and enablers.

This is an investment that can be spread out over time; it is likely to fall into the category of small incremental investments that could be funded locally and a mixture of large investments that require funding from headquarters. Even lower investment costs are sensitive to profit margins and business case for ROI. Some of these options may require organisational changes and technical changes and would require awareness and skills to be properly implemented.

This option would be linked to the enablers and barriers below.

This option impacts all pathways.

Enablers	Small incremental investments as applicable
Barriers	Uncertainty about return on capital Unfavourable market conditions People to apply the technology

4.7.5 Process Heaters and Furnaces

This is a group of options to improve the performance of existing refinery equipment by replacing older less efficient equipment with more efficient designs and different technologies for monitoring and control. They have been grouped together for the purposes of this section as they have similar barriers and enablers.

This is an investment that can be spread out over time; it is likely to fall into the category of small incremental investments that the refinery might be able to manage itself without having to request the funding from headquarters (an enabler for this option). Even lower investment costs are sensitive to profit margins and business case for ROI. Some of these options may require organisational changes and technical changes and would require awareness and skills to be properly implemented.

This option would be linked to the enablers and barriers below. This option impacts all pathways.

Enablers	Small incremental investments as applicable
Barriers	Uncertainty about return on capital Unfavourable market conditions People to apply the technology

4.7.6 Storage Tanks

This is a group of options to improve the efficiency of heavy oil storage heating by replacing older, less efficient equipment with more efficient designs and upgrading lagging and heating systems. They have been grouped together for the purposes of this section as they have similar barriers and enablers.

This is an investment that can be spread out over time; it is likely to fall into the category of small incremental investments that the refinery might be able to manage itself without having to request the funding from headquarters (an enabler for this option). Even lower investment costs are sensitive to profit margins and business case for ROI. Some of these options may require organisational changes and technical changes and would require awareness and skills to be properly implemented. There is also a move from this kind of technology in general.

This option would be linked to the enablers and barriers below.

This option impacts all pathways.

Enablers	Small incremental investments that can be potentially be signed off at a local level
Barriers	Uncertainty about return on capital Unfavourable market conditions People to apply the technology High costs and refineries looking to move away from oil storage tanks

4.7.7 Combined Heat and Power

This is a single investment option to replace older steam raising equipment and electrical producing equipment with current State-of-the-Art Technology. This is considered a high investment option and has been historically completed by third parties.

There is potential to use more CHP in the refining sector but some challenges have been reported by the industry; in particular, the sensitivity of CHP to fuel and power pricing will continue to be an influential factor in determining cogeneration viability. Some in industry have reported that they find the permitting system complex and time-consuming, and interconnection arrangements with utilities can also be a barrier. In addition, they feel that depreciation schedules do not reflect the true life of CHP assets and therefore make investments more difficult).

This option would be linked to the enablers and barriers below.

This option would have an impact on all pathways.

Enablers	Regulatory certainty
Barriers	Uncertainty about return on capital Fuel and power pricing Sources of financing and investment Regulatory uncertainty- early removal of the support mechanism for UK CHP investment Unfavourable market conditions

4.7.8 Utilities Optimisation

This is a group of options that require only low or medium capital investment. These are largely the current State-of-the-Art Technologies such as energy management, focus on maintenance, leak detection etc. They have been grouped together for the purposes of this section as they have similar barriers and enablers. Small incremental investment was identified as an enabler as the refinery typically has access to lower amounts of capital that it can control itself.

Even lower investment costs are sensitive to profit margins and business case for ROI. Some of these options may require organisational changes and technical changes and would require awareness and skills to be properly implemented.

This option would be linked to the enablers and barriers below.

These options would have an impact on all pathways.

Enablers	Small incremental investments that can potentially be signed off at a local level
Barriers	Uncertainty about return on capital Sources of financing and investment Lack of skilled labour

4.7.9 Others

Figure 23 above focus on the options that provide the most significant decarbonisation potential. From the evidence gathered as part of this roadmap, other options share many of the same enablers and barriers such as:

- Unfavourable market conditions
- Regulation and policy

- Investment and finance
- People and organisation
- Long-term stability in carbon pricing is needed in order to make major investments.

5. CONCLUSIONS - PRINCIPAL QUESTION 6

This section provides assessment of the questions under Principal Question 6: 'What future actions might be required to be taken by industry, government and others to overcome the barriers in order to achieve the pathways in each sector?'

This section is structured as follows:

- Six 'strategic conclusions' or themes have been developed by analysing the main enablers and barriers. Example next steps/potential actions are also included for each strategic conclusion.
- Four key technology groups are discussed, many of which link to the themes above. As described in section 4, a small group of technologies make a significant contribution to decarbonisation in 2050, especially for the 40-60% CO_2 reduction pathway and Max Tech pathway[18]. Example next steps are included to assist with developing, funding and implementing the technologies.

It is intended that government and industry use the roadmap to develop the example actions further in order to achieve decarbonisation while maintaining competitiveness of the sector.

5.1 Key Points

During the development of potential pathways to decarbonisation, the barriers to their implementation and enablers to promote them were summarised in section 4.7. Having cross-referenced the enablers and barriers through three different research methods, we have summarised the key points in key themes (strategic conclusions) and key technology groups.

Strategic Conclusions

Strategy, Leadership and Organisation
Leadership is important at company, sector, regional and UK government level. It links to all of the themes below. Leadership is required to drive programmes forward and involves developing solutions in response to evidence and analysis.

Business Case Barriers
The RD&D, demonstration and commercial deployment of major technologies requires significant upfront capital, which is often not available internally due to competition with UK and overseas projects with higher business priority. The long investment cycles in the industry combined with ageing UK plants and the cost of operating in the UK makes it harder for UK sites to compete for limited investment funds. In addition oil refining is low margin which reduces the ability to invest. External funding is often not available on terms that meet internal investment criteria.

Future Energy Costs, Energy Supply Security, Market Structure and Competition
The sector is characterised by high competition levels limiting the sector's collaboration on energy efficiency. Three refineries have closed between 2009 and 2014 and a number of refineries have reduced crude throughput by mothballing distillation capacity due to reducing margins and demand reductions in the sector.

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[18] These four technology groups apply to the oil refining sector and also the other seven sector roadmaps.

Energy efficiency projects are viewed as a competitive advantage and thus refiners do not share best practice information.

Industrial Energy Policy Context

Regulatory compliance is a driver of energy efficiency investments. However, oil refiners are unclear how they will survive past the medium-term regulatory compliance requirements already set out by government for improving environmental performance.

Research, Development & Demonstration

The development and demonstration of the new technologies required to deliver decarbonisation is difficult to achieve with current approaches in the sector. This includes early RD&D activity but also, crucially, progressing technology to successful commercial demonstration so that it is de-risked for future deployment. Technologies should be selected through a collaborative process. Companies may not have the time and expertise to identify if and how different options may be of benefit to them and so may not progress the RD&D activity needed (links to people and skills below).

People and Skills

New staff resources with specialised skills and knowledge in energy and heat engineering are increasingly needed by the UK oil refining sector. Currently, key responsibilities of energy teams include ensuring compliance with existing regulation which diverts attention and effort from identification and implementation of energy efficiency activities.

Key technology groups

Fuel and Feedstock Availability (including biomass)

Biomass may make a small contribution to reducing emissions in the oil refining sector, substituting for natural gas. The availability of low carbon fuels is a potential issue for sector decarbonisation. This availability issue can be between uses within the sector (biomass as a fuel) and/or with other external uses (e.g. the use of waste plastics for electricity generation). The challenges are to understand where the greatest decarbonisation potential can be achieved with a limited resource, as well as to maximise the availability of the resource. There is significant added value to use biomass for heat and power (via CHP technology) compared to power generation only, and this is recognised in government electricity market support policy.

Energy Efficiency and Heat Recovery Technology

Energy efficiency and heat recovery technologies are generally well-established, of low technical risk and can provide operational cost savings as well as reducing emissions. There is a need to improve the availability of human and financial resources to allow the potential of this option to be fully realised.

Clustering

Improving site or sector integration could enable use of CO_2 and recovered heat from oil refineries. Clustering also allows infrastructure investment to benefit from economies of scale in serving multiple sites, as well as spreading investment risk. It is recognised that relocating an oil refinery is highly unlikely due to the scale of operations and size of sites, but clustering of other industries around refining sites could still represent an opportunity to reduce emissions. Stronger encouragement for increased clustering could mitigate barriers.

Carbon Capture

Refineries could be considered a sufficient scale to justify their own CO_2 pipeline and storage infrastructure however collaboration with external sectors would support the establishment of the networks, along with the availability of sources of funding appropriate to this type of shared infrastructure. There is also a need to demonstrate the technology (links to *Research, development and demonstration*)[19].

5.2 Strategic Conclusions

5.2.1 Strategy, Leadership and Organisation

In order to take this agenda forward, it is considered important that the oil refining sector, the government, and other stakeholders **recognise the strategic and long-term importance of the oil refining sector to the UK and its decarbonisation.** This could help guide the range of actions that are needed to improve the climate for investment in refineries generally, including decarbonisation and energy efficiency projects in the UK oil refining sector. This could also help to deliver improvements needed in competitiveness, transparency and stability of regulation.

This links to other conclusions below, including research, development, demonstration, technology deployment, energy supply and financing.

A possible action to address this issue is to utilise a government-industry working group with responsibility for the oil refining sector strategic priorities. This group could bring:

- Leadership and vision to the UK sector, emphasising how oil refining production adds strategic value for the UK and why it is important to face the challenges and develop the opportunities for the sector. This vision could encompass the ambition, drive, passion and creativity required to maximise future opportunities for the sector and in doing so help to continue to spread a positive message and image.
- An approach to the need to drive forward the joint priorities of maintaining competitiveness of the existing oil refineries in the UK and also the need to increase collaboration and research and development activity and support technology and product innovation in the sector
- A high-level link between industry, the government and the EU and a clear framework within which production, technology, energy efficiency and decarbonisation agendas can be taken forward. Members of the working group could engage with executives in corporate headquarters and at UK refinery level to address the lack of collaborative innovation on decarbonisation.
- A means to take forward the roadmap agenda with shorter-term action plans, for example, in five-year intervals.

5.2.2 Business Case Barriers

High and increasing energy cost can be both a barrier and enabler for decarbonisation and energy efficiency projects. High energy prices can drive oil refiners to further focus their efforts on asset integrity and process controls and improve the payback for energy efficiency projects. However, at a certain threshold, increasing

[19] The Global CCS Institute database (http://www.globalccsinstitute.com/projects/status-ccs-project-database) lists current and proposed CCS demonstration projects.

energy prices can act as a barrier to decarbonising (without refinery closures) by further impacting on refiners margins and thereby reducing the amount of funds available to invest in energy efficiency projects. Government and industry will need to work together to deal with the impacts of energy price drivers (especially those factors that are in national government control). High energy prices increase the risk of carbon and investment leakage, especially for multi-national refiners whose headquarters may choose to invest in refineries elsewhere, where the margins are better.

Advanced technologies have long paybacks, whereas decision makers in oil refineries require shorter payback periods as low as six months in order to invest.. Alternative financing to overcome barriers including lack of capital linked to low margins can improve profit margins and therefore potentially give refineries more breathing room for taking on an energy efficiency project with a longer payback. Alternative financing, such as low cost loans, or third parties taking on the upfront financial risk can also help mitigate this barrier.

Energy efficiency and decarbonisation projects are in internal competition for capital with other investment projects that are more closely related to increasing production and meeting regulatory compliance. As oil refiners fund their own investment projects, they have limited funds to allocate across a number of projects. Projects with short paybacks or better returns will always be implemented over more energy efficient projects whose paybacks are longer. In multi-national companies, UK refineries are competing against others in other countries which may have lower energy costs and better paybacks. Alternative financing and providing a level playing field can support in overcoming this barrier.

Access to a range of alternative financing could help mitigate this barrier for example oil refineries bundling together several high impact energy efficiency projects and requesting loan guarantees from government or other investors to reduce financial risk and uncertainty. Targeted use of enhanced capital allowances, which would allow companies to write off the cost of investments for specific energy efficiency projects from their taxes is another possible action that can be taken to help improve refinery finances as the cost of upcoming regulations is seen as a key challenge for refineries.

Another possible action is **alternative financing mechanisms**. This is important to implement in order to overcome the barriers of competitive marketplace with zero profit margins, declining sector, and global competition for funding from Group headquarters for multi-national companies. These mechanisms will also help to overcome the barriers and enablers of a payback time of one year or less, along with potential rising and uncompetitive UK energy prices. Future Energy Costs, Energy Supply Security, Market Structure and Competition

Three refineries have closed between 2009 and 2014 and a number of refineries are reducing crude throughput by mothballing distillation capacity due to reducing margins in the sector. The remaining refineries have a good coverage of the UK but their product balance does not match the UK demand, as they produce too much gasoline and not enough diesel. Imports from outside the UK make up the difference of diesel and gasoline is exported. Imports of diesel does not encourage upgrades to refineries to produce more diesel as there is already enough on the open market and therefore the refineries continue to run an imbalanced product slate.

The sector is characterised by high competition levels limiting the sector's collaboration on energy efficiency. Energy efficiency projects are viewed as a competitive advantage and thus refiners do not share best practice information or share the types of energy efficiency technologies they have invested in. There is also the perception competition prevents refiners from collaborating on energy efficiency projects.

The oil refining sector has strong intra-EU competition and moderately high exposure to non-EU firms. This alongside demand destruction, unfavourable market conditions, a structural change in the products demanded, and high and increasing energy costs are leading to a declining UK oil refining sector operating at minimal margins.

5.2.3 Industrial Energy Policy Context

Regulatory compliance is a driver of energy efficiency investments. However, oil refiners are unclear how they will survive past the medium-term regulatory compliance requirements already set out by government for improving environmental performance.

A possible action to address this issue is the need for **government to strike a balance and engage with industry to understand the balance between regulatory compliance as a driver and as a barrier**.

Implementation of a level playing field with competing regions (both in terms of relevant policies and overall cumulative regulatory burden) would improve UK oil refineries' competitive position, enabling them to attract more investment, reduce energy costs, and enable them to use positive margins to invest in energy efficiency projects. Government, refineries and other industries should engage on the best mechanism for establishing a level playing field, what that may look like, and how it can be achieved.

A possible action to address this issue is **a global agreement on carbon costs to level the playing field**. This is primarily needed to overcome the *barrier of carbon leakage* as the UK's oil refineries competing against other refineries in countries where a carbon tax or price may not be included in the costs. This may also *reduce energy costs* in the UK, as these are currently perceived to be higher than in other parts of the EU, the USA, and elsewhere. This in turn would help increase the UK oil refineries competitive advantage, as energy costs (oil refinery fuel) is approximately 50% of the operational cost of a refinery. Other barriers - *competitive marketplace with lowering profit margins* and *global competition for funding from Group headquarters* to a lesser extent - are also affected by this action.

There is a major investment challenge to meet regulatory compliance in the medium term. This may tie-up capital that could be invested in disruptive technologies and in some cases may lead to further refineries closing. Government and industry may consider capital allowance schemes or other mechanisms for striking a balance between driving environmental performance and driving decarbonisation. Although one source indicated that if refiners are not profitable, they will not be paying any taxes anyway and thus a capital allowance scheme will only work if refineries are profitable.

A possible action to address this issue is a **consistent and balanced regulatory environment**. This is important in overcoming the barrier of *global competition for funding from Group headquarters for multi-national* companies, as well as *competitive marketplace with narrow profit margins* to a lesser extent. The Government has already engaged with the European Union to improve regulation. It also would help to reduce the investment challenge currently faced by refiners in meeting their regulatory obligations, potentially freeing up investment for energy efficiency projects. It is important to strike the balance between regulatory compliance as a barrier and regulatory compliance as a driver for refineries to invest in energy efficiency projects.

5.2.4 Research, Development & Demonstration

Some of the key options identified in the pathway analysis require development of new technologies and processes. Oil refineries have also reduced or removed completely their research and development funds available for developing new technologies and pilot projects. The interviews and workshops have identified that progressing the necessary RD&D into decarbonisation technologies is an important enabler. There is also a need to support funding of these activities (links to the policy and finance themes).

The most significant step change to decarbonisation of refineries is the RD&D associated with carbon capture and storage at a refinery. The focus would be on the techniques needed to be developed for the collection and cleaning of the streams from the three main sources; FCC stack, CHP stack and hydrogen plant.

5.2.5 People and Skills

From the interviews and site visits, an ageing workforce and shortage of engineers were identified as barriers to decarbonisation and to the future of the oil refining sector in the UK, as running a refinery requires highly educated engineers who can tackle new challenges including implementing advanced energy efficiency technologies. Government and industry support for developing a pipeline of new engineers through support of science, maths and engineering skills and providing graduate programmes or temporary work placements to provide new engineers with opportunities to obtain work experience could support in building up the next generation of oil refining engineers.

Some other examples of actions to overcome this barrier include:

- Investment in training and recruitment by industry to make the necessary skills available
- Government could consider support for skills development at a national level. The Science Industry Partnership could play a role here.

The other actions discussed above aimed at making decarbonisation investment more attractive would also tend to encourage the deployment and recruitment of the necessary staff.

As noted a number of times in this section, there are numerous links between the actions suggested above and it would be necessary to progress a number of the actions in combination in order for their benefits to be achieved. This reflects the interactions between long-term policy, putting a value on decarbonisation and subsequent investment.

5.3 Key Technology Groups

5.3.1 Electricity Grid decarbonisation

The scenarios include three different electricity grid decarbonisation trends as supplied by DECC. However, as the sector does not import much electricity, this technology does not have a big impact on the pathway analysis. There was no scope identified during the project for the oil refining sector to electrify its heat use, largely because a high proportion of fuel use in the sector is refinery fuels which are uneconomic to substitute.

5.3.2 Fuel and Feedstock Availability (including biomass)

The Max Tech pathway includes deployment of gasified biomass (syngas) fuel to substitute for natural gas use to a moderate extent, making a small contribution to reducing emissions in this sector. Understanding how much low-carbon fuel could be available to the sector is an important first step in delivering an option that includes such a fuel. At present, there is a lack of clarity on the long-term supply of resources such as biomass and the degree to which it can be considered low carbon. It will also be necessary to understand, both within the refining sector, other industries and across the wider economy, where these fuels and feedstock can be used to achieve the greatest decarbonisation impact.

To achieve the sensitivities presented here, significant quantities of low-carbon biomass are likely to be required and the supply of this resource will need to be maximised.

Example actions include:

- Government could consider further developing incentives to maximise sustainable supplies of low-carbon fuels to the UK as a whole.

- Industry and academia could collaborate to examine different uses of low-carbon fuels within the sector and prioritise those with greatest decarbonisation impact. This should happen in the near future (2015) to allow future focus on the options with greatest potential.
- Examine different uses of low-carbon fuels and feedstock across the economy and prioritise use of these resources in areas with greatest decarbonisation impact. A coordinated national plan for the use of biomass, including waste biomass, could be a useful output from this. Given the cross-sector nature of this action, this may be best led by government.
- Consider how supply can be de-risked and long-term security established in order to support future investment decisions (2015-2020). This might be best achieved by industry and government working together to understand the risks and how they can be mitigated.

5.3.3 Energy Efficiency and Heat Recovery

Oil refineries are energy intensive, thus there is an opportunity to improve energy efficiency through improved energy monitoring and process control systems and having greater focus on asset integrity. Interviews indicated that oil refiners focus the majority of their efforts on increasing production and throughput as this has greater returns than a focus on energy efficiency. More can be done by refineries to improve asset integrity, energy monitoring, measurement and reductions as emphasised by the results of the latest SA EII® refinery benchmarking identified that the majority of UK refineries lag behind their European counterparts in regards to energy efficiency.

Refinery fuel is approximately 50% of refining cash costs which drives efficient use of energy in refining, but energy efficiency projects are not singled out as individual projects as other investments take priority such as enhancing yield or improving product quality. However, there is still an opportunity for oil refiners to reduce their energy use and thereby their energy costs. Examples of these opportunities include:

- **Waste and Energy Recovery** – installing projects where energy that would normally be lost to air could be recovered and used an energy source for on and off-site sources.
- **Pumps, Compressor and Fans** – the majority of refinery equipment is 20+ years old and can be considered energy inefficient, the replacement of these would make efficiency improvements to the refinery either as the items fails or on a more proactive approach dependant on funding.
- **Process Heater and Furnaces** – upgrades in how fired equipment operates, through air preheat and oxygen control would minimise the waste of energy on a refinery.
- **Storage Tanks** – heated tanks on a refinery are normally in a poor condition through improvements in control and insulations, energy wastage can be reduced.
- **CHP** – with the introduction of CHP energy efficiency can be made by combining steam raising and electrical production.
- **Utilities Optimisation** – upgrading and maintaining steam networks and other utility system would make energy efficiencies through the reducing of energy losses at a refinery.

5.3.4 Clustering

Clustering can reduce emissions by optimising the use of resources, e.g. waste heat or by-products from a refinery used by an industrial neighbour nearby. By making use of these resources (which would otherwise be wasted), the industrial neighbour avoids having to generate its own energy, thus avoiding the emissions associated with doing so. In addition, the refinery avoids generating wastes which may result in further emissions. Clustering typically involves a degree of co-location in order to make energy and/or resource sharing practical.

5.3.5 Carbon Capture

The scale and significant investment that is required remains a potential barrier to widespread deployment of CCS in the UK. A strategic approach to investing in a CCS pilot plant at refineries clustered near other industries and in a geographically viable location such as the North Sea is required. A multi-stakeholder and -investor approach is needed in order to overcome the significant investment required.

CCS has a number of barriers including operational complexity and risks, lack of demonstration at scale, high level of uncertainty, costs, hidden costs, lack of infrastructure and storage. Oil refineries have also reduced or removed completely their research and development funds available for developing new technologies and pilot projects. If refineries return to being profitable, a re-establishment of research and development funds could support CCS and other new technologies.

A possible action to address these issues is to **develop a multi-stakeholder CCS project.** This is important for overcoming the variety of barriers that are associated with CCS including the large-scale costs involved, demonstrating that CCS can be proven at scale, providing further information through actually implementing CCS on its operational complexity and risks, uncertainty and hidden costs, and working out the type of infrastructure and storage that are needed to make CCS work. This project would require significant investment from government and from refineries, and could potentially be best placed in refineries that are clustered near the North Sea.

5.4 Closing Statement

This roadmap report is intended to provide an evidence-based foundation upon which future policy and actions can be built. The way in which the report has been compiled is designed to ensure it has credibility with industrial, academic and other stakeholders and is recognised by government as a useful contribution when considering future policy. It will be successful if, as a result, the government and the industrial sector are able to build on the report to deliver significant cuts in carbon emissions, increased energy efficiency and a strong competitive position of the UK oil refining industry in the decades to come.

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7. GLOSSARY

Adoption

The percentage of sector production capacity to which a carbon reduction option has already been applied. Therefore, of the list of options being assessed, this is a measure of the degree to which they have already been deployed in the sector.

Applicability

The percentage of the sector production capacity to which a particular option can be applied. This is a measure of the degree to which a carbon reduction option can be applied to a particular part of the sector production process.

Barrier to Decarbonisation or Energy Efficiency

Barriers are factors that hinder companies from investing in and implementing technologies and initiatives that contribute to decarbonisation

Business as Usual

A combination of carbon abatement options and savings that would be expected with the continuation of current rates of deployment of incremental improvement options in the sector up to 2050 without significant intervention or outside support.

Decarbonisation

Reduction of CO_2 emissions (in $MtCO_2$) – relative to the reference trend for that scenario. When we report carbon dioxide – this represents CO_2 equivalent. However, other GHGs were not the focus of the study which centred on both decarbonisation and improving energy efficiency in processes, combustion and indirect emissions from electricity used on site but generated off site. Also, technical options assessed in this work result primarily in CO2 emissions reduction and improved energy efficiency. In general, emissions of other GHGs, relative to those of CO2, are very low.

Carbon reduction band or bins

The percentage ranges of CO_2 reduction achieved for a given pathway in 2050 relative to the base year e.g. 20-40% of the base year emission.

Carbon reduction curve or profile

A quantitative graph which charts the evolution of sector carbon emissions from 2014 to 2050

Competition Law

The UK has three main tasks:

- Prohibiting agreements or practices that restrict free trading and competition between business entities. This includes in particular the repression of cartels.
- Banning abusive behaviour by a firm dominating a market, or anti-competitive practices that tend to lead to such a dominant position. Practices controlled in this way may include predatory pricing, tying, price gouging, refusal to deal and many others.

- Supervising the mergers and acquisitions of large corporations, including some joint ventures. Transactions that are considered to threaten the competitive process can be prohibited altogether, or approved subject to "remedies" such as an obligation to divest part of the merged business or to offer licences or access to facilities to enable other businesses to continue competing.

Deployment

Once the adoption and applicability of an option has been taken into account, each option can be deployed to reduce part of the sector's CO_2 emissions. Hence, the deployment of the option from 2015 through to 2050 is illustrated in our analysis by the coloured matrix on the pathway presentations.

Enabler for decarbonisation or energy efficiency

Enablers are factors that that make an investment feasible or would either help mitigate a barrier.

Grid CO_2 emission factor

A specific scenario assumption relating to the average carbon intensity of grid electricity and projection(s) of how this may evolve to 2050

Maximum Technical Pathway ('Max Tech')

A combination of carbon abatement options and savings that is both highly ambitious but also reasonably foreseeable. It is designed to investigate what might be technically possible when other barriers are set to one side. Options selected in Max Tech take into account barriers to deployment but are not excluded based on these grounds. Where there is a choice between one option or another, the easier/cheaper option is chosen or two alternative max tech pathways are developed.

Option

A carbon reduction measure, often a technical measure, such as a more efficient process or technology

Option Register

The options register was developed jointly by the technical and social and business research teams. This was achieved by obtaining the list of potential options from interviews, literature, asking participants at the information gathering workshop which options they would consider viable, and through engagement with members of the relevant trade associations.

Pathway

A particular selection and deployment of options from 2014 to 2050 chosen to achieve reductions falling into a specific carbon reduction band

Projection of Production Changes

A sector specific scenario assumption which defines the changes in production as an annual percentage change to 2050

Reference trend

the carbon dioxide emission trend that would be followed if the 2012 base year emissions were affected by production change and grid decarbonisation in accordance with the sector specific scenarios

Scenario

A specific set of conditions external to the sector which will affect the growth and costs of production in the sector and affect the timing and impact of options on carbon emissions and energy consumption

Scenario assumptions

A set of specific cost and technical assumptions which characterise each scenario. These include forward fuel and carbon price projections, grid CO_2 factor projection and background economic growth rate. The assumptions may include sector forward production projections.

Sensitivity case

The evaluation of the impact of changes in a single assumption on a pathway e.g. the availability of biomass

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