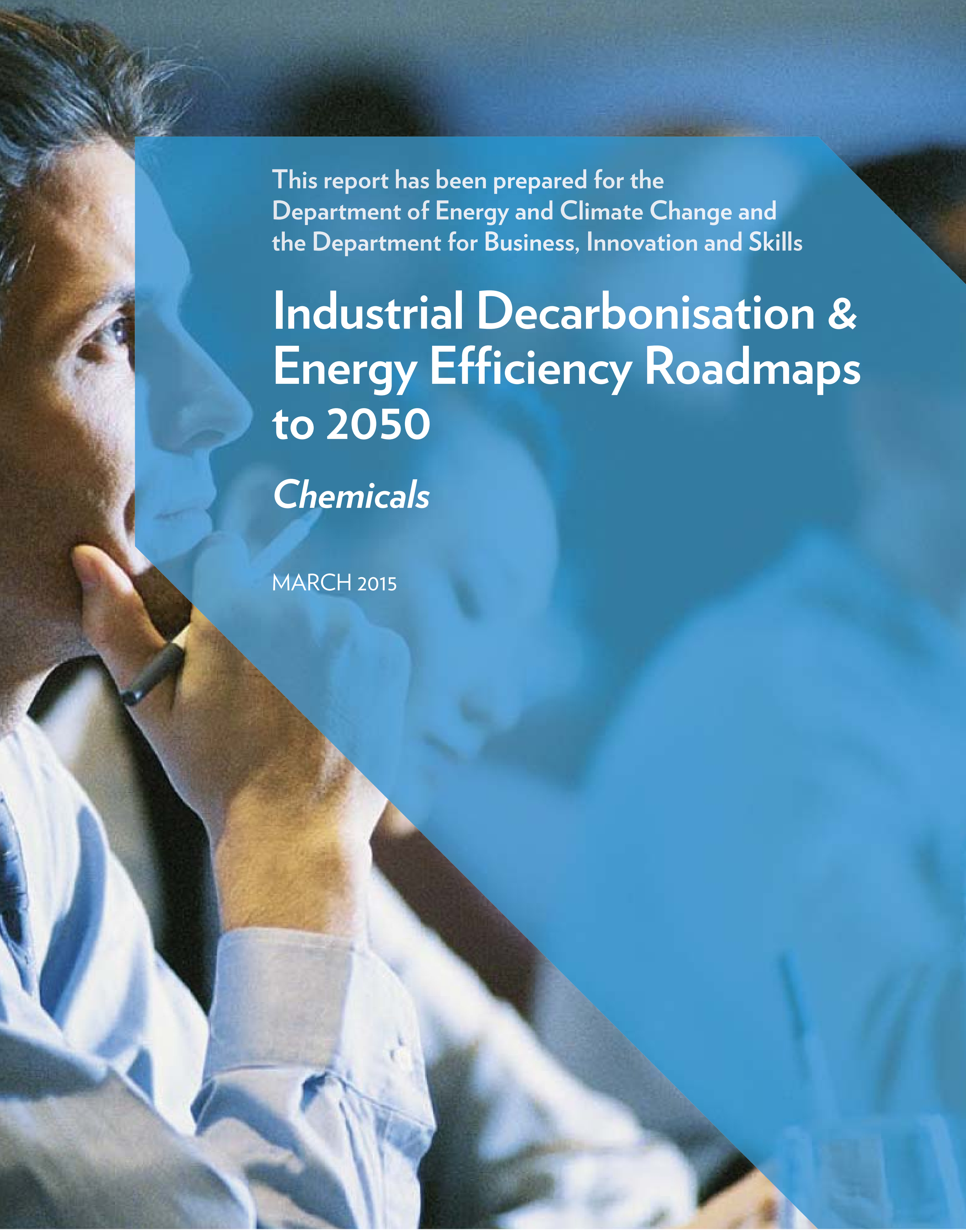

This report has been prepared for the Department of Energy and Climate Change and the Department for Business, Innovation and Skills

Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050

Chemicals

MARCH 2015

WSP | PARSONS BRINCKERHOFF

DNV·GL

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ACRONYMS

ADOP	Adoption Rate
APP	Applicability
BAT	Best Available Technology
BAU	Business as usual
capex	Capital Expenditure
CC	Carbon Capture
CCA	Climate Change Agreement
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CEFIC	European Chemistry Industry Council
CGP	Chemistry Growth Partnership
CHP	Combined Heat and Power
CIA	Chemical Industries Association
CRCs	Carbon Reduction Commitments
EIUG	Energy Intensive Users Group
EMS	Environmental management system
EU ETS	European Emissions Trading System
Feedstock	Raw material used in a chemical process
GCCSI	Global Carbon Capture and Storage Institute
GHG	Greenhouse Gas
IEA-ICCA	International Energy Agency – International Council of Chemicals Association
LOCIMAP	Low carbon industrial manufacturing parks
Max Tech	Maximum Technical
N_2O	Nitrous Oxide
NAEI	National Atmospheric Emissions Inventory
ONS	Office of National Statistics
R&D	Research and Development
RD&D	Research Development and Deployment
REA	Rapid Evidence Assessment
ROI	Return on Investment
SIC Codes	Standard Industrial Classification codes
SMEs	Small and Medium Sized Enterprises
SWOT	Strengths, Weaknesses, Opportunities and Threats
TRL	Technology Readiness Level
TUC	Trade Union Congress
UK PRTR	UK Pollutant Release and Transfer Register

1. EXECUTIVE SUMMARY

1.1 Introduction: What is the 'Decarbonisation and Energy Efficiency Roadmap' for the Chemicals Sector?

This report is a 'decarbonisation and energy efficiency roadmap' for the chemicals 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 to 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 aims of the roadmap project 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 consultation with 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 Chemicals Sector Roadmap

The development of the chemicals sector roadmap consisted of three main phases:

1. Collection of evidence relating to technical options and business-related enablers and barriers for decarbonisation. Evidence was collected via a literature review, analysis of publicly available data, interviews, workshops, and a survey of chemicals manufacturing companies. Validation of evidence and early development of the decarbonisation potential took place during an initial workshop of key sector stakeholders.
2. Development of decarbonisation 'pathways' to 2050 to identify and investigate an illustrative technology mix for a range of emissions reduction levels, subject to different global economic and environmental scenarios. Draft results were validated at a second workshop.
3. Interpretation and analysis of the technical and business-related 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 and identifying opportunities for delivery of

technologies within the decarbonisation and energy efficiency pathways, while maintaining competitiveness.

A sector team comprising representatives from a chemical industry trade association (the Chemical Industries Association (CIA)), the government and Sheffield University 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. 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 chemicals sector covers a wide range of diverse processes, ranging from complex continuous processes making large-volume basic chemicals to smaller scale batch processes producing speciality chemicals and pharmaceutical ingredients. Energy use in the sector is characterised by the use of natural gas to generate steam or for direct heating, and the use of electricity for a range of activities such as for pumping, compression, chilling, and lighting. The combustion of fossil fuel, indirect emissions from electricity consumption, and process emissions (resulting from processes than create CO_2 as a by-product of chemical reactions) make up the chemicals 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 Climate Change Agreements (CCA), European Union Emissions Trading Scheme (EU ETS) and National Atmospheric Emissions Inventory (NAEI))

The chemicals sector is highly energy intensive, consuming 16.5% of all industrial energy used in the UK in 2012 (Dukes, 2013). This reflects the energy-intensive nature of many chemical processes, which require high temperatures and consequently high energy inputs.

[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 were 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 UK chemicals sector operates in a global market, and one that is highly competitive. Competition from Asia and the US is an increasing challenge to UK production and it can be difficult to secure funding for investment in UK sites when better returns can be achieved elsewhere where feedstock and energy costs may be lower.

1.4 Enablers and Barriers for Decarbonisation in the Chemicals Sector

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

- A level playing field globally for energy and policy costs
- A stable and predictable policy framework
- A strong business case and the ability to demonstrate payback
- Financial incentives to address the costs associated with adopting technologies
- Recognition of key technologies and developing strategies for these

The main barriers to decarbonisation have been identified as:

- Internal competition for resources and funding
- Energy prices and policy costs
- Stringent return on investment (ROI) requirements
- Uncertainty in policy and regulation
- Access to capital and funding
- Commercialisation of new and unproven technology
- High cost of research, development and demonstration (RD&D) of new technology
- Long lifetime of major equipment

1.5 Analysis of Decarbonisation Potential in the Chemicals Sector

A 'pathway' represents a particular selection and deployment of options from 2012 to 2050 chosen to achieve reductions falling into a specific decarbonisation 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 (maximum technical, Max Tech). A pathway is an illustration of how the chemicals industry could potentially decarbonise from our reference year 2012 to 2050. These pathways include deployment of options comprising (i) incremental improvements to existing technology, (ii) upgrades to utilise best available technology (BAT), 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 investigated created in the current trends scenario, the central of three scenarios used in this study, are shown below in Figure 1[3].

[3] Two versions of Max Tech are presented to illustrate the options with and without biomass

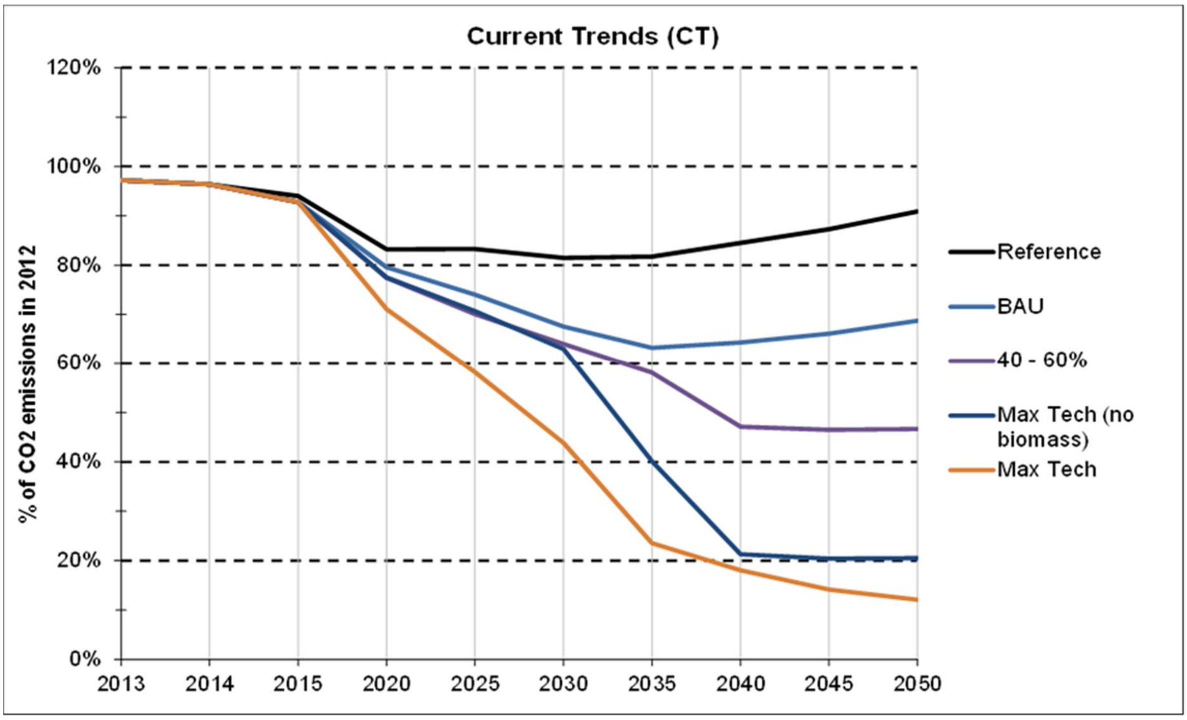

Figure 1: Overview of the different decarbonisation and energy efficiency pathways

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 £600 million[4] to £4 billion[5]. There is a large degree of uncertainty attached to the cost analysis, especially for options which are still in the R&D 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.

1.6 Conclusions and Key Technology Groups

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

Strategy, Leadership and Organisation

The chemical sector illustrates good practice in relation to strategy through the Chemistry Growth Partnership (CGP), the industry-led council which was formed to enable government and industry to work together over the long term to address the key challenges and opportunities for the chemicals sector. This approach should be continued.

[4] For the BAU pathway in the current trends scenario
[5] For the Max Tech pathway in the current trends scenario

Business Case Barriers

One of the most important barriers to decarbonisation and increased energy efficiency is lack of funding for investment projects. UK site managers often find that the return of investment is not attractive enough to meet their internal funding criteria or that they are competing for capital against sites in other countries where the return on investment (ROI) is more attractive.

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

It is clearly critical to ensure that future decarbonisation and energy efficiency actions reflect the need to maintain overall cost-competitiveness of the UK sector compared to businesses operating in other regions of Europe, Asia and the US. This strategic conclusion links to a number of external factors that influence the business environment in which the sector operates. These include energy security and energy cost comparison to other regions (both the reality and the perception), as these factors are important when investment decisions are made.

Industrial Energy Policy Context

Long-term energy and climate change policy is key to investor confidence. Many in the industry believe that there is a need for incentive schemes to become long-term commitments, as changes in policy can be damaging, particularly when the business case for investment is marginal and is highly dependent upon factors such as (fluctuating) energy related costs.

Life-Cycle Analysis

The sector uses raw materials from and provides its products to other parts of the economy, and there needs to be a common and quantifiable means of understanding the overall carbon impact of the entire product life-cycle. The interactions involved are complex – for example, producing biomass absorbs carbon; if this carbon is then 'sequestered' in a plastic derived from this biomass there might be a long-term societal carbon benefit, but this will depend on factors such as how the biomass is produced, the end-of-life disposal or re-use of the plastic and the alternative materials that the plastic may be replacing. There are also interactions with products from other sectors that need to be taken into account. If an appropriate value can be put on life-cycle (carbon) benefits which better aligns the industry incentives for generating revenue and maintaining competitiveness with societal incentives for decarbonisation, investment in decarbonisation becomes easier to justify.

This accounting would also help to determine, for example, how to compare the uses of a limited resource such as biomass (i.e. as a feedstock or a fuel) by assessing the overall life cycle carbon impact compared to that of alternatives (e.g. the continued use of fossil hydrocarbons).

Value Chain Collaboration

Collaboration between different parties in the value chain can provide opportunities for decarbonisation beyond those related to individual sites. For the chemical sector, this could include clustering, collaborative RD&D, and the development of comprehensive carbon accounting.

Research Development and Deployment

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 R&D activity but also, crucially, progressing technology to successful commercial demonstration so that it is de-risked for future deployment. Companies may not have the time, expertise and funding to identify if and how different options may be of benefit to them and so may not progress the R&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 chemicals 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 and key organisational issues that, in this investigation, make the largest contributions to sector decarbonisation or energy efficiency are as follows:

Electricity Grid Decarbonisation

Decarbonisation of this key source of energy could provide a significant contribution to the overall decarbonisation of the sector. Actions will be required to ensure that this takes place while maintaining cost-competitiveness. The Government's reforms of the electricity market are already driving electricity grid decarbonisation, and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with Government methodology and modelling.

Fuel and Feedstock Availability (Including Biomass)

The availability of local carbon fuels and feedstocks is a key issue for sector decarbonisation, given the importance of biomass for achieving the emissions reductions within the pathways. However, given the uncertainties around the amount of biomass that will be available and its carbon intensity, a pathway has been developed to illustrate that significant decarbonisation can be achieved without it. This availability issue exists between uses within the sector (e.g. use of biomass as a fuel or as a feedstock) and/or with external uses (e.g. the use of waste plastics for electricity generation). Key challenges include understanding where the greatest decarbonisation potential can be achieved with a limited resource, and how to maximise the availability of the resource.

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 resources to allow the potential of this option to be fully realised.

Clustering

The UK has a number of strong chemicals clusters, which benefit from selling their by-products and waste streams to neighbouring sites, from shared infrastructure, and from developing a local supply chain. However, clustering of sites to optimise resource use can be a challenge given the need for collaboration across companies and the risk that cluster partners will exit, leaving a crucial gap in the supply chain. Stronger encouragement for increased clustering needs to be established, including a means for companies to reflect the benefits of clustering in business cases.

Carbon Capture

Emissions from individual chemical plants in the UK are not considered to be of a sufficient scale to justify their own CO_2 pipeline and storage infrastructure. Collaboration both within the sector and externally is necessary to establish the networks, along with the availability of sources of funding appropriate to developing this type of shared infrastructure and the demonstration of this technology.

Other Technologies

Other decarbonisation technologies have been identified during the development of this roadmap, such as generating hydrogen by electrolysis and the recycling of plastics to generate syngas feedstock. The enablers and barriers for these technologies are similar to those identified above such as the need for further RD&D and cost-competitiveness.

As the electricity grid becomes progressively lower carbon, converting processes to use electricity in place of other energy sources could contribute to decarbonisation. Industry, together with other stakeholders, could take action, in collaboration with academic and other partners, to assess which processes this could be applied to in order to inform future RD&D.

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

The UK needs to make the transition to a low-carbon economy to meets its climate change objectives but 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 employment, economic growth and rebalancing the economy. Changes in the international economy, such as the availability of low-cost feedstock and substantial investment in the US, Middle East and Asian economies, and coupled with the need to decarbonise, mean that UK businesses face increased competition as well as new opportunities. The government and industry have developed this report in partnership to drive coordinated and long-term action which will enable UK businesses to compete and grow while moving to a low-carbon economy.

Overall, industry is responsible for nearly a quarter of the UK's total emissions[6] (DECC, 2011). 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.

DECC and 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 different 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

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

[6] It has also been estimated that 70% of industrial energy use is for heat generation (DECC, 2014).
[7] The 'non-metallic minerals' sector has been divided into three sectors: glass, ceramics and cement.

impacts. This project aims to improve evidence on decarbonisation and energy efficiency for eight energy intensive industry sectors, with chemicals being 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 CIA, 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 enablers and to decarbonisation
ii. Development of sector decarbonisation and energy efficiency 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:

1. What are the current emissions from each sector and how is energy used? – Section *3.3*
2. 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*
3. How might the baseline level of energy and emissions in the sectors change over the period to 2050? - Section *4.3*
4. What is the potential to reduce emissions in these sectors beyond the baseline over the period to 2050? - Section *4.4*
5. What emissions pathways might each sector follow over the period to 2050 under different scenarios? - Section *4.4*
6. 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, which technologies will need to be implemented in order to extend that potential, and how businesses will be affected. The roadmaps aim 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, R&D, 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.

<table>
<tr><th colspan="4">INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAP TO 2050</th></tr>
<tr><th>SOURCES OF EVIDENCE</th><th>INTERMEDIATE OUTPUTS</th><th>PATHWAYS</th><th>STRATEGIC CONCLUSIONS AND EXAMPLE ACTIONS</th></tr>
<tr><td>Literature</td><td>Validated emission data</td><td rowspan="4">Analysis of evidence to construct decarbonisation and energy efficiency pathways</td><td rowspan="4">Analysis of evidence and pathways to develop strategic conclusions and possible next steps to:
• Overcome barriers and strengthen enablers
• Implement pathways</td></tr>
<tr><td>Publicly available emissions data</td><td>Decarbonisation options and associated data</td></tr>
<tr><td>Interviews, survey, meetings and workshops with stakeholders</td><td>Energy efficiency options and associated data</td></tr>
<tr><td>Government policy and analytical teams, trade associations, academics as part of engagement with the sector team</td><td>Enablers and Barriers to decarbonisation and energy efficiency options and investment</td></tr>
</table>

Table 3: Inputs and outputs for the industrial 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 A Short Introduction to the UK Chemicals Sector

The UK chemicals sector is diverse and includes a wide range of organisations using different chemical processes to convert raw materials to products for sale to customers. For the purposes of this study, the sector team defined the chemical sector as being those industries included in Standard Industrial Classification (SIC) codes 20 and 21, i.e. those involved in the manufacture of chemicals and pharmaceuticals. As described in section 3, the majority of emissions from the sector arise from chemicals manufacturing (i.e. SIC code 20[8]) and the roadmap therefore focusses on these activities.

In total, there are more than 2,500 enterprises involved in chemicals manufacturing (SIC code 20) with an annual turnover of around £32 billion and approximately 106,000 employees. The sector is extensively involved in international trade with total exports of £27.1 billion and total imports of £26.6 billion in 2013. In

[8] SIC codes are the Standard Industrial Classification codes used in the UK to classify businesses according to their type of activity. SIC code 20 covers the manufacture of chemicals and chemical products. SIC code 21 covers the manufacture of basic pharmaceutical products and pharmaceutical preparations.

2013 £617 million was spent by industry on R&D in the UK on chemicals and chemical products (excluding pharmaceuticals). Pharmaceuticals covered under SIC code 21 include more than 500 further enterprises with around £15 billion annual turnover and approximately 50,000 employees (ONS, 2014).

Many different process technologies are used in the sector, ranging from large-scale continuous processes making millions of tonnes per year of bulk products, to small batch processes making speciality chemicals and intermediates. Much of the sector produces intermediate products that are then further converted by others in the sector before being sold to customers outside the sector. Basic chemicals are used in a wide variety of industrial and consumer chemicals including plastics in primary form, paints, rubber, fertilisers and pharmaceuticals. The automobile, aerospace, construction, food and drink, and energy sectors are all major users of chemical products. Figure 2 below shows an example of the complexity of supply chain links in the sector[9].

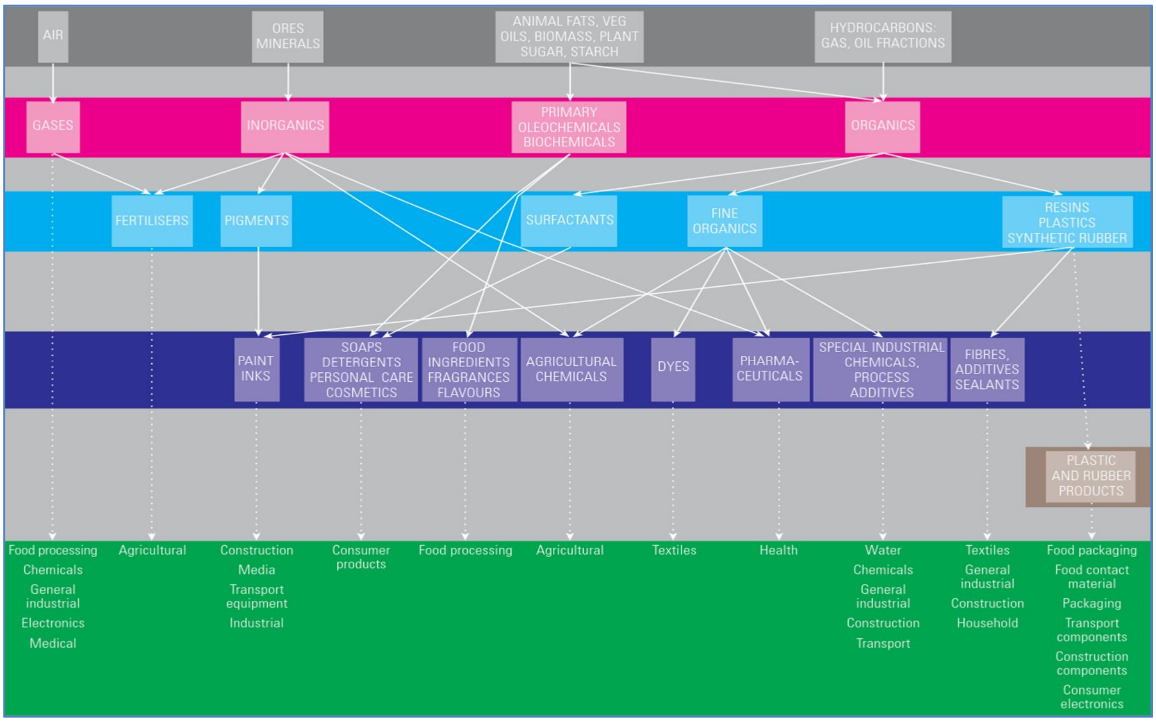

Figure 2: Example of chemicals sector supply chain links (Chemistry Growth Strategy Group)

The UK chemicals sector is one of the largest energy-using sectors in the UK, consuming 16.5% of all industrial energy in 2012 (DUKES, 2013). This reflects the energy-intensive nature of many chemical processes that require high temperatures and consequently high energy inputs. Reflecting the high levels of energy use, the sector had total emissions (direct and indirect) of 18.4 million tonnes of CO_2 in 2012 (Dukes, 2013).

It must be appreciated that many chemical processes will always require a certain minimum amount of energy in order to achieve the desired chemical reactions. One of the decarbonisation challenges for the sector is therefore to provide this energy while minimising the associated emissions.

[9] The diagram is an example, and other links exist. For example, inorganic chemicals are used in soaps and detergents, and in the manufacture of glass.

The sector is characterised by a small number of large plants that emit a high proportion of the sector's CO_2 emissions, and a large number of smaller operations which collectively also have significant CO_2 emissions. section 3.3.1 includes further discussion of the major emitting processes and their contribution to sector emissions.

2.3 Overall Methodology

The overall methodology is illustrated in Figure 1 and shows the different stages of the project. As shown below, stakeholders from the sector were engaged throughout the process: evidence gathering, modelling and pathway development, and drawing out the conclusions and potential next steps. A detailed description of the methodology can be found in appendix A.

Evidence was gathered covering technical, social and business aspects from literature reviews, interviews, survey and workshops 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 enablers and barriers for decarbonisation, and a register of technical options for the industry. This was subsequently used to develop a set of decarbonisation and energy efficiency pathways to evaluate the decarbonisation potential of the UK chemical sector and the main technical options required within each pathway.

Key to the overall roadmap methodology was engagement with all stakeholders, including with industry 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 CIA, DECC and BIS to identify and involve the most appropriate people from the chemical sector, relevant academics and other stakeholders, such as representatives from the financial sector.

Figure 3: Roadmap methodology

2.3.1 Evidence

Evidence Gathering

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

- Decarbonisation options (i.e. technologies)
- Enablers and Barriers 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, focused review of over 150 documents all published after 2000 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[10] 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 DECC, BIS and the CIA, eight interviews were carried out with key representatives of the chemicals industry. The purpose of the interviews was to obtain further details on the different subsectors within the chemical sector and to begin to answer the principal questions, including how companies make investment decisions, how advanced technologies are financed, and what a company's strategic priorities are and where climate change sits within this. 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 subsectors and emissions and also take into account company headquarters location, production processes and company size.
- **Survey:** A survey was conducted with 17 businesses in the sector to assess the impact of the identified enablers and barriers from literature review and interviews. The questions were drawn up in consultation with DECC and BIS and the sample of respondents were selected based on coverage of a high proportion of sector emissions (nb the survey was not a census). The response rate of the survey was 23% which included a distribution of respondents across the various subsectors. The key questions focused on the respondents' view on the level of impact of the top enablers and barriers on the implementation of energy and decarbonisation options as identified from the interviews and literature review.
- **Workshops:** Two workshops were held, attendees for which were identified in consultation with CIA, DECC and BIS. The first workshop focused on reviewing potential technological decarbonisation and energy efficiency options (that had been provisionally generated from the literature review) and discussing adoption rate, applicability, improvement potential, ease of implementation, capital expenditure (capex), ROI, reduction potential, and timelines for the different options. This was done through two breakout sessions: 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 to energy efficiency and decarbonisation investment, and how to overcome them. The second workshop focused on reviewing the draft pathways and identifying potential actions for delivering them. The workshop participants included the relevant trade associations, large companies with the aim of achieving representation of key companies and/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.

By using a range of information sources, the evidence was 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 and workshops. The data from the literature was corroborated by comparing it with evidence from the interviews and workshops. Likewise, information gaps identified during the interviews and workshops were, where possible, populated using literature data. In addition, CIA collected data from its members that further helped to fill gaps and triangulate multiple data sources. It should be noted that the

[10] DECC, BIS and the consultants of Parsons Brinckerhoff and DNV GL

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 and survey 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 are detailed in appendix A. Interviewees included UK decision makers and technical specialists in the sector.

The different sources of evidence together with the associated outputs are shown in Figure 4.

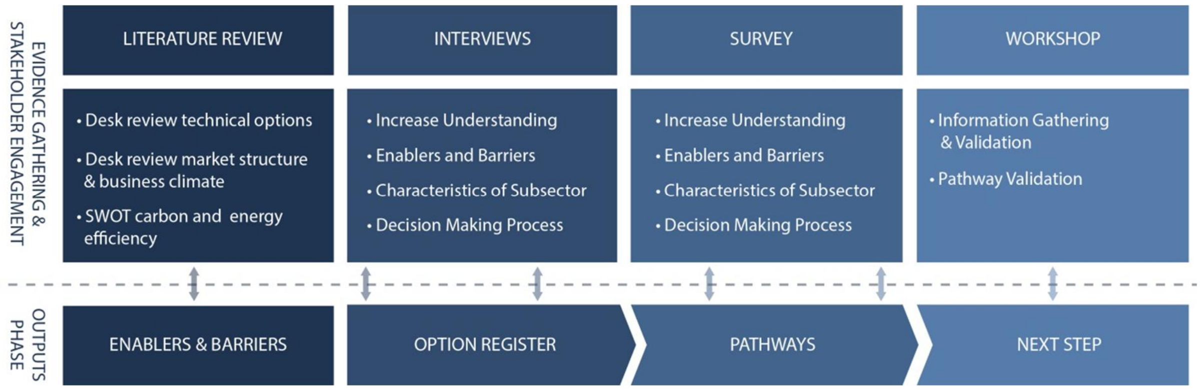

Figure 4: Evidence-gathering process

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 chemical sector. Evidence on ADOP, APP, improvement potential, ease of implementation, capex, ROI and reduction 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, the SWOT analysis was used to develop a narrative about the business and market environment in which chemicals companies in the UK operate. Further information on the SWOT analysis is provided in appendix B. Enablers and barriers were prioritised as a result of the outcomes and analysis of the evidence gathering process and workshop scores. The SWOT analysis was used to further understand and validate the initial findings from the literature review and provided the basis for workshop and interview discussions. Subsequently, it was used to qualify the interview and workshop outcomes.

This information and analysis was used to inform the development of a set of pathways to illustrate the decarbonisation potential of the chemical sector in the UK. The summary and outcomes are discussed in section 4.

The evidence gathering exercise was subject to limitations based upon the scale of activities and sample sizes that could be conducted within the time and resources available. The literature review was not intended to be exhaustive and aimed to capture key documentation that applied to the UK. The companies interviewed represented the largest emitters based on information from the EU ETS and the UK Pollutant Release and Transfer Register (UK PRTR) datasets. Interviewees included UK decision makers and technical specialists within these companies. These interviews were conducted to provide greater depth and insight on the decarbonisation issues faced by companies in this sector.

The identification of relevant information and data was approached from a global and UK viewpoint. The global outlook examined dominant technologies and process types, global production and CO_2 emissions (in the EU-28) and the global outlook to 2050, including the implications for chemical producers and consumers, and production and demand uncertainties. The UK outlook examined 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. The major UK chemical producers and their key sites, dominant technologies, and processes have been reviewed.

The number and diversity of the plants and processes within the sector is a practical challenge in developing decarbonisation options. It was agreed by the sector team at an early stage that the processes that the pathways would focus on would be: (i) generic options that could apply across much of the sector (e.g. energy efficiency measures, waste heat recovery, fuel switching, carbon capture (CC), and (ii) process-specific options relating to the sector's major emitting processes (as listed in Table 4). The generic options can apply to all subsectors while process-specific options could include modifications to existing processes, or completely new processes

The aim of developing these two groups of options was to ensure that decarbonisation and energy efficiency options were identified to reflect the structure of the sector as described in section 2.2 (i.e. a small number of sites with individually high emissions and a large number of smaller sites with significant collective emissions).

The options considered covered all emissions sources ranging from combustion processes (e.g. steam boilers, fired heaters, furnaces) to indirect sources (e.g. electricity use for pumps, compressors, refrigeration, lighting etc.) to process emissions (e.g. CO_2 from the steam reforming of methane in the ammonia and hydrogen processes). The sector also uses significant quantities of fossil fuels as feedstock (i.e. raw material) and so options to use alternative feedstock (e.g. biomass or recycled plastics) were considered.

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 enablers and barriers (section 3.4.6), 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, the evidence gathering workshop, and additional information provided by CIA 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.

2.3.2 Pathways

The pathways analysis is an illustration of how the chemical sector 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 includes a number of key input parameters, including CO_2 reductions, 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[11] 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 CO_2 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 additional interventions were taken to accelerate decarbonisation (BAU) or (ii) the maximum possible technical potential for decarbonisation in the sector (Max Tech)[12].

The BAU pathway consists of the continued deployment 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 chemical sector, two different Max Tech pathways were developed to reflect what would happen if no availability of biomass is assumed.

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, which is available through DECC and BIS, is summarised in appendix A.

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

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.

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 continuous growth of the industry in the UK.
- **Challenging world**: This would represent a future world with a more challenging economic climate, where the industry is declining in the UK, and where decarbonisation is not a priority.
- **Collaborative growth**: This would represent a future world with a positive economic climate, where the industry has a higher growth rate in the UK, 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 is 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 workshops. The uncertainties in this process are large given this level of judgement, however, these 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 (CO_2) – this represents CO_2 equivalent. However, other greenhouse gases (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 greenhouse gases, relative to those of CO_2, are very low.

Assumptions in relation to the Max Tech pathway

Max Tech pathway: A combination of carbon abatement options and energy 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): The process or technology is 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 assumes unlimited availability. Carbon intensity and sensitivities are included in each sector.
6. 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’ for carbon capture storage or usage. 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 for 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 is likely to be representative of reality; the actual pathway trend would lie between the two. The two methods therefore provided a theoretical bound on the uncertainty relating to interaction in results that occurs in 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 amount of emissions 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 i.e. it is possible for a pathway of lower emission levels in 2050 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 the pathways (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 sets 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 proposes 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 a 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.

2.3.3 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 enhance enablers and overcome barriers that were identified 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 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 5.3 are:

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

3. FINDINGS

3.1 Key Points

The sector in the UK is diverse, with a small number of major sites responsible for around half of sector emissions but also a significant number of smaller sites that, collectively, account for the remainder of the sector's emissions. Total sector emissions in 2012 were 18.4 million tCO_{2eq} (DEFRA, 2014 and Dukes, 2014) with direct emissions from the sector of 11.2 million tCO_2 (10.0 million tCO_{2eq} from fuel combustion and 1.2 million tCO_2 from processes that produce CO_2 as a by-product). The remaining 7.2 million tCO_2 are from indirect emissions, i.e. related to electricity used by the sector. Other indirect emissions (e.g. from road transport of goods) were considered to be outside the sector and are not included.

From the responses to interviews and surveys and the workshops, the sector considers energy efficiency and decarbonisation to be important and many organisations report having strategies and goals in place. Significant progress has been made over recent decades to reduce energy consumption per unit of product (e.g. GJ of energy used to produce each tonne of product). A message emerging from the interviews and surveys is that, particularly at the level of individual sites, it is typical to think in terms of energy use and efficiency rather than carbon emissions, and that decarbonisation is often a lower priority than projects addressing issues such as regulatory compliance. Interviews and surveys also indicated a degree of risk aversion with respect to new technology, requiring successful demonstration at a commercial scale to de-risk the major investment required and the potential disruption to on-going production.

The main enablers for decarbonisation in the chemicals sector are:

- A level playing field globally for energy and policy costs
- A stable and predictable policy framework
- A strong business case and the ability to demonstrate payback
- Financial incentives to address the costs associated with adopting technologies
- Recognition of key technologies and developing strategies for these
- Infrastructure requiring replacement for other reasons, allowing deployment of more efficient technology

The main barriers to decarbonisation are:

- Internal competition for resources and funding
- Energy prices and policy costs
- Stringent ROI requirements
- Uncertainty in policy and regulation
- Access to capital and funding
- Commercialisation of new and unproven technology
- High cost of R&D and demonstration of new technology
- Long lifetime of major equipment

High energy costs are seen as a barrier rather than an enabler as they tend to encourage production to move to lower cost locations, rather than incentivising investment in energy efficiency. This risks plants being starved of development spending and ultimately becoming unattractive due to the age of the original assets and their low book value.

3.2 Chemical Processes

As described in section 2, the chemicals sector covers a wide range of diverse processes. These range from complex continuous processes making large-volume basic chemicals to smaller scale batch processes producing speciality chemicals and pharmaceuticals. Many chemical sites operate a number of different processes which are linked together to carry out a number of sequential steps to convert raw materials (feedstock) into products.

While the diversity of processes means that a single description of a chemical process is impossible, the key elements in most chemical processes are the transfer of materials and energy. Transfer of materials involves moving raw materials, intermediate products and finished products from one stage of processing to the next. Materials may be liquid, solid or gaseous and equipment including pumps, piping, conveyors and fans is used depending on the requirements of the transfer in question. Often materials will change their state or properties during processing and so material transfer equipment for any process is typically a combination of different types.

Chemical reactions are at the heart of many processes. Reactions can be carried either continuously or in batches and usually take place in vessels where the optimum conditions of temperature and pressure can be maintained to achieve the desired reaction. Following reaction, separation of different products and unreacted raw materials is often necessary, and a wide range of techniques and equipment are used to achieve this (including distillation, absorption, crystallisation and sedimentation). Separation can require significant amounts of energy e.g. in providing heat to distillation processes.

After separation, products may go onto further reaction or processing steps and unused raw materials will generally be recycled for re-use. The recycling stages of a chemical process can be significant processes in themselves, involving further separations, reactions etc.

Material transfer, reaction, separation and recycling all require energy which is provided as heat or electricity. Heat is needed to provide the high temperatures necessary for many reactions and separations (e.g. distillation), while electricity is used to drive pump motors, compressors, chillers etc. Some chemical reactions are exothermic (i.e. they generate excess heat) and this heat is often captured through heat recovery for use elsewhere in the process.

A range of technologies are used to deliver heat to chemical processes. The most widespread is the use of steam at a variety of different pressures. Steam is generated in boilers which are fired by natural gas or other fuels, or by heat recovery techniques. These techniques include heat removal from exothermic processes (those that generate heat as a by-product), heat recovery from waste streams, or heat exchange where a feedstock stream is pre-heated by cooling a product stream.

Furnaces are also used to provide heat directly in some processes where very high temperatures are required, for example in the cracking stage of olefin production. Furnaces provide direct radiant heat compared to conduction of heat through a vessel or tube wall where steam heating is used. Natural gas or recovered waste gases are typically used as furnace fuels, although other fuels can also be used.

Where the relative demand for heat and electricity is appropriate, many chemical plants improve their overall energy efficiency by using combined heat and power (CHP). CHP units may be physically integrated with the site, or located on a neighbouring site. This is typically done using a natural gas fuel in a gas turbine to generate electricity, followed by a heat recovery steam generator. Alternatively, a steam boiler is used to raise steam to both provide heat and generate electricity via a steam turbine. CHPs often also make use of fuel or waste heat provided by the chemical process. CHP is used at 53 chemical sites in the chemicals sector (Dukes, 2013) and generates a significant proportion of the energy used in the sector. Electricity not supplied by CHP is sourced from the national grid.

3.3 Current Emissions and Energy Use – Principal Question 1

This section provides an assessment of the range of questions under 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, heat and power demand of chemical manufacturing facilities 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 Emissions

The chemicals sector is responsible for greenhouse gas emissions either directly through emissions from chemical process plants, or indirectly through the use of electricity generated by others. Direct emissions can be further divided into combustion emissions (e.g. related to burning fuel in boilers) or process emissions (where a greenhouse gas is produced as a by-product of the chemical reaction).

In 2012, emissions from the UK chemicals sector for each of these sources, as also illustrated in Figure 5 below, were (DEFRA, 2014 and Dukes, 2014):

- Direct combustion: 9,966,202 tCO_2
- Direct process: 1,233,163 tCO_2
- Indirect (electricity): 7,162,209 tCO_2

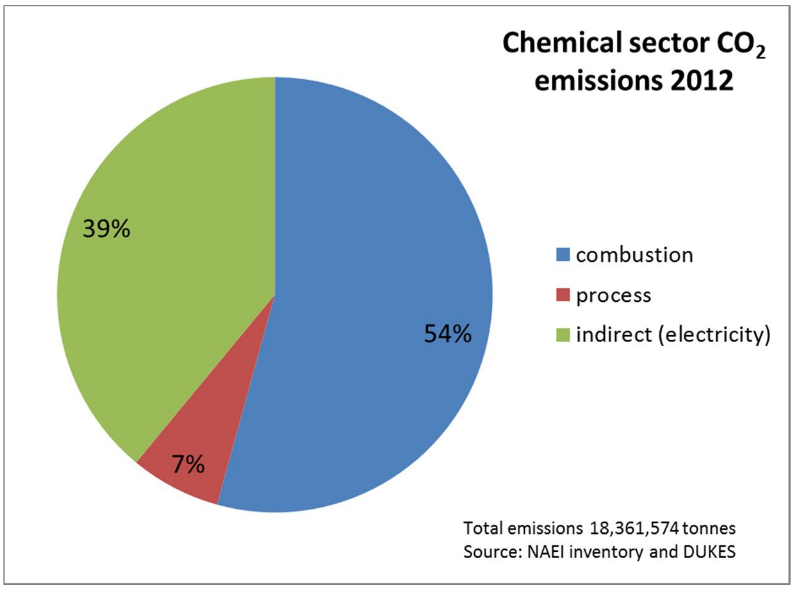

Figure 5: UK chemicals sector emissions 2012 (DEFRA, 2014 and Dukes, 2014)

As Figure 5 shows, 93% of emissions relate to combustion or to electricity use and so these are the areas where decarbonisation options can have the greatest impact.

A large proportion of the sector's emissions come from a relatively small number of major UK chemical plants that use significant emitting processes, based on data from the EU ETS installation level data and DEFRA's Pollutant Release and Transfer Register (PRTR). Plants using these processes and emitting more than 100,000 t CO_2 per year are shown in Table 4 below.

The ammonia and hydrogen processes, which make CO_2 as a by-product, are responsible for the majority of the process emissions from the sector.

Process	Number of UK plants	Locations	Company	% of direct sector emissions	Estimated % of total sector emissions[13]	Comments
Olefins	3	Teesside	SABIC	25%	17%	Olefins also produced at a 4th plant integrated into Stanlow refinery
		Grangemouth	Ineos			
		Mossmorran	Exxon			
Ammonia	2	Teesside	Growhow	13%	8%	Majority of emissions are process
		Ince	Growhow			
Chlorine	1	Runcorn	Ineos	1%	5%	Majority of emissions relate to electricity used
Acrylonitrile	1	Teesside	Ineos	4%	3%	
Acetic acid	1	Humberside	BP	3%	2%	
Titanium dioxide	2	Teesside	Huntsman	3%	2%	
		Humberside	Cristal			
Soda ash	1	Lostock	Tata	1%	1%	Data includes a 2nd plant, recently closed
Methyl methacrylate	1	Teesside	Lucite	2%	1%	
Hydrogen	1	Teesside	BOC	2%	1%	Majority of emissions are process

Table 4 Most significant emitting processes in the UK chemicals sector (DEFRA, 2014)

Together, these nine processes are estimated to account for approximately 54% of direct sector emissions, and 40% of total sector emissions in the UK (DEFRA, 2014). The different proportions of direct and total emissions reflect the relatively higher use of combustion processes at the larger sites. As Table 4 shows, many of these plants are based in or around the major chemical-producing areas of the UK such as Teesside and Humberside. This provides the opportunity for common decarbonisation solutions such as clustering to share materials and infrastructure.

The plants listed in Table 4 above all have direct emissions in excess of 100,000 tonnes CO_2 per year. From the EU ETS installation level data, there are further 26 sites with direct emissions of between 10,000 and 70,000 tonnes CO_2 per year. These sites cover a wide range of different production processes but many are located in the North East (e.g. Teesside, Humberside), North West (e.g. Runcorn) and central Scotland (Grangemouth), further emphasising clustering opportunities.

We note that there are a number of chemicals sector sites that are closely integrated with refineries at Stanlow, Grangemouth and Fawley. These have been discussed with the team developing the refining

[13] Estimate based on EU ETS and PRTR data for direct emissions. Note that there is not precise alignment between the data sources, however they agree on the order of magnitude values for each process. Indirect emissions were allocated in proportion to direct emissions with the exception of chlorine, where an estimate on electricity usage for the single UK plant was made based on publicly available data and converted to indirect emissions using the grid emissions factor from DUKES. In practice, ratio of direct and indirect emissions will vary for each site.

sector roadmap and to avoid double counting it has been agreed that for Stanlow and Fawley, where it is not possible to separate the emissions, emissions are reported as part of the refining sector. For Grangemouth, the data reported above refers only to the emissions that clearly derive from chemicals sector operations[14].

3.3.2 Heat and Power Demand

Based on Dukes (2014), the chemicals sector in the UK used 47,706 GWh of energy in 2012, of which 36% was electricity. Figure 6 provides a breakdown of energy sources used. Electricity demand includes the use of electricity to provide cooling. This data excludes the use of fuels as feedstock, e.g. the use of natural gas as a raw material in the production of ammonia, or the use of naphtha as a feedstock for olefin production. A further 52,126 GWh of fuels were used as feedstock in 2012.

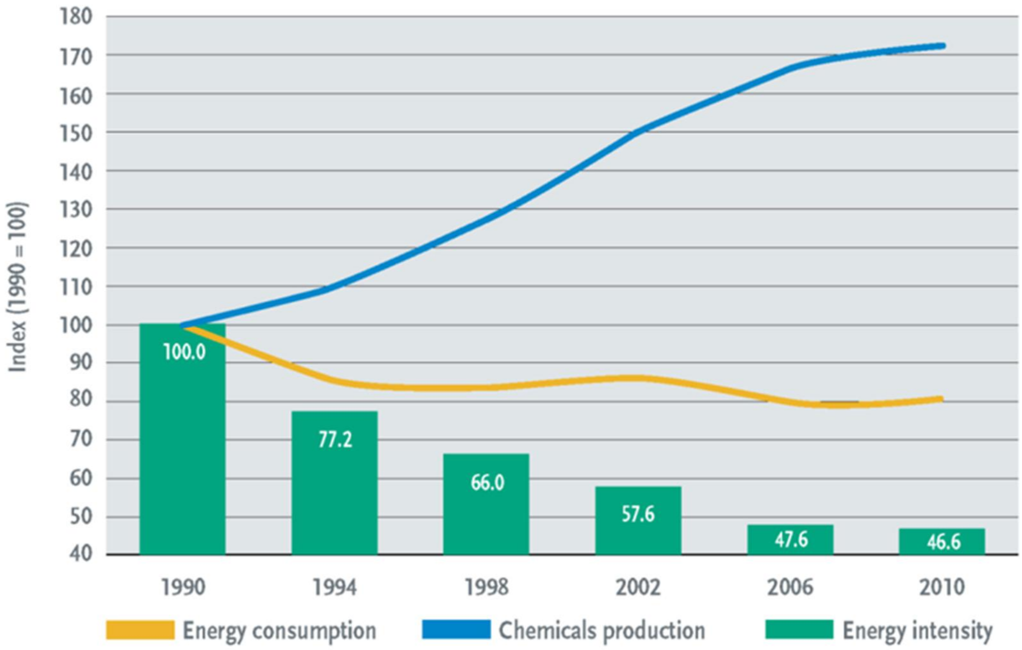

Figure 6: European chemical production, energy consumption and energy intensity (CEFIC and Ecofys, 2013)

The energy consumption of the chemicals sector has generally decreased over time (as illustrated by Figure 6 above for the sector at a European level), while energy intensity has decreased more significantly with more than 50% reduction achieved over the 20 years to 2010. Energy consumption is the total energy consumed by the sector. In this example, chemicals production represents the value of the chemicals produced so energy intensity represents the energy consumption divided by the production value.

According to the IEA, CCA and DECHEMA roadmap (2012), further incremental improvements in energy efficiency can be expected in the future. These are expected to occur as a result of retrofitting to existing plants (allowing wider deployment of best practice technology), the deployment of new plants (which are assumed to use best practice technology), and the continued implementation of energy efficiency improvements on existing plants. The European Chemistry Industry Council (CEFIC) and Ecofys roadmap (2013) notes heat recovery and reuse, more efficient use of electricity, and improvements to on-site energy generation and distribution as ways to improve the energy efficiency of existing processes.

[14] It has also been agreed with the refining sector team that emissions relating to the Petrochem Carless Harwich site should be counted in the chemicals sector, given the range of different chemical products produced there. EU ETS emissions in 2012 were 25,933t, representing less than 0.25% of the sector total. This is one of the 26 sites noted in 3.2.1 above.

3.3.3 Fuels Used

The energy sources used by the sector are shown in Figure 7 below.

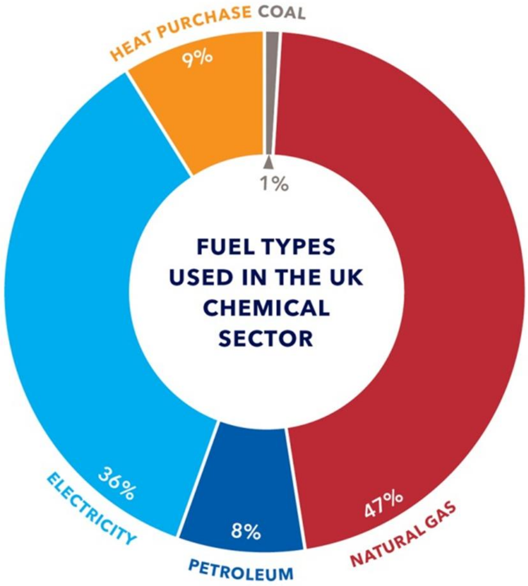

Figure 7: UK chemicals sector energy sources (Dukes, 2014)

As shown, natural gas is the major source of heat energy. Heat purchases are a significant contributor, representing the purchase of heat from sources outside the sector.

3.3.4 Lifespan of Equipment and Key Timings

Chemical plants are typically built and operated for at least 20 years, meaning that the existing plant 'fleet' is only replaced very slowly (Ricardo-AEA). According to CEFIC and Ecofys (2013), large plants producing basic chemicals can have typical lifetimes of 50 years, assuming some debottlenecking over time. These long lifetimes apply to major equipment items also: for example, evidence from the sector workshops is that steam boilers will typically have a lifetime of 30 years.

Overhauls take place at regular intervals, typically every few years, providing opportunities for incremental process improvements or upgrades and replacements to smaller equipment items. Major upgrades or refits may take place at less frequent intervals where more significant equipment modification or replacement takes place. In summary, however, the number of major investment cycles between now and 2050 is very limited, providing limited opportunities for major process changes to be implemented.

3.4 Business Environment and Enablers and Barriers– Principal Question 2

This section provides 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?'

3.4.1 Market Structure

The UK chemicals sector operates in a global market, and one that is highly competitive. The European Climate Foundation states that "*Over the last 20 years, the global chemicals sector has gone through a fundamental shift. From very low activity in 1990, the Asian countries have increased their gross output to a level that in 2011 exceeded that of Europe*". Gilbert et al. (2013) consider that "*The industry is struggling competitively with the Middle East due to the lower costs of energy and chemical feedstock demand and cheap labour", and also that "shale gas is increasing the US's competitiveness"*. Growth in US natural gas production is set for an average of 1.6% annually between 2012 and 2040 (EIA, 2014).

The structure of the chemicals sector is complex. The European Chemistry Industry Council describes the chemicals sector today as being 'diverse and essential' and it can be subdivided and categorised in a number of different ways. At a European level, the European Chemistry Industry Council identifies the subsectors of petrochemical (organic), basic inorganic, polymer, speciality chemicals and consumer chemicals. Speciality and consumer chemicals are reported to account for 40% of total sales (based on 2010 data). The split is illustrated in Figure 8 below.

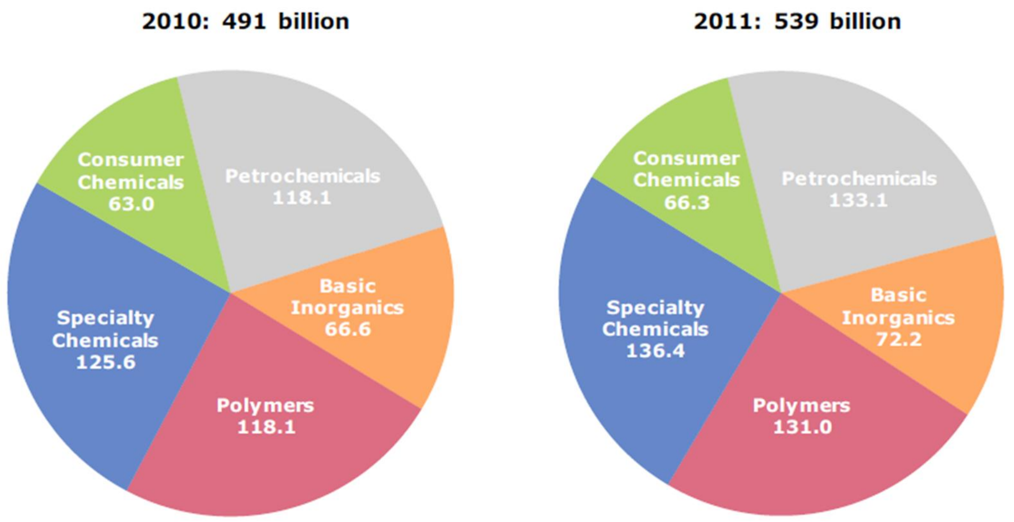

Figure 8 Chemical production by subsector in billion € sales (CEFIC, 2013)

The petrochemical (organics) subsector includes olefins and other associated intermediates. The basic inorganic subsector includes ammonia, chlorine, soda ash and titanium dioxide production. These two subsectors represent the majority of the large emitting plants listed in Figure 8.

In the UK there have been significant changes in recent years, driven by changes in demand and competition. Developing countries are increasingly competing with the UK sector, up and down the value chain. The government estimates that over 99% of UK chemical companies are small and medium sized enterprises (SMEs) (House of Commons Library, 2014), however, the UK has experienced an overall reduction in supply chain capabilities (particularly in upstream commodity chemicals) and now increasingly imports supplies i.e. the 'hollowing out' of the supply chain.

The basic inorganic subsector in the UK is concentrated in the North of England, and companies requiring chemical products are drawn to these areas as a result. The market includes few companies with greater than 5% market share, but IBIS (2014) expects the concentration to increase in future years due to mergers and acquisitions. The organics sector has similar structure, with a low level of concentration and key locations in the North West and North East.

Basic organic chemicals sales growth forecasts do not present a clear picture. Basic inorganic chemicals and chemical product manufacturing are projected to return to growth as the UK economy recovers from the financial crisis.

For organics, IBIS (2014) states that "*New capacity in low-cost countries, particularly in the Middle East, has made it difficult to regain lost ground over the past five years*", however steady growth is projected from increasing demand from downstream manufacturers. Inorganics suffered during the financial downturn, and according to IBIS (2014) this led to *"…declines in the level of industrial production, hurting downstream markets and leading to a sharp decline in industry revenue*…" In the next five years the sector is projected to grow as sales recover in line with the wider economy. Chemical product manufacturing is projected to rise gradually, in line with a gradual economic recovery and downstream demand for products.

3.4.2 Decarbonisation Strategies

The survey results on business decision making related to decarbonisation (see below) showed that the majority of respondents (12 out of 17 respondents) either agreed or strongly agreed that their organisation has well defined goals and/or targets in place. This finding reflects the interview findings, where the majority of interviewees reported that they have a strategy or targets in place, and well defined roles in terms of energy and carbon.

Question	Survey participants who agreed or strongly agreed
Our organisation has well defined goals and objectives and/or targets on energy and decarbonisation	12

Table 5: Goals and targets on energy and decarbonisation

At the workshop when participants were asked whether energy efficiency is important compared to other priorities in their organisation, all participants considered energy efficiency to be important but only half said it was important compared to other priorities in their organisation (see appendix B).

This distinction between energy (efficiency) and carbon was also highlighted during interviews. Although most of the interviewed companies (eight in total) reported having strategies for decarbonisation in place, they tend to think in terms of energy and efficiency. Improvement projects are not labelled as a 'decarbonisation project' and are not thought of in this way. There is a view that there is a potential tension between having a top-down strategy in place (i.e. an overarching emissions target), and improvement projects being identified using a bottom-up approach from site level. The result is that an emissions target may not be acting as a driver for projects, and indeed the majority of interviewees indicated that projects focus firstly on regulatory compliance and operational needs, and improvements (such as decarbonisation) will come last, only if funds and time remain. A shift in perception of the priority of decarbonisations will be necessary at all levels of the organisations to fully yield the benefits of investing in decarbonisation. This can be supported by government and key stakeholder groups starting to use language that better matches businesses' language e.g. energy efficiency.

The majority of companies interviewed had either a climate change strategy or environmental policy in place, supported by (relative) decarbonisation targets. A small number of interviewees highlighted the difficulties with setting targets (in the light of demand fluctuations), and that targets were considered valuable given the importance of energy to their business (from a cost perspective).

When survey respondents were asked what their position was in regards to carbon and energy efficiency reduction, 12 out of 17 of respondents considered themselves to be an early adopter or part of the early majority of adopters. However, the majority of interviewees indicated that their companies were risk-averse, and would be unlikely to pursue unproven technologies without demonstrations elsewhere. The breakdown of survey responses is shown in Figure 9 below.

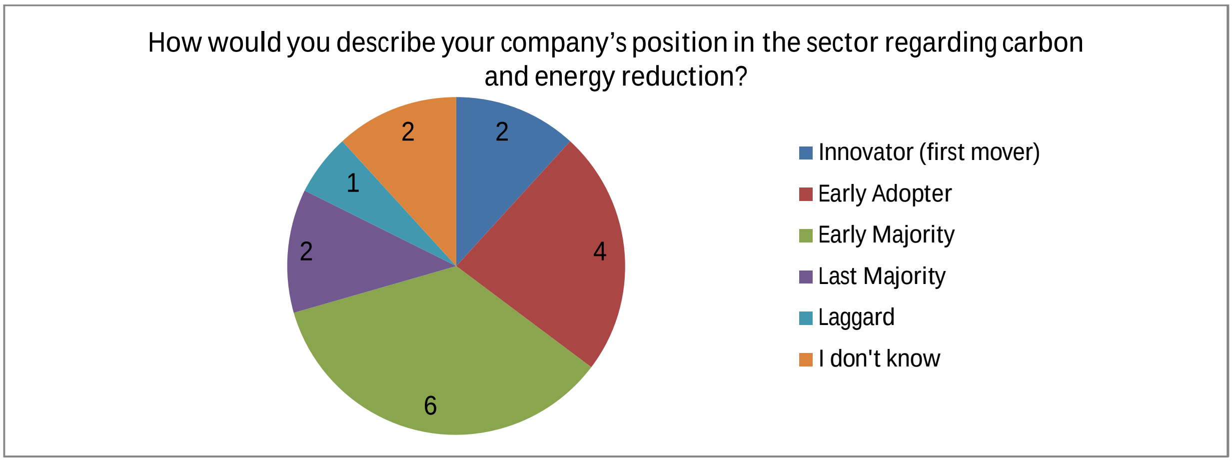

Figure 9: Breakdown of survey responses to company position on carbon and energy reduction

Several interviewees as well as industry representatives at the workshops highlighted that the UK chemicals sector has already invested heavily in process improvement and energy efficiency. Both indicated that the 'low-hanging fruit' had gone. This view was not held by all, as others stated that there will still be good opportunities for marginal improvements through cost-effective measures.

Existing sector plans: There is currently no UK-level decarbonisation sector plan for the chemicals sector. However, there is the growth strategy of the Chemistry Growth Strategy Group (2013), the industry-led council for the chemicals and chemistry-using sectors in the UK. The strategy indicates that, with the right conditions, the chemicals sector could reduce its carbon emissions by 30% by 2030. The strategy includes the desire to support *"…the proposal to work with government to develop a 'roadmap' for this sector, focusing on those parts of the sector that represent the greatest CO_2 emissions and use the greatest amount of heat".*

A roadmap exists at European level, titled "European Chemistry for Growth: Unlocking a Competitive, Low Carbon and Energy Efficient Future" (CEFIC, 2013). The roadmap was produced to explore the impact, opportunities, and risks of various energy and technology development scenarios for the European chemicals sector, from 2020 to 2050. A key finding of the roadmap was that the potential for energy and emission efficiency solutions will be reduced by fragmented and isolated EU policies at both national and European level. The report also found that deeper emissions reductions are technically possible through decarbonising the power sector and through CC, which both sit outside the chemicals sector's control. The pathways developed for this roadmap (see section 4) consider the decarbonisation contributions that can be made from these options.

A range of options were identified to contribute to the emissions reduction of the European chemicals sector, including energy efficiency improvements, fuel mix changes, Nitrous Oxide (N_2O) abatement, the decarbonisation of electricity production, and carbon capture and storage (CCS). The reduction to acceptable levels is achievable under what is called the 'level playing field scenario', where energy and policy costs in the EU are comparable to competitor regions.

In 2013, in another strategic initiative, the CGP was formed to enable government and industry to work together over the long term to address the key challenges and opportunities for the chemicals sector. The council, comprising mainly business leaders from the chemicals sector, has agreed to pursue key work themes around energy and feedstock, innovation, and supply chains in order to achieve its vision of a 50% growth in sector Gross Value Added by 2030. The CGP is co-chaired by an industry member and a government minister (Chemistry Growth Strategy Group, 2013).

These existing plans highlight the need for energy reduction and decarbonisation to be considered within the context of global competition. This point was reiterated by a number of the managers interviewed who indicated that this was vital in order to be able to attract the private sector investment that is needed.

3.4.3 Business Environment and Perception of Decarbonisation

The business environment: The UK chemicals sector has suffered from the financial downturn as demand from other parts of the economy declined.

Revenues in the organic sector plummeted and it will be difficult to regain lost ground against cheaper competitors. The organic sector has since recovered somewhat, but market data shows that production volumes are still 10% below pre-recession size (IBIS, 2014). New capacity in low-cost countries, particularly in the Middle East, has made it difficult for the UK to increase its market share over the past five years. Asian economies in the Far East have also rapidly expanded their capacity to manufacture organic chemicals and industrial production levels in these countries have boomed. In the medium term, the planned import by UK operators of lower cost feedstock from US shale reserves will go some way towards meeting this competitiveness challenge.

In the inorganics sector, there was also a sharp decline in revenue, but changes in export markets and the depreciated pound resulted in UK supplies being more attractive to overseas buyers. This served to offset a subdued domestic market, which is now projected to grow in the region of 6% from 2015-19 (IBIS, 2014). Companies in the sector indicate that the business environment remains challenging, with much of the literature pointing to the difficulties the UK sector has in terms of maintaining competitiveness against emerging markets. If poor economic performance continues, this will impact on the ability of the chemicals sector to invest in decarbonisation and look beyond the short payback required. There are also challenges in relation to higher policy and energy costs, alongside differences in operational cost bases. According to the European Climate Foundation (2014), CEFIC and Ecofys (2013), and other literature sources, the UK is struggling to compete with Asia, the United States and the Middle East, and this is projected to continue and to limit the ability to attract the investment for decarbonisation. Two environmental managers interviewed and workshop participants from industry reinforced this view. A stable business platform is identified by the evidence gathering as a key requirement to attract investment, and the current domestic business environment is one of high cost and uncertainty.

Policy: Current energy and carbon policies, both at European and UK level, are perceived by industry to have a significant impact on the competitiveness of the sector in a global context.

The EU ETS, Carbon Reduction Commitments (CRCs), CCAs, and the UK Carbon Price Floor were identified by industry as being contributors to competition issues. However, it is important to recognise that there are many other factors that contribute, including operational and labour costs, energy and raw material costs, and changing demand patterns.

The European Chemistry Industry Council concludes that the *“Fragmentation of policies and isolated EU approaches will reduce the European chemicals sector’s potential for energy and greenhouse gas efficiency solutions”.* This perspective was shared by the majority of interviewees and workshop participants, who reported that decarbonisation efforts must be coordinated at the appropriate level, and not come at the expense of competition. Energy prices and policy costs were identified in the survey as being a barrier with a medium-to-high impact upon decarbonisation. Interviewees and workshop participants supported this view, explaining that in many cases even simply the *perception* of the UK having a greater risk of policy uncertainty compared to other countries is sufficient to undermine investments. There is a clear need for a long-term direction from the UK government on energy and climate change policies in order to restore investment confidence and competitiveness of the industry.

Ricardo-AEA (2008) found that the *"lack of a stable policy regime"* was a barrier to investment, alongside a low carbon price, and the International Energy Agency found that *"high investment costs are not cost effective without a higher carbon price".* This view was supported by the majority of workshop participants, who reported that it is difficult to invest in projects or technologies given the uncertainty of the carbon price and future changes. This is because a change in price (or in policy costs) can undermine the business case upon which a project was taken forward. There is not always a clear business case, and some have a marginal benefit that could be eroded by changes in policy costs or energy costs.

3.4.4 Decision-Making Processes

Several interviewees (eight) identified that decision-making processes vary by company. The majority of companies select projects based on annual capital expenditure programmes (i.e. pre-agreed budgets and projects), with a small number appraising projects on an ongoing basis as they are identified.

Projects will typically be identified at site level by engineering and technical experts. Site managers will then prioritise projects and make recommendations to the next level of decision making, which is typically at country level or business unit level. If the projects are low-value, then they may be authorised at this level and need not progress further. For large and capital-intensive projects, another filtering process will take place and recommendations are made for which projects may move to the next level of decision making, at corporate or board level. The level of decision making depends on the size of the project, the capital requirements, and the level of risk.

At each of the levels, there exists competition between projects, for example:

- At a site level, the selection is based on factors including site priorities, operational considerations and downtime requirements, and available time and financial resource.
- At a country or business unit level, sites may be competing for investment against others (including in other countries).
- At a corporate level, large-scale projects are selected based on strategic decisions for the organisation, and influenced by competitive forces between geographies.

Projects that may appear attractive at one level may ultimately not be pursued due to decisions made at higher levels, for example, in response to the strategic aims of a company or where investment is preferred in other (commonly non-European) geographies.

Business cases are required at all levels, and the level of detail and interrogation will tend to increase as projects move up the decision-making hierarchy. Although climate change policies are considered as part of the decision-making process, for the majority of companies interviewed, environmental and climate change benefits are not the primary criteria for decision making. Such projects are not commonly labelled as being a 'decarbonisation' project, and it is the financial and operational impact of a proposed project that is the key determinant in decision making.

The majority of companies consulted reported that projects are classified in terms of being a 'compliance' project, or a 'production efficiency' project. Decarbonisation projects commonly fall into the category of 'improvement' projects, which tend to be considered if there is budget remaining following the compliance and production-type projects. The terminology used for this varies between companies, but a hierarchy of project types exist, with numerous interviewees indicating that compliance projects will be funded, whilst improvement projects will be subject to more scrutiny in terms of risk and expected financial performance (ROI, payback).

The survey results displayed in the table below show that the majority (12 out of 17) of companies responding have corporate energy and decarbonisation targets in place, and a higher number have site-level targets (13 out of 17). Nine respondents indicated that they have systematic decision making process in place with regards to energy and decarbonisation, and 11 indicated energy and decarbonisation were tracked at management meetings. Overall, the survey results suggest that carbon and energy reduction receives appropriate attention within organisations, and that decision-making processes are established. Survey results are shown in Table 6 below.

Question	Highlights of responses
Our company goals and objectives get translated to targets at site level	13 of responders agree or strongly agree
We have a systematic decision-making process for new initiatives w.r.t energy and decarbonisation that works well	9 of responders agree or strongly agree
We track progress of energy and carbon improvement projects in management meetings	11 of responders agree or strongly agree
We have some specific roles or allocated responsibilities within the company w.r.t. energy or decarbonisation	10 of responders agree or strongly agree
Our organisation has strong communication and information sharing channels that successfully support the implementation of options w.r.t. energy and decarbonisation	12 of responders agree or strongly agree
We have an understanding of which energy and decarbonisation technologies can be implemented in our organisation	11 of responders agree or strongly agree
We have a sufficiently skilled workforce to implement and handle energy and decarbonisation technologies	10 of responders agree or strongly agree

Table 6: Survey responses to company policies and targets

3.4.5 Financing Investments

From the eight interviews conducted with large chemical manufacturers, it was identified that the need for financing decarbonisation and energy efficiency technologies varies between companies. It was reported by some interviewees that the availability of capital remains a real challenge, whilst others have access to capital. However, current disincentives for investing in the UK (and Europe) present an obstacle compared to other markets. Very large projects, for example, in excess of £100 million, will typically be financed externally and the level of risk that is posed is a key consideration for financiers. Interviewees reported that small-scale investments will typically be financed internally and potentially at the local (i.e. site, business unit) level. The financing of medium-to-large scale investments varies between companies, with public companies or those that are part of large multinationals not identifying access to external finance as an issue. However, a key barrier is the limited availability of capital for improvement projects due to the high level of competition for internal funds in multinational companies and other projects that are more closely related to the core business.

A view shared among the interviewed companies is that internal financing is generally available, but that decision-making processes tend to go against UK sites and operations as the business case is stronger elsewhere. The primary reasons, according to these interviewees, are the lower cost of energy and labour in other markets, and stronger government incentives (e.g. in Germany), which result in a more financially sound business case compared to the UK. These factors were discussed by interviewees and supported in the literature e.g. European Climate Foundation (2014). The age of UK assets does not help in this regard, with operators being less willing to invest heavily in sites with a low book value.

The majority of managers interviewed reported that investments would be primarily financed internally, and be subject to the decision-making issues outlined above. The level of risk that an investment presents is a key determinant in whether a project is approved and subsequently financed.

Two managers interviewed indicated that they would not expect major investments in new plants to be made in the UK, given the higher potential returns that could be achieved in other markets (particularly Asia). Other interviewees indicated that it is difficult for the UK to demonstrate a strong business case and to get to the point of financing.

Payback periods of two to three years were commonly cited by interviewees as the threshold used internally. Paybacks beyond such at timescale were reported as unattractive to senior decision-makers, particularly due to the uncertainty around medium-to-long term energy and policy costs. One interviewee indicated that when attractive grant and financial support schemes are available, this gives confidence to (overseas) decision-makers as it demonstrates government commitment.

3.4.6 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 enablers and barriers have been identified through a number of different research methods, namely literature review, interviews, surveys and workshops.

Table 7 and Table 8 below indicate the most prevalent enablers and barriers across literature and interviews, as well as the perceived level of impact to decarbonisation as assessed by survey respondents and workshop participants. Although the number of times an enabler or barrier was referenced or highlighted provides guidance as to the strength of sentiment towards a particular enabler or barrier, the discussions during workshops and interviews provided a greater understanding as to the detail and context.

- There were 20 documents reviewed in detail as part of the literature review. The number in the literature column below indicates the number of sources that discuss enabler or barrier.
- There were eight semi-structured telephone interviews conducted in total. The number in the interview column below indicates the number of interviewees that discussed the enabler or barrier.
- The survey column shows the impact level of the enabler and barrier as assessed by 17 survey respondents (predominantly management-level representatives of UK chemicals manufacturers).
- The workshop column shows the impact level of the enabler and barrier as discussed and agreed by the evidence gathering workshop group.
- The numbers on the left-hand side do not represent 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 interviews, workshops and literature. Further depth and interpretation is provided in the following paragraphs.

Top Enablers

#	Category	Top enablers	Prevalence in occurrence		Level of impact	
			Literature	Interviews	Survey	Workshop
1	Market	Level playing field for energy	3	3	Medium-to-High	High
2	Legislation and Policy	A stable and predictable policy framework	1	5	Medium	High
3	Organisation	A strong, evidence based business case	1	4	Medium	High
4	Financial	Financial incentives	2	1	Medium-to-High	High
5	Legislation and Policy	Recognition of key technologies	-	4	n/a	High
6	Operational	Infrastructure replacement	-	1	n/a	High

Table 7: Top enablers

The first enabler – **a level playing field for energy** – was identified during the literature review (Chemistry Growth Strategy Group, 2013) and confirmed by interviewees, workshop participants, and survey respondents as having a high impact on implementing decarbonising options. Energy and policy costs are seen by the sector to be key contributors to losing competitiveness. This is directly related to the attractiveness for inward investment, and therefore the ability to fund improvement projects. This enabler is applicable now and will continue to grow in importance

The Chemistry Growth Strategy Group has established a common goal to "create a regulatory climate and culture that strengthens international competitiveness and delivers growth while addressing social and environmental responsibilities".

One environmental manager for a large manufacturer concluded that "investment partly depends on the price of carbon, and also on the balance of cost between regions" and that "the conditions need to be right [to invest in Europe], and the current competition issues need to be addressed".

The comments from workshop participants indicated that "the attractiveness of the UK for investment is essential to fund energy efficient and low-carbon technologies. This can be achieved by extending support packages for energy intensive industry and working to drive down the costs associated with low-carbon energy".

The second enabler – **a stable and predictable policy framework** – was identified during the literature review (European Chemistry Industry Council, 2013) and confirmed by interviewees, workshop participants, and survey respondents as having a medium-to-high impact on implementing decarbonising options. The need for stability and certainty was identified as key to ensuring confidence in the investment climate by the vast majority of interviewed managers. This covers two perspectives – firstly, the need for policy reversals to be avoided, and secondly, the uncertainty of future policy and the associated costs. A stable and predictable policy framework is perceived by the industry to have a strong correlation with ensuring a levelled playing field and these two enablers must be in place to facilitate the uptake of energy efficiency and decarbonising technologies. The need for certainty was highlighted as an issue, particularly for larger investments with payback over five years. The uncertainty over policy and energy costs can undermine business cases, particularly when in competition internally with other regions where returns have been more attractive (e.g. Asia). This enabler is applicable now and will continue to grow in importance.

The Chemistry Growth Strategy Group has established a common goal to "create a regulatory climate and culture that strengthens international competitiveness and delivers growth while addressing social and environmental responsibilities".

While discussing the renewable heat incentive for CHP, one technical manager of a large multinational concluded that "The economics [of projects] can be finely balanced, and changes in policy can have significant impacts. Regulatory changes can leave you high and dry."

An environmental manager stated that "certainty around the future policy landscape is needed – in the past there have been reversals and changes in direction. We need stability to make energy efficiency and reducing carbon emissions a priority."

The third enabler – **a strong, evidence-based business case** – was identified during the literature review (Carbon Trust), confirmed by interviewees, workshop participants, and survey respondents as having a high impact on implementing decarbonising options. Capturing all costs and financial savings is believed by industry managers to provide the support to get executive buy-in and pursue more energy-efficient technologies. Industry representatives who attended the workshop described this enabler as an 'absolute necessity' for senior management to even consider any energy-related projects, more so than for product development or marketing projects. This appears to be largely driven by increased risk aversion, which is due to the weak economic climate and rising pressure from competitors overseas. This enabler is applicable now and will continue to grow in importance when and if the economic climate stabilises and new technologies are commercialised.

The Carbon Trust identified that business cases for investments "will need to be robust. Savings must be deliverable and all financial savings and costs captured".

Industry representatives at the workshops indicated that an evidence-based business case requires data, and good data helps to identify quick wins. It was mentioned that government needs to better realise that legislation (and costs) affects the business case, and therefore investment decisions.

The fourth enabler – **financial incentives** – was identified by interviewed managers of large manufacturers in the UK and confirmed by workshop participants and survey respondents as having a medium impact on the implementation of decarbonisation technologies. This enabler has a different level of importance depending on the need for financial support of each organisation. An environmental manager reported during an interview that finance was available internally and that meeting financial requirements of energy-related projects was the main challenge. In general, smaller organisations (e.g. UK companies that are not part of a multinational) perceive the access to financing as a barrier. Financial incentives are directly linked to reducing costs of energy and/or carbon, and are seen by management as enablers regardless of the size of organisations. It was suggested that government should take into account that incentive schemes need to be long-term commitments, as reversals in policy (e.g. incentive schemes) can be damaging, particularly when the business case for investment is marginal and is highly dependent upon factors such as (fluctuating) energy prices. This enabler is applicable now.

The Chemistry Growth Strategy Group identified the need to *"incentivise and increase updates of existing energy efficiency measures…"* and to "*ensure the right framework and incentives for the adoption of energy-efficient and low-carbon technologies to reduce emissions".*

Industry representatives at the workshops indicated that "incentives to lower lending rates were identified as a means to enhance the enabler, in order to promote the business case."

The fifth enabler – **recognition of key technologies** – was identified by managers interviewed and confirmed by workshop participants as having a high impact on implementing decarbonisation technologies. This enabler signifies the need for greater focus and direction from the industry and government in terms of the key technologies for decarbonisation. The risk of not defining the key technologies is wasted resource in the development of applications that will not have the required level of impact (i.e. disruptive impact). This enabler is applicable now.

An environmental manager of a large manufacturer concluded that "we need to decide what the overall value position of the UK is going to be… If we understand how the parts of the industry can fit together, then collaborations can be based upon this" and "there is a need to convince and bring appropriate parties together".

A technical manager stated "We need to recognise which technologies should be implemented. Policy statements that give direction on this are really important when going to the [company] board."

The sixth enabler – **infrastructure replacement** – was identified by a technical manager interviewee and confirmed by members of the workshop groups as having a high impact on implementing decarbonising options. In their view, there is a need to periodically replace and improve assets to provide opportunities for marginal gains. Most of the workshop participants rated this as having a very high impact, given that the business case is strengthened by an operational need for upgrades and short-term benefits. This enabler is applicable now.

Top Barriers

#	Category	Top Barriers	Prevalence of occurrence		Level of impact	
			Literature	Interviews	Survey	Workshops
1	Organisation	Internal competition for funding and resources	3	4	Low-to-Medium	High
2	Financial	Energy prices and policy costs	4	3	Low-to-Medium	High
3	Financial	Unattractive payback and stringent ROI	2	3	High	Medium-to-High
4	Legislation and Policy	Uncertainty from policy and regulation	2	1	Medium	Medium-to-High
5	Financial	Access to capital and funding	1	1	Low-to-Medium	Medium-to-High
6	Technology	Lack of commercialisation of new and unproven technologies	-	1	Medium	High

Table 8: Top barriers

The first barrier – **internal competition for funding and resources** – was identified during the literature review (Ricardo-AEA and Imperial College, 2013) and confirmed by industry representatives at the workshop as having a high impact on implementing decarbonising options. Sites that are part of multinational companies feel threatened by competition for funding at a number of levels. Interviewees with responsibilities for energy-efficient investments highlighted that it was difficult to justify major investments in UK plant and assets, when management is given a choice over other locations. A number of factors contribute to this, including policy costs (for carbon and renewable energy, energy and raw material costs, compliance costs, and labour costs). An opinion was shared that there was little appetite to invest in large-scale UK decarbonisation projects if payback and returns on investment are more favourable in other countries. On a more practical level, industry representatives highlighted the resourcing issues that they face. With limited resource, engineers focus their efforts on compliance and process-related improvements. There is limited resource to focus on 'improvement projects' for decarbonisation. The impact of this barrier was reported to have increased following the financial crisis, given changes in workforces and the reduced availability of sufficiently skilled talent. This barrier is applicable now.

Ricardo-AEA and Imperial College (2013) found that barriers for industrial emissions abatement include "…the availability of capital for investment, and available man-hours to drive projects through" and that "many commodity chemicals are made by global companies who look globally for the best capital investment opportunities. Increasing costs in the UK can erode the ROI, making investment opportunities outside of the EU look relatively more attractive."

An environmental manager for a large manufacturers concluded that "Wider corporate and strategic drivers may mean than one project is selected over another [despite the local business case]. We struggle to compete for capital internally… There is a preference to invest in areas of greater return."

The second barrier – **energy and policy costs** – was identified during the literature review (Centre for Low Carbon Futures) and confirmed by workshop participants as having a high impact on implementing decarbonising options. 'Policy costs' refers to the extra cost of production as result of government policies and regulations. High energy and policy costs were cited by industry representatives as one of the top barriers. Workshop participants also did not consider high energy costs to be an enabler or to stimulate investment in energy reduction and efficiency; rather, they see them as a business cost that reduces global competitiveness and lowers the attractiveness of investment in the UK. This barrier is applicable now.

The Centre for Low Carbon Futures found that the price of energy is "a barrier to investment. Parent companies see a poor ROI in the UK compared to elsewhere."

A technical manager of a large manufacturer concluded "there is a barrier related to government changing its legislative positions, creating uncertainty… [around energy prices and cost of policy]."

The third barrier – **unattractive payback and stringent ROI** – was identified during the literature review (Sorrell et al, 2000) and confirmed by interviewees, during workshops, and by the survey respondents as having medium-to-high impact on implementation of decarbonisation technologies. This barrier is closely related to the level of internal competition for funding, particularly within large companies with operations worldwide, which constitute a large proportion of the sector's emissions. Companies have a range of investment opportunities, and business case and payback periods are considered critical by management to securing investment. Interviewees and workshop participants highlighted the relative unattractiveness of investing in the UK versus locations in Asia, for example, where the business case is stronger and returns are more predictable. This barrier is considered to be applicable now.

Sorrell et al, 2000 identified that "…use of very stringent payback periods" of less than two years was an example of an 'organisational failure' for energy efficiency".

A manager of large multinational concluded that "payback on projects is the main consideration. Projects must meet the relevant financial criteria".

The fourth barrier – **uncertainty from policy and regulation** – was identified during the literature review (European Chemistry Industry Council) and confirmed by interviewees, workshop participants, and survey respondents as having a medium impact on implementing decarbonising options. Industry representatives share the view that policy uncertainty makes it difficult for companies to take large investment decisions, especially since the payback time is longer than the policy horizon. This is an issue particularly with regards to CCS, where the regulatory requirements are perceived as stringent and at present are not sufficiently developed to allow companies to understand the potential costs and risks. This barrier is applicable now.

A technical manager from a large manufacturer assessed that "CCS is an area that could be a strategic opportunity, but policy cost and regulatory uncertainty are all barriers to investment".

Workshop participants from the sector indicated that "there are perceived risks from regulation but also in terms of uncertainty in outcomes. It was reported that there would be limited investment with regulatory uncertainty, particular in terms of new technologies".

The fifth barrier – **access to capital and funding** – was identified during the literature review (Centre for Low Carbon Futures) and confirmed by interviewees, workshop participants, and survey respondents as having a medium impact on implementing decarbonising options. The barrier of access to capital can exist in two forms; firstly, directly in terms of a lack of funding. This was regarded by industry representatives as being more of an issue for smaller companies. The majority of the large manufacturers interviewed did not identify capital as an issue at all. Secondly, the barrier also persists indirectly, when finance is available but it is not possible to demonstrate a strong enough business case to obtain funding or where the level of risk is considered too high to warrant investment. This barrier is considered to be applicable now.

An environmental manager of a large manufacturer explained that "it can be difficult to get senior management to understand [the policy setting in the UK]… It is difficult for them to assess risk and the UK appears a lot more complex to other regions we are competing with for capex".

Industry representatives attending the workshop indicated that "the importance of this barrier depended on profitability. Minor projects with returns within two years would more likely receive funding due to certainty of returns and lower risk".

The sixth barrier – **lack of commercialisation of new and unproven technologies** – was identified during the literature review (International Energy Agency) and confirmed by workshop participants and survey respondents as having a medium-to-high impact on implementing decarbonising options. This is a very significant barrier for small technology developers (due to difficulties in accessing skills and finance, for example), but less so for large commodity producers. Commodity producers highlighted that they will tend to make incremental changes to established plants, rather than introduce new technologies due to risk of disruptions in production. The high cost of new technologies was cited by large manufacturers as one of the key reasons why companies do not pursue commercialisation by themselves. There is therefore an opportunity for the sector to collaborate to develop and co-finance innovative technologies in order to overcome these issues. The current focus for R&D is upon aspects other than decarbonisation (e.g. product development). This barrier is considered to be applicable now.

The Chemistry Growth Strategy Group found that "much greater research is urgently required on the potential for commercialisation of CCS".

3.5 Technologies to Reduce Carbon Emissions

The options distilled from the literature review, interviews, evidence-gathering workshop, and discussions with the CIA and the sector team are presented in appendix C (the cost data for these options are also listed). The energy-efficiency and decarbonisation opportunities are classified into the following categories:

- **Fuel substitution:** These options relate to changing the fuel used to provide energy to the chemical process and include options such as biomass fuel and using low-carbon methane.
- **Feedstock switch:** These options involve changing the feedstock (raw material) used for a process to a lower carbon alternative, for example, using recycled plastics to provide feedstock.
- **CHP:** These options reduce emissions by using combined heat and power generators to provide energy and so reducing emissions by getting energy from the fuel used.

- **CC:** CC options involve capturing CO_2 generated in the sector and either storing it to prevent its emission or re-using it as a feedstock for the sector.
- **Energy efficiency:** These options are generally incremental in nature and use known technologies to reduce the amount of energy required to carry out current processes (e.g. by improving process control, reducing heat losses). It should be noted that the sector has already deployed many of these options to a significant degree; however, potential remains for further energy efficiency gains and thus decarbonisation using these options.
- **New process technologies:** These options make use of new technologies to carry out existing processes but to do so more efficiently (e.g. by using membrane technologies to replace energy-intensive distillation separation steps).
- **New chemical pathways:** These options represent new chemical routes to produce existing products (i.e. new chemical feedstock or reactions). Many of these options are at an early stage of development.
- **Clustering:** The clustering option refers to chemical sites and processes (and sites from other sectors) that are located near to each other sharing energy and raw materials to increase efficiency and reduce overall emissions.

These options do not include the development of new sector products to replace those currently manufactured. Analysis of this kind of market change was outside the scope of this roadmap. This short list of options was used in the pathway analysis (section 4).

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) derived from a low scenario from the DECC-commissioned Bio-Energy Emissions and Counterfactual Model report (2014). An emission value of 20 kg CO_{2e}/MWh_{th} has been used for solid biomass use, and this has been modified to 25 kg CO_{2e}/MWh_{th} if the pathway includes pyrolysis, and 30 kg CO_{2e}/MWh_{th} if the pathway 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 decarbonisation and energy efficiency 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 and energy efficiency pathways. For example, some options (e.g. CC 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 4.7. There is a large degree of uncertainty attached to the cost analysis, especially for options which are still in the R&D 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

In order to understand how different decarbonisation options could result in different levels of sector decarbonisation depending on the global economic and collaborative environments, a series of pathways was developed under each of three scenarios (current trends, challenging world and collaborative growth). These show different possible decarbonisation paths based on different levels of ambition in option deployment through to 2050, with more ambitious pathways including greater or more rapid option deployment. The pathways allow the combined effect of the technological options to be understood and the influence of the different scenarios to be taken into account.

The pathways were developed from an analysis of the evidence gathered on the possible decarbonisation options (from literature, interviews, workshops, and surveys). This analysis was then used to provide the inputs to the pathways model. A pathways development meeting of the sector team then generated the pathways using the model. A detailed description of the pathways inputs, development and analysis can be found in appendix A.

The pathways development and analysis showed that, with a continuation of existing trends in energy efficiency and decarbonisation, the decarbonisation potential of the sector is emissions of 12.6 $MtCO_2$ in 2050. This corresponds to a reduction of 31% compared to the base year emissions in 2012[15] of 18.4 million tonnes CO_2, which can be referred to as the potential additional reduction achieved under the BAU pathway under the current trends scenario. With extra drivers for decarbonisation in the 40-60% CO_2 reduction pathway, a potential emissions reduction of 54% was achieved.

With the right enablers in place and barriers removed, and taking no account of cost, the maximum decarbonisation (or Max Tech) potential of the sector was emissions of 2.2 million tonnes CO_2 in 2050, which corresponds to a reduction in emissions of 88% compared to emissions in 2012. The analysis indicated that this could only be achieved under the current trends scenario, although reductions of 64% could be achieved under the challenging world scenario and 83% under the collaborative growth scenario (based on the assumptions of the pathways analysis and model)[16]. These reductions refer to the Max Tech pathway for each scenario and were achieved through a range of options, the most significant of which were:

- Decarbonisation of heat by supplying heat using low-carbon biomass
- Use of CCS on both process and combustion emissions
- Use of biomass as a source of chemical feedstock, partially replacing the use of natural gas and petroleum derived feedstock
- Decarbonisation of methane[17]
- Further deployment of energy efficiency measures
- Clustering of chemical production to optimise the use of energy and materials

In addition, decarbonisation of the electricity grid was found to be a significant contributor to overall decarbonisation.

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[15] Note that this reduction is similar to the potential 15-25% described in the CEFIC and Ecofys roadmap (2013).

[16] Potential decarbonisation in 2050 under collaborative growth is less than under current trends because the higher production growth under collaborative growth results in extra emissions.

[17] Decarbonised methane refers to production of methane by low-carbon means, e.g. on-site anaerobic digestion, or electrolysis of water followed by methanation.

It should be noted that some of these options are outside the direct control of the sector itself (e.g. electricity grid decarbonisation), while others will be dependent in part on progress outside the sector (e.g. supply of low-carbon biomass and development of CC networks). Further options, such as ongoing deployment of energy efficiency and clustering, could be delivered by the sector itself. Achieving any of the decarbonisation and energy efficiency pathways will require a mix of options delivered both within and outside the sector.

The different decarbonisation and energy efficiency pathways explored under the current trends scenario are set out in Figure 10, showing emissions (relative to 2012) through to 2050 based on different deployment of the various decarbonisation options. Pathways where decarbonisation options are deployed earlier or to a greater extent show a faster reduction in emissions.

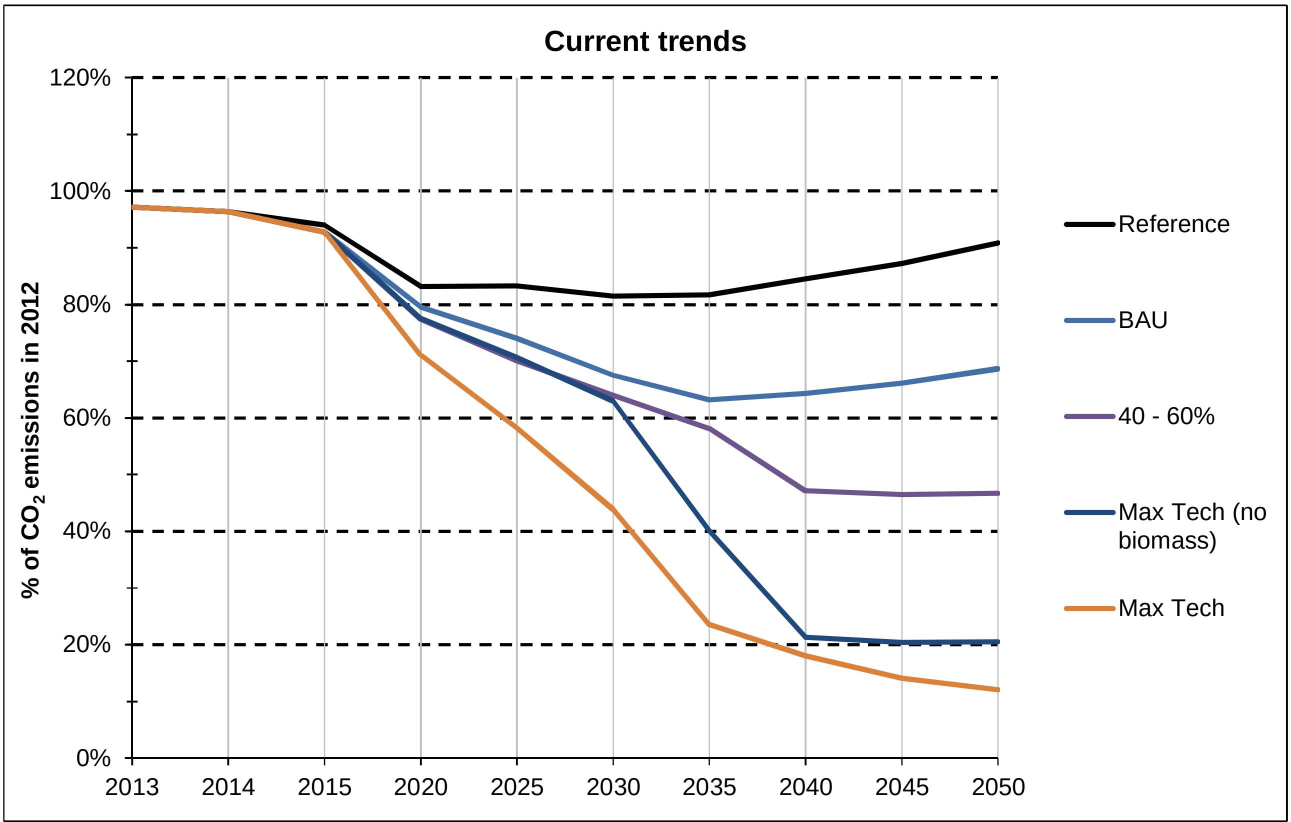

Figure 10: Performance of pathways under current trends

- Reference is a pathway where no decarbonisation options are deployed and shows only the combined effect of production growth and grid decarbonisation over time.
- BAU is a pathway where existing trends in energy efficiency and decarbonisation continue. This provides the 20-40% reduction pathway.
- 40-60% is a pathway where there are some increased drivers for decarbonisation (e.g. policy incentives or increased demand from customers for low-carbon products), resulting in more or faster deployment of some decarbonisation options.
- Max Tech is a pathway where all potentially technically feasible options are deployed when they become available without cost being a limitation, but while also being reasonably foreseeable with further technical development.
- Max Tech (no biomass) is a pathway similar to Max Tech but where low-carbon biomass is not available. As a result some other technologies are deployed more extensively. This pathway was selected due the high contribution being made by biomass to the other pathways and current

uncertainties about the decarbonisations that can be provided by biomass. This pathway also provides the 60-80% reduction pathway.

For all these pathways, decarbonisation in the period 2015-2025 is achieved by further deployment of established energy efficiency technologies and by the decarbonisation of grid electricity. From 2025 onwards (2020 for the Max Tech pathway), biomass fuel is deployed and contributes significant decarbonisation in the two Max Tech pathways. In the 2030s, CC is deployed to varying degrees in all but the BAU pathway, resulting in greater divergence between this pathway and the others. From 2040, the major contributing technologies in the 40-60% reduction and Max Tech (no biomass) pathways have been deployed and so the trend of decarbonisation levels off. In the BAU pathway, fewer of these options are deployed and so emissions begin to rise again after 2035.

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 characterise 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). These scenarios were used during the workshop to help decide on deployment rate for the different options.

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 reductions 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 or 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 11.

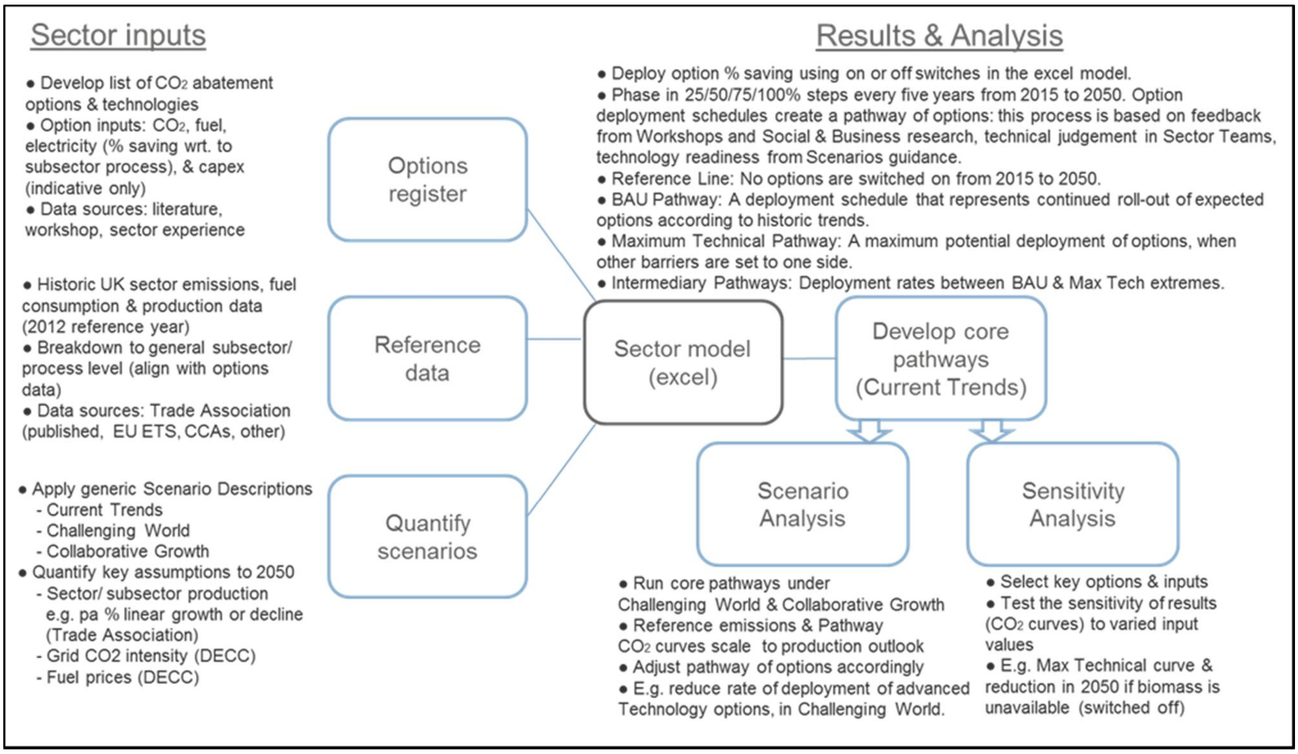

Figure 11: Summary of analysis methodology

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 9 illustrates this structure and acts as a guide to the section. Section 4.5 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 are deployed in the model.		
BAU	Builds on the base year 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%[18]	Builds on BAU for example by: deploying more advanced options, extending further across sector, deploying options earlier. Run under current trends.	Builds on 20-40% CO_2 reduction pathway current trends in the same way. Run under challenging world.	Adjust 20-40% CO_2 reduction pathway current trends in the same way. Run under collaborative growth.
40-60%	Builds on 20-40% in the same way. Run under current trends.	Builds on 20-40% CO_2 reduction pathway current trends in the same way. Run under challenging world.	Adjust 20-40% CO_2 reduction 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% CO_2 reduction pathway current trends in the same way. Run under challenging world	Adjust 40-60% CO_2 reduction pathway current trends in the same way. Run under collaborative growth.
Max Technical	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 9: Pathways and scenario matrix

Section 4.6 presents results from the sensitivity analysis, which aims to demonstrate the impact of key options and sensitivity of the pathways to critical inputs while Section 4.7 presents the analysis of pathway costs. Section 4.8 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?'

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

The sector team used the generic scenarios to develop sector-specific descriptions of how these scenarios might apply to the chemicals sector in the UK. These take account of factors such as the high levels of international trade within the sector, the importance of feedstock supply issues such as shale gas, and the impact that growth (or the lack of it) can have on the ability to invest in new technology.

Based on this analysis, the sector team developed sector production growth rate estimates for the three scenarios as follows:

- Current trends – 1% annual growth
- Challenging world – 0.5% annual decline
- Collaborative growth – 2% annual growth

The sector-specific scenarios assume that all subsectors grow at these rates and therefore baseline energy and emissions are assumed to change at these rates through to 2050. Emissions were assumed to have a linear relationship to production i.e. a 1% change in production results in a 1% change in emissions.

4.4 Pathways Analysis – Principal Questions 4 and 5

In order to understand how different decarbonisation options could contribute to sector decarbonisation under the different scenarios (current trends, challenging world and collaborative growth), a series of pathways were developed under each scenario. These show different possible decarbonisation paths based on different levels of ambition in option deployment through until 2050, with greater or more rapid option deployment in the more ambitious pathways. The pathways allow the combined effect of the options to be understood and the influence of the different scenarios to be taken into account.

The pathways were developed from an analysis of the evidence gathered on the possible decarbonisation options (from literature, interviews, workshops and surveys). This analysis was then used to provide the inputs to the pathways model. A pathways development meeting the sector team then generated the pathways using the model. A detailed description of the pathways inputs, development and analysis can be found in appendix A.

The pathways deployment tables presented in section 4.4 include grid decarbonisation as an option. This was retained on the option list to show that it has been included, but deployment in all pathways has been set to zero since grid decarbonisation is included in the background assumption of the pathways model.

A further option that emerged at the second workshop is process electrification. This would involve converting processes to use electricity in place of other fuels (such as natural gas). This has not been included in the pathways in this report because the option was not identified in the earlier stages of the evidence gathering process which provided the inputs to the pathway development. Process electrification could provide additional decarbonisation opportunities, assuming that the carbon intensity of the grid is lower than that of the existing fuel use. It should be noted that the increased use of electricity in processes is included in other options, for example, the use of electrolysis to generate hydrogen, or the use of membrane separation technologies.

The option ‘recycled plastics as syngas’ is included in the deployment tables but has zero deployment in all pathways. This is because the pathways modelling found it to be marginal in terms of emissions reductions, and resulted in slight increases in emissions under some pathways. The energy use for this option is suggested as a potential sensitivity in section 4.6, to assess whether a reduction in energy requirements could allow it to make a decarbonisation contribution.

A small number of other options shown in the deployment tables are not deployed in any pathways, based on evidence from interviews and workshops that any deployment of these options was not foreseeable in the

UK in the period to 2050. These have been retained in the tables for completeness but show zero deployment.

The use of shale gas was not included as a decarbonisation option as the evidence from interviews and workshops is that it would not directly provide emissions reductions (although current investment in import facilities is resulting in plant upgrades that are likely to improve energy efficiency overall). Future use of shale gas is used to inform the development of the pathways, however, because it is a potentially important future supply of feedstock to the sector[19] and therefore has an impact on how other options may be deployed.

Pathway analysis was based on the 'maximum interaction' case, as this gave the minimal, worst-case CO_2 reductions. Maximum interaction means that where multiple options could apply to the same portion of emissions, the emissions reductions are made by a combination of contributions from the different options while avoiding potential double-counting of reductions.

4.4.1 Business as Usual Pathway

Pathway Summary

In line with the definition of BAU (see section 4.2), this pathway was developed by deploying options at the time and scale expected where no additional interventions are made to promote decarbonisation. However, it is expected that some investment into energy efficiency and decarbonisation is being made (in line with current levels).

The effect of decarbonisation of grid electricity was significant in relation to the options deployed. The total overall reductions of 31.3% are a result of 22.2% reductions from the options, 36.3% reductions from grid decarbonisation and a 27.2% *increase* in emissions as a result of production growth.

The BAU pathway provides the pathway meeting the 20-40% decarbonisation band.

Deployment under Current Trends

The deployment of each of the options in the BAU pathway under **current trends** can be seen in Figure 12. Additionally, the contribution of the principal options and grid decarbonisation to absolute emissions reduction is shown in Figure 13 and the breakdown of emissions reductions from the leading options in 2050 is shown in Figure 14.

In this pathway, grid decarbonisation accounts for more than half of the total emissions reductions. The principal options that contribute to the emissions reductions in 2050 are:

- Biomass fuel, deployed to 5% of its full potential in 2020 and rising to 15% and 25% in 2025 and 2030 respectively. This was based on the assumption that supplies of low-carbon biomass, constraints on investment, and levels of incentives will limit deployment to a proportion of the total potential. This deployment profile results in 8.6% emissions reductions in 2050 compared to the 2012 base trend. This represents more than a third of the total emissions reductions from the options.
- The combined energy efficiency options (numbers 16-20) are deployed gradually from 2015 on the basis that, under BAU current trends, these options will be deployed as equipment needs to be replaced, with some constraints on funding restricting deployment to projects with higher returns. These result in 7.2% emissions reductions in 2050 compared to the base trend, which is about one third of the total emissions reductions from the options.

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[19] For example, further indigenous or imported supplies of ethane could increase investment in production plants for its downstream sectors and increase emissions from the organics sector due to the resulting growth in production.

- CCS (process) is split between ammonia and hydrogen with a larger proportion of reductions coming from ammonia. Both are deployed to 33% in 2035 and remain at this level of deployment until 2050. This deployment gives 3.6% emission reductions in 2050 compared to the 2012 baseline. This represents 16% of the total emissions reductions from the options.
- Waste fuel is deployed to 5% of full potential in 2015, rising to 10% from 2025 onwards. This is on the assumption that limited deployment will occur due to limited availability of waste fuel for the sector. This results in 2.0% emissions reduction in 2050 compared to the base trend which is 9% of the total emissions reductions from the options.

The following options have been also deployed in the BAU pathway, and result in modest emissions reductions of 0.2-0.3% each in 2050:

- Clustering
- CHP
- Process intensification

Figure 12 below shows the deployment of each option used to derive the BAU pathway under current trends. In this table:

- 'Category' describes the broad technical category to which each option is allocated.
- 'ADOP' (Adoption) refers to the level at which an option is currently adopted. In many cases, this is set at 0% because the option refers to future potential so by definition current adoption is zero. For example, options 16-20 on energy efficiency have 0% adoption because they refer to future adoption and not to energy efficiency measures which have already been implemented.
- 'APP' (Applicability) refers to how much of the sector (or subsector) the option could potentially be deployed e.g. membrane technology could only apply to a maximum of 10% of the sector.
- 'Deployment' shows how much of the option's potential is deployed and at what time. Values here refer to how much of the difference between ADOP and APP is deployed. For example, CHP has an ADOP of 30% and an APP of 50%, so a 10% Deployment refers to deploying a tenth of the 20% potential i.e. moving to an ADOP level of 32%[20].

[20] Final Adoption = (Initial Adoption) + (Deployment x (Applicability – Initial Adoption)) = 30% + 10%x(50%-30%) = 32%

BAU - current trends

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Biomass as fuel	0%	50%	0%	0%	5%	15%	25%	25%	25%	25%	25%
02 Waste as fuel	0%	25%	0%	5%	5%	10%	10%	10%	10%	10%	10%
03 Low carbon electricity	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04 Decarbonised methane as fuel	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
05 Biomass as feedstock	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 Hydrogen by electrolysis - Ammonia	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 Hydrogen by electrolysis - Hydrogen	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
09 Recycled plastics - syngas	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10 CHP	30%	50%	0%	0%	5%	10%	15%	15%	15%	15%	15%
11 Integrate gas turbines with cracking furnace	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
12 CCS - combustion (incl. biomass)	0%	60%	0%	0%	0%	0%	0%	0%	0%	0%	0%
13 CCS - process - Ammonia	0%	100%	0%	0%	0%	0%	0%	33%	33%	33%	33%
14 CCS - process - Hydrogen	0%	100%	0%	0%	0%	0%	0%	33%	33%	33%	33%
15 CCU	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
16 Improved insulation	0%	100%	0%	5%	10%	25%	50%	50%	75%	75%	75%
17 Improved waste heat recovery	0%	100%	0%	5%	10%	25%	25%	25%	25%	25%	25%
18 Improved process control	0%	100%	0%	10%	25%	50%	75%	100%	100%	100%	100%
19 More efficient equipment	0%	100%	0%	10%	25%	50%	75%	100%	100%	100%	100%
20 Improved steam system efficiency	0%	100%	0%	0%	10%	25%	50%	50%	75%	75%	75%
21 Membrane technology	0%	10%	0%	0%	0%	0%	0%	0%	10%	10%	10%
22 Process Intensification	0%	20%	0%	0%	0%	0%	0%	5%	10%	15%	15%
23 High temperature cracking	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24 Catalytic cracking	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
25 Retrofit ODC for chlorine production	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%
26 Bioprocessing	0%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%
27 Methanol-to-olefins	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28 High temperature steam electrolysis	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
29 Solid state synthesis	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30 Clustering	25%	50%	0%	0%	0%	5%	5%	5%	5%	5%	5%

Figure 12: Deployment of options for BAU pathway, current trend scenario

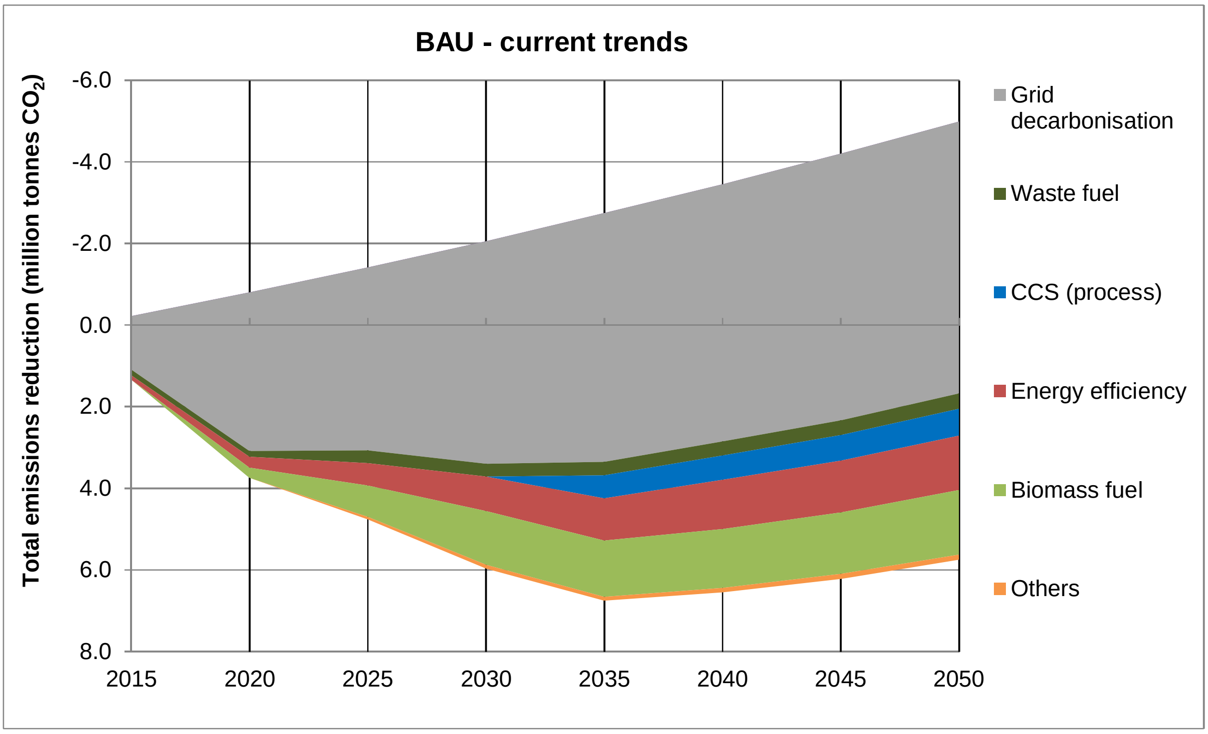

Figure 13: Contribution of principal options to the absolute emissions reductions throughout the study period, for the BAU pathway, current trends scenario

Figure 13 shows the absolute emissions reductions from grid decarbonisation and the principal options over the study period. With no grid decarbonisation or options deployed, emissions would rise due to the production growth in the current trends scenario. The contribution of the options (i.e. excluding grid decarbonisation) is 4.1 $MtCO_2$ in 2050.

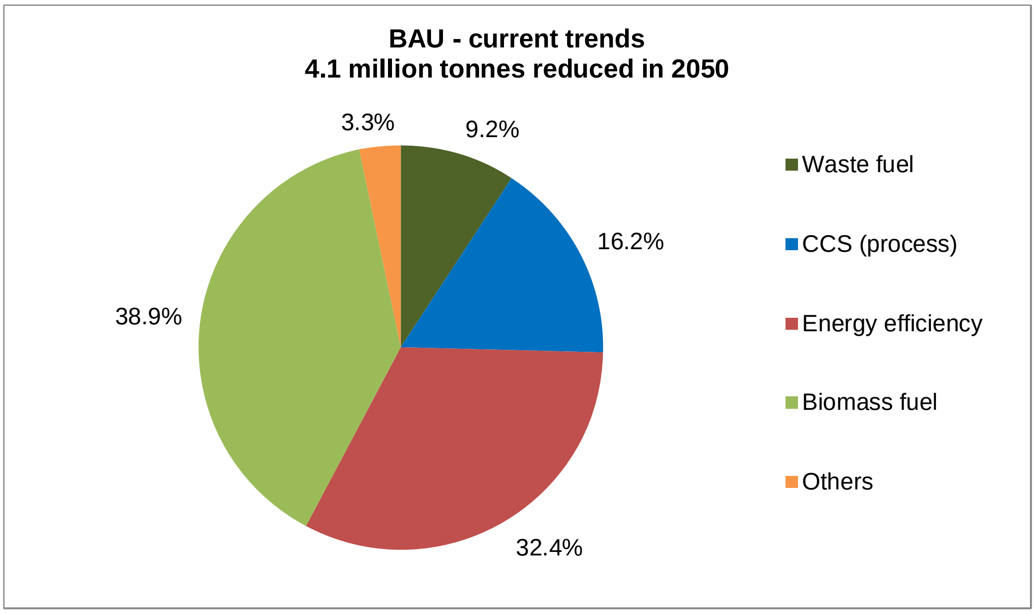

Figure 14: Breakdown of 2050 emissions reductions for the BAU pathway, current trends scenario

Figure 14 shows the relative contribution of the principal options (i.e. excluding grid decarbonisation[21]) to the total options reduction of 4.1 million tonnes of CO_2.

Option Deployment under Other Scenarios

BAU pathways under the other scenarios are discussed in section 4.5 and the associated deployment tables are provided in appendix D.

4.4.2 40-60% CO_2 Reduction Pathway

Pathway Summary

Under this pathway, deployment of some options takes place earlier or to a greater extent to reflect the extra policy or other decarbonisation drivers present under this pathway.

Compared to the BAU pathway, the options are making a larger contribution although the effect of decarbonisation of grid electricity remains significant. The total overall reductions of 53.6% are a result of 44.5% reductions from the options, 36.3% reductions from grid decarbonisation and a 27.2% increase in emissions as a result of production growth.

This provides the pathway meeting the 40-60% decarbonisation band.

Deployment under Current Trends

The deployments of each of the options in the 40-60% CO_2 reduction pathway under current trends can be seen in Figure 15. Additionally, the contribution of the principal options and grid decarbonisation to absolute emissions reductions is shown in Figure 16 and the breakdown of emissions reductions from the leading options in 2050 is shown in Figure 17.

[21] 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

In this pathway, grid decarbonisation is a significant contributor to emissions reductions. The principal options that contribute to the emissions reductions in 2050 are:

- Biomass fuel is deployed to 10% of its full potential in 2020 and rises to 40% by 2040, reflecting a higher level of deployment than under BAU in response to stronger drivers towards decarbonisation. This results in 12.1% emissions reduction in 2050 compared to 2012, which is 27% of the total options reductions.
- CCS (combustion) is deployed to 25% from 2040 onwards on the assumption that this option has become technically and economically viable for this proportion of potential plants and that sufficient drivers exist to encourage investment. This level of deployment results in 8.5% emissions reductions in 2050, which is about a fifth of the total options reductions in that year.
- The combined energy efficiency options, deployed gradually from 2015 but at a faster rate than under the BAU pathway, result in 7.5% emissions reductions in 2050 compared to the base year, which is nearly a fifth of the total options reduction.
- Decarbonised methane as fuel is deployed to 5% of potential in 2040. This results in 3.6% emissions reduction in 2050 compared to the base year, which is 8% of the total options reduction.
- CCS (process) is split between ammonia and hydrogen with a larger proportion of reductions coming from ammonia. Both are deployed to 33% in 2035 and remain at this level of deployment until 2050. This deployment gives 3.1% emission reductions in 2050 compared to the 2012 base year. This represents 7% of the total emissions reductions from the options.
- Biomass feedstock is deployed to 10% of potential in 2035 and increased by 5% in each five-year increment thereafter. Again, this represents some conversion of feedstock supply for the most favourable processes in response to the extra drivers under this pathway (compared to no deployment under the BAU pathway). This provides 2.7% emissions reduction in 2050 compared to the base year, which is 6% of the total emissions reduction from the options.

The following options have also been deployed in the 40-60% reduction pathway, and result in modest emissions reduction (0.3-2.6% emissions reduction for each):

- Catalytic cracking
- Waste as fuel
- Integrated gas turbines with cracking furnace
- Clustering
- Bioprocessing

40 - 60% - current trends

OPTION	ADOP.	APP.	DEPLOYMENT								
			2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Biomass as fuel	0%	50%	0%	0%	10%	25%	30%	35%	40%	40%	40%
02 Waste as fuel	0%	25%	0%	5%	5%	10%	10%	10%	10%	10%	10%
03 Low carbon electricity	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04 Decarbonised methane as fuel	0%	100%	0%	0%	0%	0%	0%	0%	5%	5%	5%
05 Biomass as feedstock	0%	100%	0%	0%	0%	0%	0%	10%	15%	20%	25%
07 Hydrogen by electrolysis - Ammonia	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 Hydrogen by electrolysis - Hydrogen	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
09 Recycled plastics - syngas	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	10%
10 CHP	30%	50%	0%	0%	30%	30%	30%	5%	5%	5%	5%
11 Integrate gas turbines with cracking furnace	0%	100%	0%	0%	0%	33%	66%	66%	66%	66%	66%
12 CCS - combustion (incl. biomass)	0%	60%	0%	0%	0%	0%	0%	0%	25%	25%	25%
13 CCS - process - Ammonia	0%	100%	0%	0%	0%	0%	0%	33%	33%	33%	33%
14 CCS - process - Hydrogen	0%	100%	0%	0%	0%	0%	0%	33%	33%	33%	33%
15 CCU	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
16 Improved insulation	0%	100%	0%	5%	20%	50%	75%	100%	100%	100%	100%
17 Improved waste heat recovery	0%	100%	0%	0%	20%	50%	50%	50%	50%	50%	50%
18 Improved process control	0%	100%	0%	10%	30%	70%	100%	100%	100%	100%	100%
19 More efficient equipment	0%	100%	0%	10%	20%	30%	50%	70%	100%	100%	100%
20 Improved steam system efficiency	0%	100%	0%	0%	20%	50%	75%	100%	100%	100%	100%
21 Membrane technology	0%	10%	0%	0%	0%	0%	10%	15%	20%	20%	20%
22 Process Intensification	0%	20%	0%	0%	0%	0%	10%	15%	20%	20%	20%
23 High temperature cracking	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24 Catalytic cracking	0%	100%	0%	0%	0%	0%	0%	0%	33%	66%	100%
25 Retrofit ODC for chlorine production	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%
26 Bioprocessing	0%	10%	0%	0%	0%	0%	10%	20%	30%	40%	50%
27 Methanol-to-olefins	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28 High temperature steam electrolysis	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
29 Solid state synthesis	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30 Clustering	25%	50%	0%	0%	5%	5%	10%	10%	15%	15%	15%

Figure 15: Deployment of options for 40-60% CO2 reduction pathway, current trends scenario

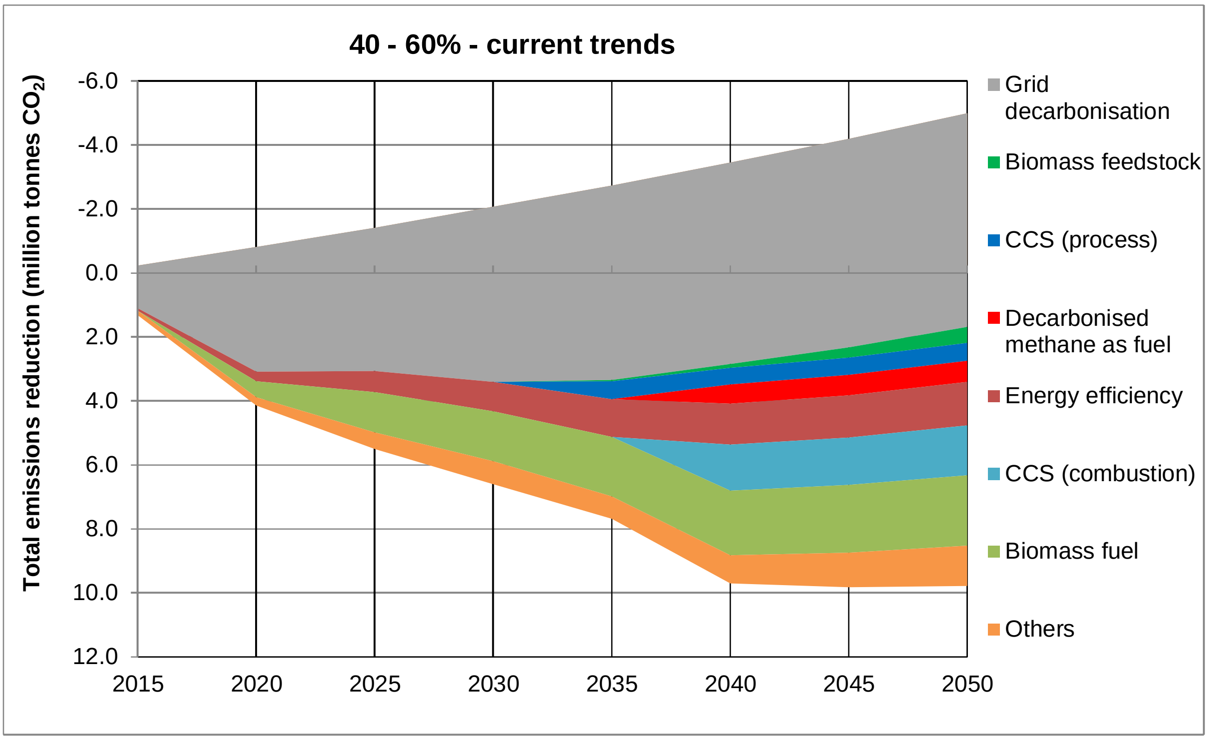

Figure 16: Contribution principal options to the absolute emissions reduction throughout the study period, for the 40-60% CO2 reduction pathway, current trends scenario

Figure 16 shows the absolute emissions reduction from grid decarbonisation and the principal options over the study period. With no grid decarbonisation or options deployed, emissions would rise due to the production growth in the current trends scenario. The contribution of the options (i.e. excluding grid decarbonisation) is 8.1 million tonnes of CO_2 in 2050.

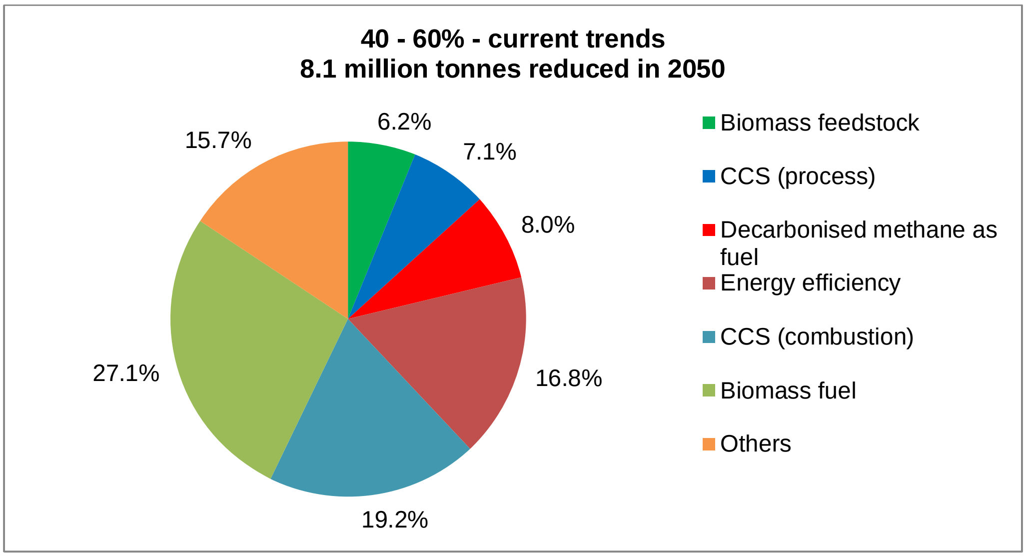

Figure 17: Breakdown of 2050 total emissions reduction for the 40-60% CO2 reduction pathway, current trends scenario

Figure 17 shows the relative contribution of the principal options (i.e. excluding grid decarbonisation) to the total options reduction of 8.1 million tonnes of CO_2.

Option Deployment under Other Scenarios

Equivalent pathways under the other scenarios are discussed in section 4.5 and the associated deployment tables are provided in appendix D.

4.4.3 Max Tech Pathway

Pathway Summary

Under this pathway, decarbonisation options are generally deployed to their maximum extent (within the boundaries of what is considered reasonably foreseeable) and are deployed rapidly once available. In the context of this pathway, rapid deployment means within 10 years in order to provide a reasonable period for the numerous organisations and sites in the sector to deploy the option. Where options are not 100% deployed, this is based on a judgment that the technology will not be fully developed by 2050 for some processes within the sector and so it is not possible to deploy at 100%. In the case of clustering, there is gradual on-going deployment but it was not considered realistic to expect the full potential of this option to be reached by 2050 given the significant plant relocation that would be likely to be required.

The total overall reduction of 87.9% are a result of 78.8% reduction from the options, 36.3% reduction from grid decarbonisation and a 27.2% increase in emissions as a result of production growth.

Deployment under Current Trends

The deployments of each of the options in the Max Tech pathway under current trends can be seen in Figure 18. Additionally, the contribution of the principal options and grid decarbonisation to absolute emissions reduction is shown in Figure 19, and the breakdown of emissions reduction from the leading options in 2050 is shown in Figure 20.

In this pathway, grid decarbonisation remains a significant contributor to emissions reductions. The principal options that contribute to the emissions reduction in 2050 are:

- CCS (combustion) is deployed to 50% in 2035 and 100% from 2040, representing a rapid deployment of this option once the technology becomes available in the 2030s (as defined in the project's generic scenarios). This results in 26.7% emissions reduction in 2050 compared to the a base year, which is just over a third of the total options reduction in that year.
- Biomass fuel, deployed to 25% of potential in 2020 and reaching 100%. This assumes that incentives are in place to make this an attractive option to invest in and that there is no limitation on the availability of low-carbon biomass. This results in 23.7% emissions reduction in 2050 compared to the base year, which is just under a third of the total options reduction.
- CCS (process) is split between ammonia and hydrogen with a larger proportion of reduction coming from ammonia. Both are deployed to 50% in 2030 and increased to 100% in 2035. This deployment gives 7.2% emissions reduction in 2050 compared to the 2012 base year. This represents about a tenth of the total emissions reduction from the options.
- The combined energy efficiency options are deployed to 50% in 2015 and 100% in 2020 – these are technically well-established options and so deployment is assumed to move rapidly to 100% in this pathway. This results in 6.4% total emissions reduction in 2050 compared to the base year which is 8% of the total options reduction.
- Biomass feedstock is deployed to 20% in 2030 and increased to 40% in 2035 and 80% in 2040. Deployment does not reach 100% by 2050 because this option includes developing new technologies for a number of different processes and it was considered likely that a proportion of these will not have developed a suitable biomass feedstock process by that time. The assumed

deployment gives 5.6% emissions reduction in 2050 compared to the base year which is 7% of the total options reduction.

The following options have been also been deployed in the Max Tech pathway, and result in modest emissions reduction (0.9%-2.2% reduction for each):

- Carbon capture and utilisation (CCU)
- Catalytic cracking
- Clustering
- Integrated gas turbines with cracking furnace
- CHP
- Clustering

Max Tech - current trends

OPTION	ADOP.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Biomass as fuel	0%	50%	0%	0%	25%	50%	75%	100%	100%	100%	100%
02 Waste as fuel	0%	25%	0%	5%	5%	10%	10%	0%	0%	0%	0%
03 Low carbon electricity	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04 Decarbonised methane as fuel	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
05 Biomass as feedstock	0%	100%	0%	0%	0%	0%	0%	0%	80%	80%	80%
07 Hydrogen by electrolysis - Ammonia	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
08 Hydrogen by electrolysis - Hydrogen	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
09 Recycled plastics - syngas	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10 CHP	30%	50%	0%	0%	50%	100%	100%	100%	100%	100%	100%
11 Integrate gas turbines with cracking furnace	0%	100%	0%	0%	0%	50%	100%	100%	100%	100%	100%
12 CCS - combustion (incl. biomass)	0%	60%	0%	0%	0%	0%	0%	50%	100%	100%	100%
13 CCS - process - Ammonia	0%	100%	0%	0%	0%	0%	50%	100%	100%	100%	100%
14 CCS - process - Hydrogen	0%	100%	0%	0%	0%	0%	50%	100%	100%	100%	100%
15 CCU	0%	100%	0%	0%	0%	0%	0%	0%	5%	5%	5%
16 Improved insulation	0%	100%	0%	0%	50%	100%	100%	100%	100%	100%	100%
17 Improved waste heat recovery	0%	100%	0%	0%	50%	100%	100%	100%	100%	100%	100%
18 Improved process control	0%	100%	0%	10%	50%	100%	100%	100%	100%	100%	100%
19 More efficient equipment	0%	100%	0%	10%	50%	100%	100%	100%	100%	100%	100%
20 Improved steam system efficiency	0%	100%	0%	0%	50%	100%	100%	100%	100%	100%	100%
21 Membrane technology	0%	10%	0%	0%	0%	0%	0%	0%	100%	100%	100%
22 Process Intensification	0%	20%	0%	0%	0%	0%	10%	25%	25%	30%	30%
23 High temperature cracking	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24 Catalytic cracking	0%	100%	0%	0%	0%	0%	0%	33%	100%	100%	100%
25 Retrofit ODC for chlorine production	0%	25%	0%	0%	0%	100%	100%	100%	100%	100%	100%
26 Bioprocessing	0%	10%	0%	0%	0%	25%	50%	75%	100%	100%	100%
27 Methanol-to-olefins	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28 High temperature steam electrolysis	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
29 Solid state synthesis	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30 Clustering	25%	50%	0%	0%	5%	10%	15%	20%	25%	30%	35%

Figure 18: Deployment of options or the Max Tech pathway, current trends scenario

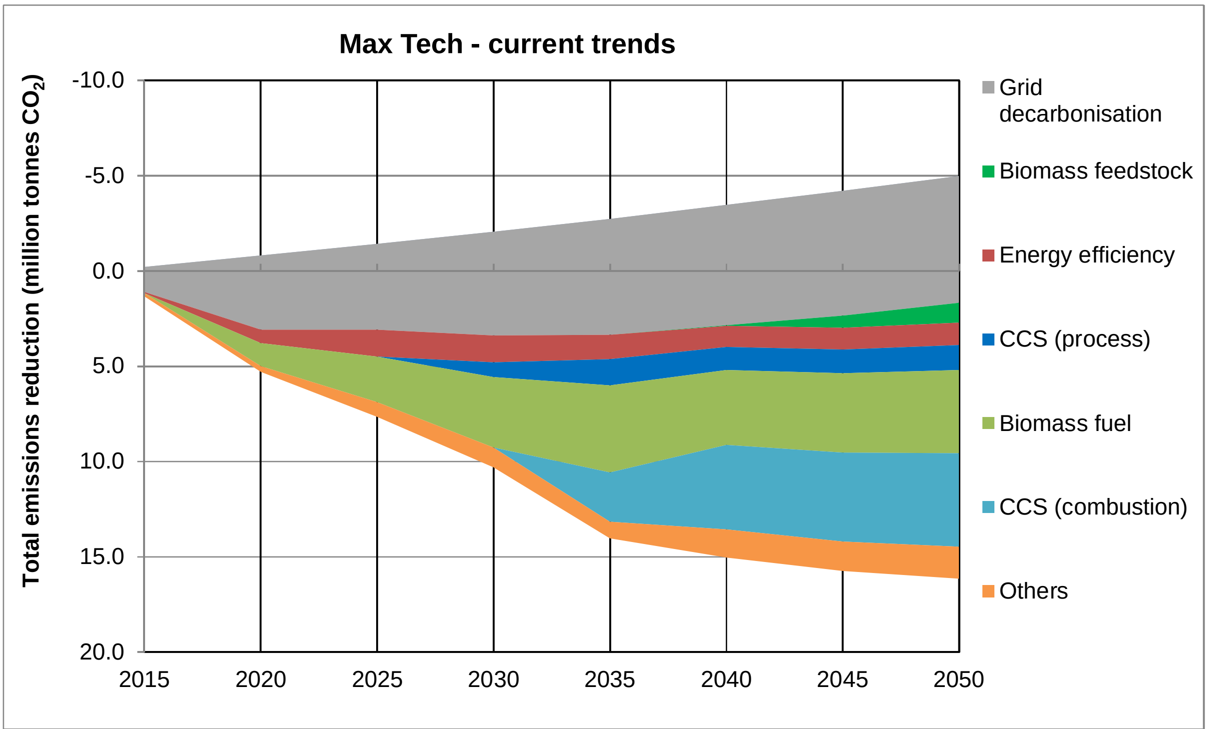

Figure 19: Contribution of principal options to the absolute emissions reduction throughout the study period, for the Max Tech pathway, current trends scenario

Figure 19 shows the absolute emissions reduction from grid decarbonisation and the principal options over the study period. With no grid decarbonisation or options deployed, emissions would rise due to the production growth in the current trends scenario. The contribution of the options (i.e. excluding grid decarbonisation) is 14.5 $MtCO_2$ in 2050.

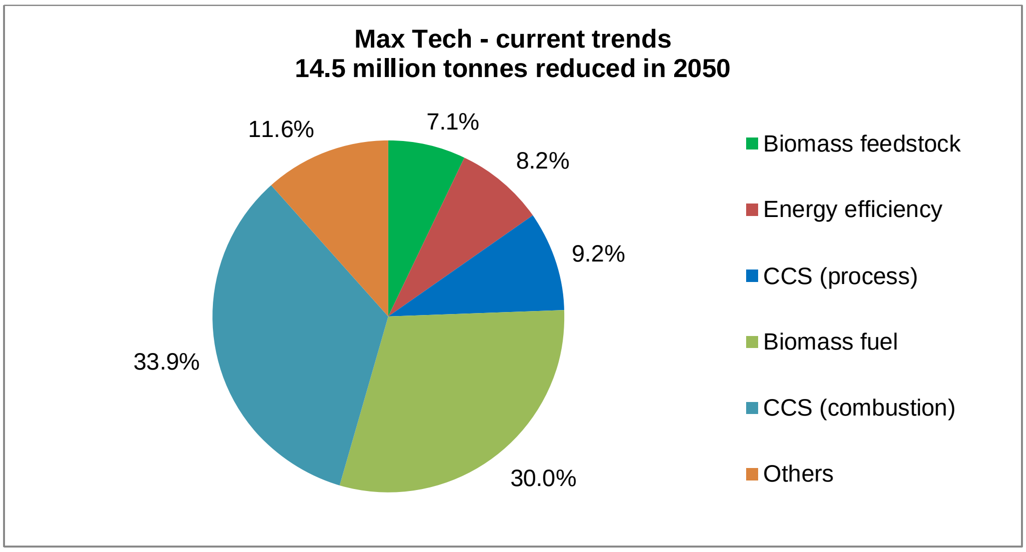

Figure 20: Breakdown of 2050 total emissions reduction for the Max Tech pathway, current trends scenario

Figure 20 shows the relative contribution of the principal options (i.e. excluding grid decarbonisation) to the total options reduction of 14.5 million tonnes of CO_2.

Option Deployment under Other Scenarios

Max Tech pathways under the other scenarios are discussed in section 4.5 and the associated deployment tables are provided in appendix D.

4.4.4 Max Tech (No Biomass) Pathway

Pathway Summary

In the Max Tech (no biomass) pathway, no low-carbon biomass is available. Otherwise the same drivers as the Max Tech pathway exist and, in the absence of biomass, some other options are deployed to a greater extent to reflect these drivers.

The total overall reduction of 79.5% are a result of 70.4% reductions from the options, 36.3% reductions from grid decarbonisation and a 27.2% increase in emissions as a result of production growth.

This provides the pathway in the 60-80% decarbonisation band.

Deployment under Current Trends

The deployments of each of the options in the Max Tech (no biomass) pathway under current trends can be seen in Figure 21. Additionally, the contribution of the principal options and grid decarbonisation to absolute emissions reduction is shown in Figure 22 and the breakdown of emissions reduction from the leading options in 2050 is shown in Figure 23.

In this pathway, grid decarbonisation remains a significant contributor to emissions reduction. The principal options that contribute to the emissions reductions in 2050 are:

- CCS (combustion) is deployed to 50% in 2035 and 100% from 2040 which is the same as under the Max Tech pathway on the basis that the technology could not be deployed earlier or faster than under Max Tech. This results in 32.4% emissions reduction in 2050 compared to the base year, which is just under half of the total options reduction in that year.
- CCS (process) is split between ammonia and hydrogen with a larger proportion of reduction coming from ammonia. Both are deployed to 50% in 2030 and increased to 100% in 2035. This deployment gives 8.6% emission reductions in 2050 compared to the 2012 base year. This represents 12% of the total emissions reductions from the options.
- The combined energy efficiency options are deployed to 50% in 2015 and 100% in 2020, again reflecting the same deployment as under Max Tech. This results in 7.8% emissions reductions in 2050 compared to the base year, which is just over a tenth of the total options reductions.
- Decarbonised methane as fuel is deployed to 5% in 2035 and 10% in 2045. This option is not deployed under Max Tech but, in the absence of biomass, some deployment takes place under this pathway as non-biomass options are developed more extensively. This option results in 6.8% emissions reduction in 2050 compared to the base year which is about a tenth of the total options reductions.

The following options have been deployed in the Max Tech (no biomass) pathway, generally to a higher level than under the Max Tech pathway, and result in modest emissions reductions of between 1.6 and 2.6% each:

- CCU
- Catalytic cracking
- Waste as fuel
- Clustering

- Integrated gas turbines with cracking furnace

For the CCU option, there was a range of opinions expressed during the development of this roadmap as to the appropriate deployment level. While we consider that the level shown in Figure 22 is reasonable, although with higher deployment this option could make a significant contribution to decarbonisation and generate value rather than an overall cost from CC. This is an area for sensitivity analysis (see section 4.6).

Max Tech (no biomass) - current trends

OPTION	ADOP.	APP.	DEPLOYMENT								
			2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Biomass as fuel	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
02 Waste as fuel	0%	25%	0%	5%	5%	10%	10%	10%	10%	10%	10%
03 Low carbon electricity	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
04 Decarbonised methane as fuel	0%	100%	0%	0%	0%	0%	0%	5%	5%	5%	5%
05 Biomass as feedstock	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
07 Hydrogen by electrolysis - Ammonia	0%	100%	0%	0%	0%	0%	0%	0%	5%	10%	10%
08 Hydrogen by electrolysis - Hydrogen	0%	100%	0%	0%	0%	0%	0%	0%	5%	10%	10%
09 Recycled plastics - syngas	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
10 CHP	30%	50%	0%	0%	50%	100%	100%	100%	100%	100%	100%
11 Integrate gas turbines with cracking furnace	0%	100%	0%	0%	0%	50%	100%	100%	100%	100%	100%
12 CCS - combustion (incl. biomass)	0%	60%	0%	0%	0%	0%	0%	50%	100%	100%	100%
13 CCS - process - Ammonia	0%	100%	0%	0%	0%	0%	50%	100%	100%	100%	100%
14 CCS - process - Hydrogen	0%	100%	0%	0%	0%	0%	50%	100%	100%	100%	100%
15 CCU	0%	100%	0%	0%	0%	0%	0%	0%	5%	5%	5%
16 Improved insulation	0%	100%	0%	0%	50%	100%	100%	100%	100%	100%	100%
17 Improved waste heat recovery	0%	100%	0%	0%	50%	100%	100%	100%	100%	100%	100%
18 Improved process control	0%	100%	0%	10%	50%	100%	100%	100%	100%	100%	100%
19 More efficient equipment	0%	100%	0%	10%	50%	100%	100%	100%	100%	100%	100%
20 Improved steam system efficiency	0%	100%	0%	0%	50%	100%	100%	100%	100%	100%	100%
21 Membrane technology	0%	10%	0%	0%	0%	0%	0%	0%	100%	100%	100%
22 Process Intensification	0%	20%	0%	0%	0%	0%	10%	25%	25%	30%	30%
23 High temperature cracking	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24 Catalytic cracking	0%	100%	0%	0%	0%	0%	0%	33%	100%	100%	100%
25 Retrofit ODC for chlorine production	0%	25%	0%	0%	0%	100%	100%	100%	100%	100%	100%
26 Bioprocessing	0%	10%	0%	0%	0%	25%	50%	75%	100%	100%	100%
27 Methanol-to-olefins	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28 High temperature steam electrolysis	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
29 Solid state synthesis	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30 Clustering	25%	50%	0%	0%	5%	10%	15%	20%	25%	30%	35%

Figure 21: Deployment of options for Max Tech (no biomass), current trends scenario

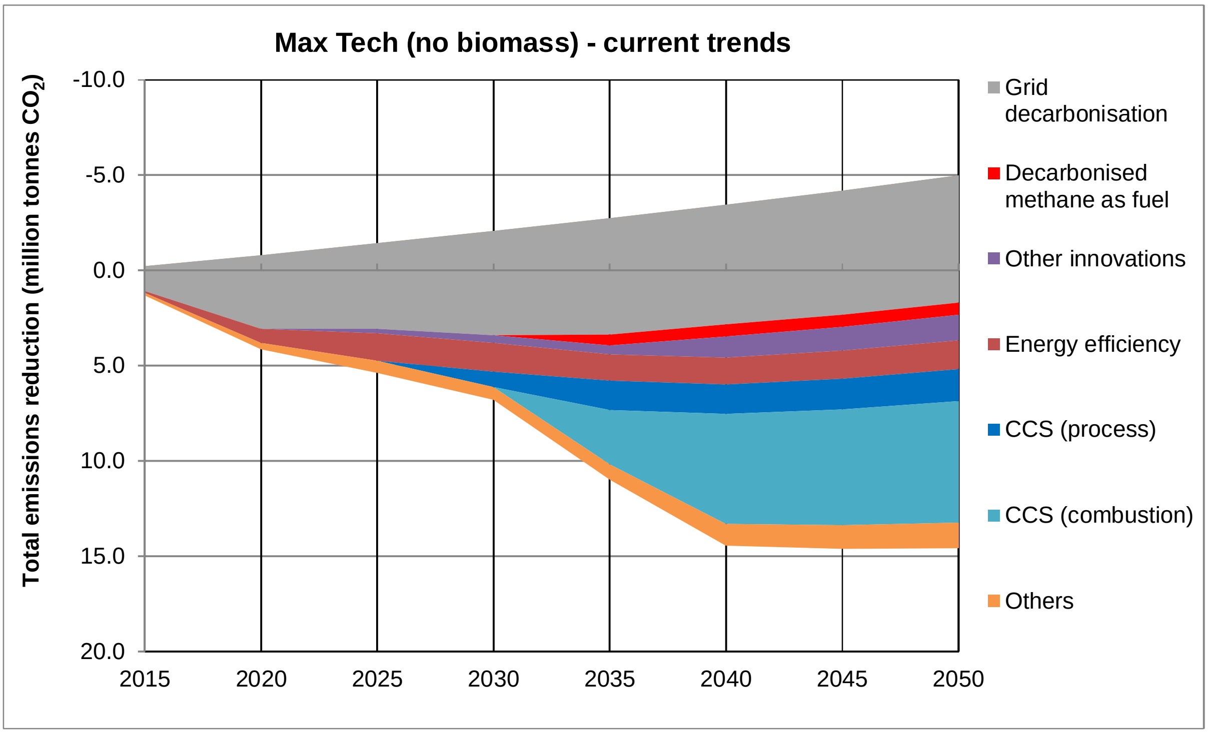

Figure 22: Contribution of principal options to the absolute emissions reduction throughout the study period, for the Max Tech (no biomass) pathway, current trends scenario

Figure 22 shows the absolute emissions reductions from grid decarbonisation and the principal options over the study period. With no grid decarbonisation or options deployed, emissions would rise due to the production growth in the current trends scenario. The contribution of the options (i.e. excluding grid decarbonisation) is 12.9 million tonnes of CO_2 in 2050.

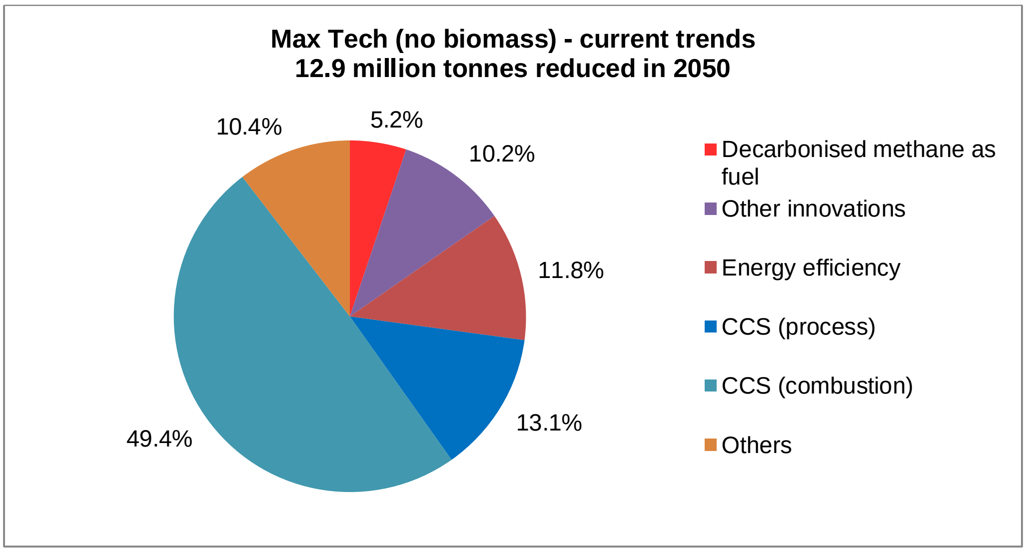

Figure 23: Breakdown of 2050 total emissions reductions for the Max Tech (no biomass) pathway, current trends scenario

Figure 23 shows the relative contribution of the principal options (i.e. excluding grid decarbonisation) to the total options reduction of 12.9 million tonnes of CO_2.

Option Deployment under Other Scenarios

Max Tech (no biomass) pathways under the other scenarios are discussed in section 4.5 and the associated deployment tables are provided in appendix D.

4.5 Scenario Analysis

The figures within this section of the pathways development and analysis show the CO_2 reduction trends of the pathways under each scenario.

The sector-specific assumptions are provided in appendix A.

4.5.1 Current Trends

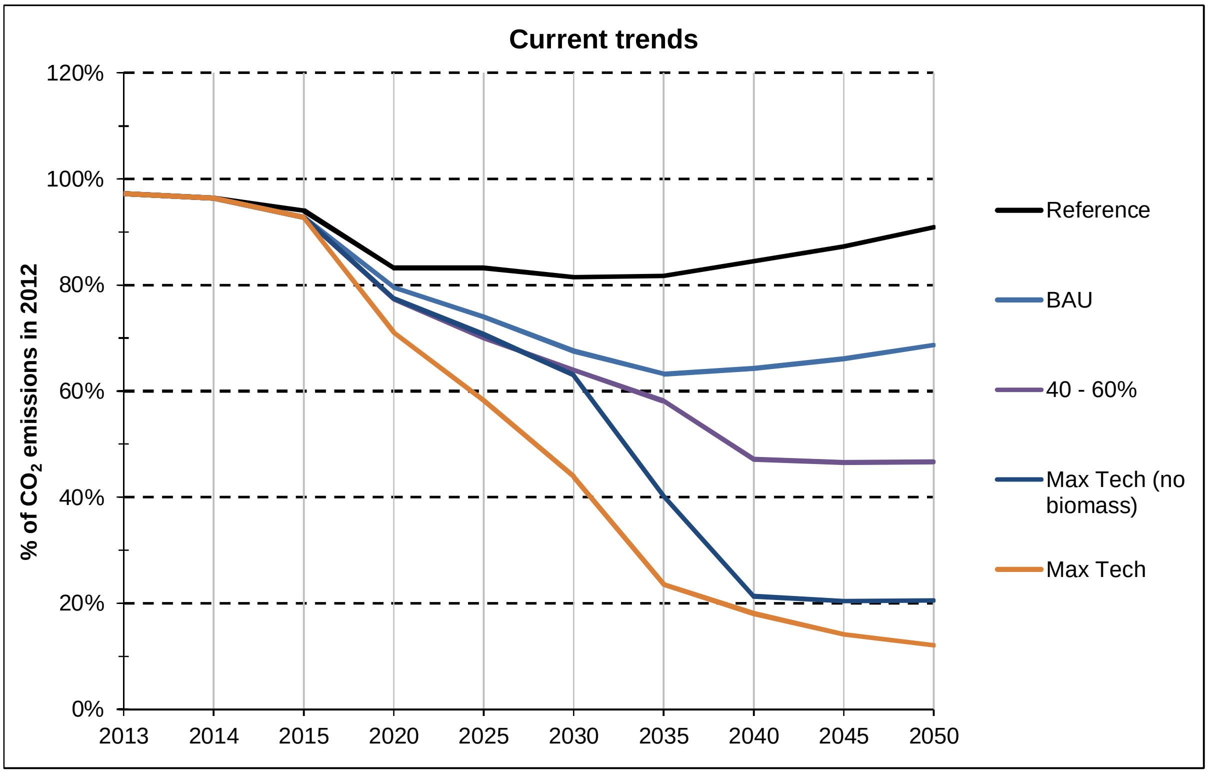

Figure 24: Performance of pathways under current trends

The pathways under current trends are discussed in detail in section 4.4. Under the current trends scenario, production is assumed to increase from 2013 onwards by 1.0% in all years. CO_2 emissions from grid electricity were assumed to reduce to 100 g CO_2 per kWh by 2030, then 30 g CO_2 per kWh by 2050, resulting in the initial reduction shown in the reference pathway. After 2030, increasing production outweighs the reduction from a decarbonised grid and overall reference pathway emissions begin to rise.

As noted in section 4.4, the decarbonisation of the grid accounts for a significant amount of the total CO_2 reduction for all pathways in the period 2015-2030.

4.5.2 Challenging World

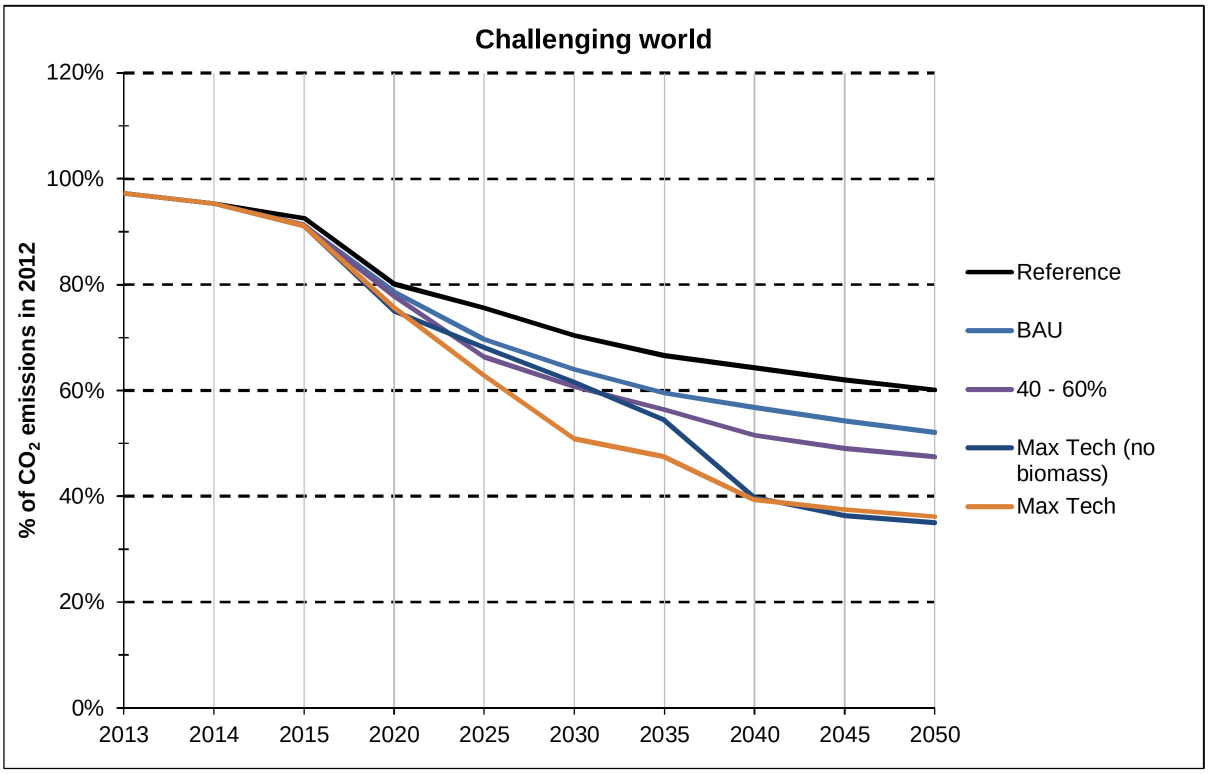

Figure 25: Performance of pathways under challenging world

Under challenging world, production was assumed to fall by 0.5% annually from 2013 onwards in all years and the CO_2 emissions from electricity were assumed to reduce to 200 g CO_2 per kWh by 2030, then 150 g CO_2 per kWh by 2050.

The reference pathway in Figure 25 shows the result of these factors, which is a 40% reduction in emissions by 2050 without the deployment of any decarbonisation options.

When options are deployed, the CO_2 reduction potential of the sector under this scenario was between 48% (under the BAU pathway) and 65% (under the Max Tech (no biomass) pathway) compared to the 2012 emissions. This corresponded to absolute emissions in 2050 of 9.6 million tonnes of CO_2 and 6.4 million tonnes of CO_2 respectively. The Max Tech (no biomass) pathway provides slightly greater emissions reductions in 2050 than Max Tech because of extra non-biomass option deployment under this pathway.

The BAU pathway falls in the 40-60% decarbonisation band and the two Max Tech pathways in the 60-80% band. With the reference pathway providing 40% decarbonisation, no 20-40% band pathway was possible.

Under the challenging world scenario, the sector generally deploys fewer decarbonisation options and deploys them more slowly than under current trends. This is as a result of fewer decarbonisation drivers (e.g. a slow-down in climate policies) and reduced investment in new plant, equipment or innovation under this scenario. For example, CCS is not deployed under challenging world in the BAU pathway, and is deployed to a lesser extent than in current trends in the two Max Tech pathways. Under the BAU pathway, energy efficiency and biomass fuel are the major decarbonisation options, with CCS also being a significant contributor under the two Max Tech pathways.

As a result, the decarbonisation options provide a smaller contribution than under current trends and the pathways move closer together. For completeness, the same pathways were modelled as under current trends; however, as Figure 25 shows, the decline in production and grid emissions that lie behind the reference pathway were the main drivers behind the CO_2 reduction under this scenario.

4.5.3 Collaborative Growth

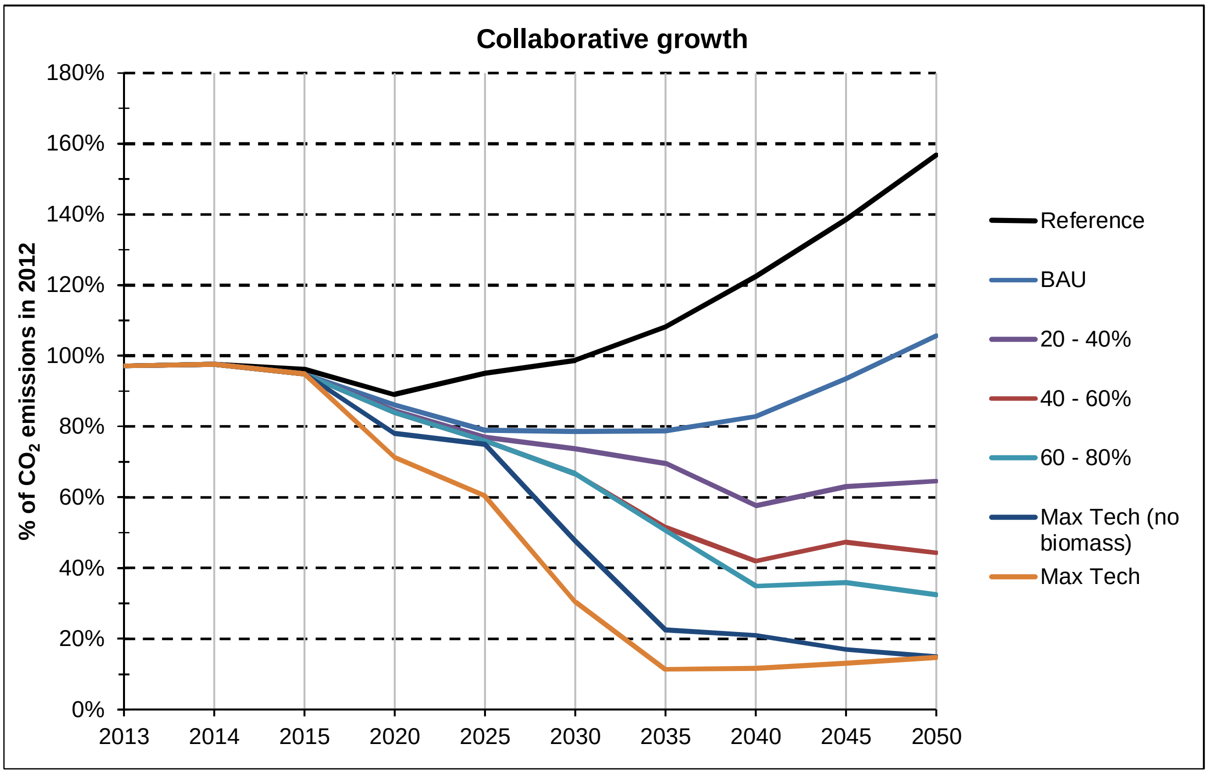

Figure 26: Performance of pathways under collaborative growth

Under collaborative growth, production was assumed to grow by 2.0% annually from 2013 onwards in all years and the CO_2 emissions from electricity were assumed to reduce to 50g CO_2 per kWh by 2030 and then reach 30g CO_2 per kWh by 2050. As shown in the reference pathway in Figure 26, with no decarbonisation options deployed, the effect of grid decarbonisation is outweighed by production growth after 2020 and sector emissions rise to 158% of 2012 levels by 2050.

The CO_2 reduction potential of the sector under this scenario was between a 5% increase (BAU pathway) and an 83% reduction (two Max Tech pathways) compared to the 2012 emissions. This corresponds to absolute emissions in 2050 of 19.5million tonnes of CO_2 and 3.2 million tonnes of CO_2.

For the collaborative growth scenario, decarbonisation options are deployed more extensively and more rapidly than under current trends, driven by stronger internationally agreed climate policies, greater levels of collaboration and higher levels of investment and innovation. The more technically straightforward options (e.g. those related to energy efficiency) are deployed to their maximum extent earlier than under current trends and there is greater deployment of innovative technologies such as membrane separation and process intensification. There is also a higher level of clustering, resulting from the higher levels of investment taking place in a more collaborative environment.

Under the two Max Tech pathways, technologies are deployed faster, resulting in emissions reductions of about 80% by 2035 (earlier than under current trends). After this date, however, emissions level off because production growth continues while the major decarbonisation options have already been deployed. The profiles of the other pathways after 2035 are also as a result of the balance between further option deployment and the effect of production growth.

The overall result is that emissions in 2050 for all comparable pathways except Max Tech (no biomass) are higher under collaborative growth than under current trends.

4.5.4 Scenario Comparison

The pathways for BAU and Max Tech under each scenario are grouped together in Figure 27 and Figure 28 below for ease of comparison

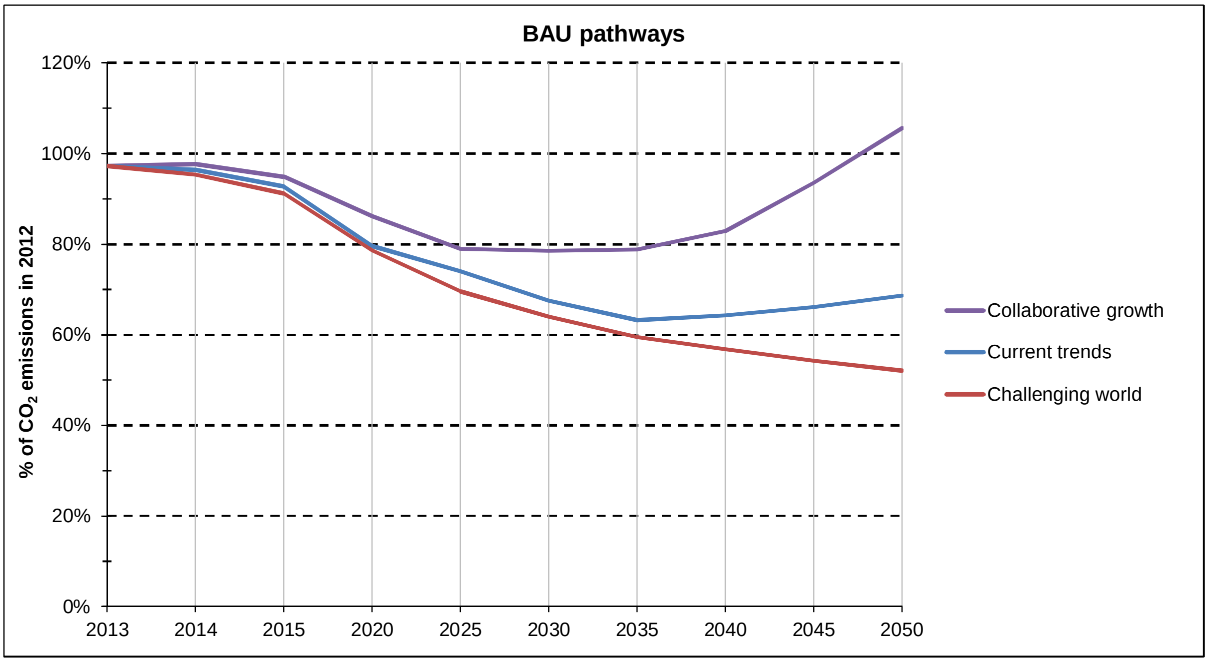

Figure 27: Comparison of BAU pathways under different scenarios

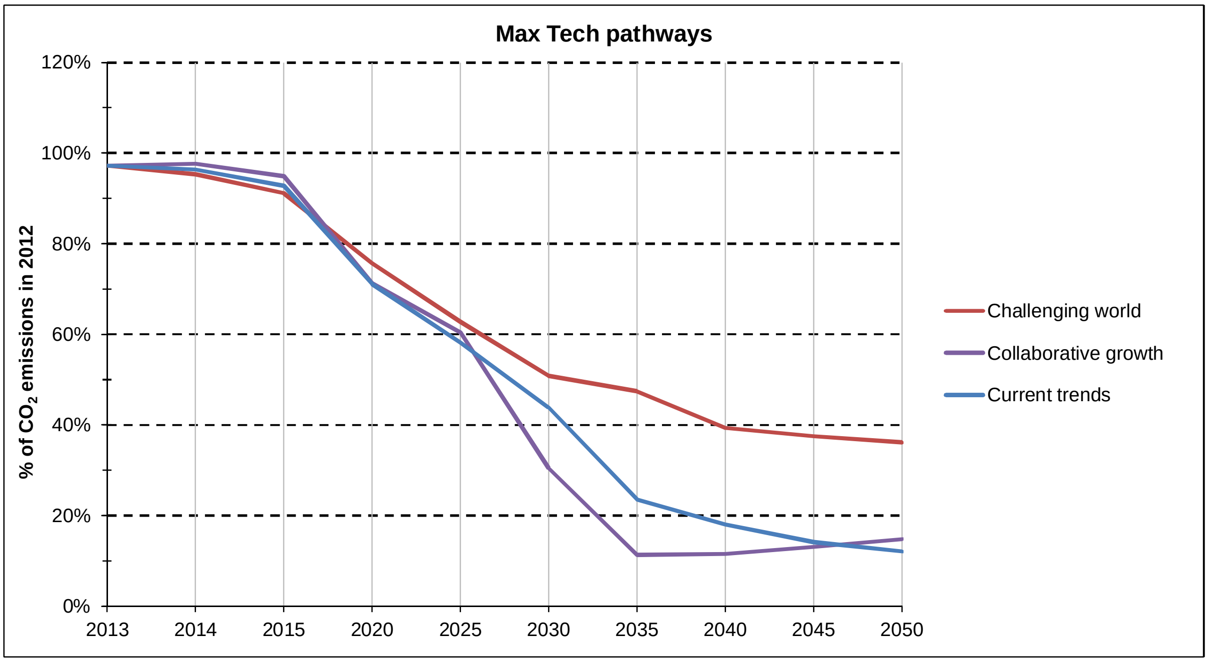

Figure 28: Comparison of Max Tech pathways under different scenarios

4.6 Sensitivity Analysis

The Max Tech (no biomass) pathway described in section 4.4.4 above illustrates the sensitivity of the pathways to the use of biomass.

Other sensitivities, as suggested by the pathways analysis, have been examined under the current trends scenario:

1. Lower availability of CCS

   If CCS for combustion emissions is less widely available (e.g. more limited pipeline networks are developed), the emissions reduction from this option are reduced. By reducing the APP of this option in the pathways model from 60% to 30%, total emissions reductions in 2050 are reduced from 88% to 80% in the Max Tech pathway. The reduction is from 79% to 64% in the Max Tech (no biomass) pathway.

2. Higher deployment of CCU

   If deployment of this option increases from 5% to 10% in 2050, total emissions reductions in 2050 are increased from 88% to 90% in the Max Tech pathway. The increase is from 79% to 82% in the Max Tech (no biomass) pathway

3. Higher deployment of energy efficiency options

   If all energy efficiency measures are deployed to 100% by 2050 in the BAU pathway, total emissions reduction in 2050 increase from 31% to 33%.

4. Higher deployment of clustering

   If deployment of clustering is increased from 5% to 25% in the BAU pathway, total emissions reductions in 2050 increase from 31% to 32%. A 50% deployment would increase the reductions to 33%.

Other potential sensitivities suggested by the pathways analysis which have not been modelled include factors such as:

- Biomass emission factors
- Degree of grid decarbonisation

In the option interaction calculation, the ‘no interaction’ case adds approximately 10% to the decarbonisation in 2050 in the Max Tech pathway.

4.7 Pathway Costs

4.7.1 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 and energy efficiency pathways will have a major impact on any economic assessment. For example, some options (e.g. CC and electrification of firing) greatly increase energy use and/or operating costs of a process plant.

4.7.2 Calculation of Pathway Costs

The pathway costs and CO_2 reduction are measured with respect to the reference trend, i.e. they are calculated as the difference between costs and emissions under the decarbonisation and energy efficiency 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 decarbonisation and energy efficiency 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 CO_2 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 CO_2 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 efficiency or decarbonisation. Capital costs are applied at the year of each deployment step (as modelled in the decarbonisation and energy efficiency 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. This analysis covers capital costs for decarbonisation: changes to energy use and energy costs (as a result of deployment of the options) have not been quantitatively included although it will be significant for many options.

4.7.3 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 decarbonisation and energy efficiency pathways.

All costs in the data input tables are subject to wide variation, for example between sites and subsectors 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.

4.7.4 Cost Analysis Results

The results of the cost analysis of decarbonisation for the various pathways within the current trends scenario are summarised in Table 10 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 CO_2 emission abatement offered by each pathway has been totalled for each year to present a **cumulative** carbon abatement figure for the period 2014-2050 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 2013-2050 £m[22]	Cumulative Carbon Dioxide Abated 2013-2050 ($MtCO_2$)[23]	Projected Impact on Fuel / Energy use and Fuel / Energy cost
BAU	600	90	This pathway includes deployment of options such as fuel switch (biomass), energy efficiency measures and CCS (process). In the study period 2014-2050, this pathway is projected to result in an overall reduction in energy and fuel used. The value of this saving will depend on the fuel cost forecast adopted.
40-60%	2,000	140	This pathway includes deployment of options such as fuel switch (biomass), biomass feedstock, energy efficiency measures and CCS (process and combustion). Overall, this will increase energy use, and therefore a large overall increase in energy use and costs is projected. The scale of the cost increase will depend on the fuel cost forecast adopted.
Max Tech	4,000	270	This pathway includes further deployment of options such as fuel switch (biomass), biomass feedstock, energy efficiency measures and CCS (process and combustion). Overall, this will substantially increase energy use, and therefore a large overall increase in energy use and costs is projected. The scale of the increased cost will depend on the fuel cost forecast adopted.

Table 10: Summary costs and impacts of decarbonisation for the pathways

4.8 Implications of Enablers and Barriers

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:

- Biomass as a fuel
- Biomass as a feedstock
- Decarbonised methane as fuel
- CCS (combustion and process)
- Energy efficiency measures
- Clustering
- Decarbonised grid electricity

[22] Model output rounded to 1 significant figure to reflect ‘order of magnitude’ input data
[23] Model output rounded to nearest million tonnes of CO_2

From the evidence gathered during the project (from literature, interviews, surveys, and workshops) there are a number of enablers and barriers associated with these options. These barriers would need to be overcome and the enablers would need to be made use of in order for these technologies to fulfil their decarbonisation potential and for the pathways to be achieved. These are discussed below.

4.8.1 Biomass as a Fuel

This option relates to the use of low-carbon biomass as fuel, replacing natural gas or other fossil fuels. One of the key barriers to the adoption of biomass as a fuel, as identified by the manufacturers interviewed and reinforced by discussions on pathways at the second workshop, is the high level of uncertainty around the sufficient supply of low-carbon biomass. Interviewees and workshop attendees suggested that a national industrial policy on biomass to provide more clarity in the long term would support building solid investment cases for this option. Compiling a robust business case has also been identified by the Carbon Trust as a key enabler. Interviews identified the need for consistency of bankable incentives in order to allow investments to proceed. In addition, there are technical barriers to be overcome, as identified in the literature: the IEA found that the "commercial scale-up of new and unproven technologies" is an issue for future deployment as unproven technology is often perceived as highly risky, while recent work (DECC 2014) identified a number of technical developments in areas such as burner design that are needed to help overcome this risk.

Enablers	National policy on biomass Developing robust business case Consistent, bankable incentives
Barriers	Uncertainty on biomass availability Technology development and demonstration required

4.8.2 Biomass as a Feedstock

This option relates to the use of biomass to provide chemical feedstock. This feedstock could be syngas (produced from biomass gasification) for use in the production of ammonia or hydrogen, or the production of methanol which could in turn be used to make olefins. It also includes the replacement of natural gas with methane from the anaerobic digestion of biomass and the production of other longer chain hydrocarbon feedstock e.g. from algae. Similarly to biomass as a fuel, one of the key barriers to the adoption of this option, as identified by the manufacturers interviewed and reinforced by discussions at the second workshop, is the high level of uncertainty around the sufficient supply of low-carbon biomass. Furthermore, workshop attendees concluded that currently there are no means to account for life-cycle decarbonisation (i.e. from biomass growth through to disposal of final products) and to provide appropriate financial credit for these reductions that could support investment decisions.

A further barrier identified by interviewees is that some sector processes (e.g. ammonia) use very large quantities of natural gas feedstock and a very large gasification capacity (and biomass supply) would be required to replace it; this was considered unrealistic on the basis of cost and available feedstock.

Literature (e.g. IEA, ICCA and DECHEMA, 2012) has suggested that further demonstration of the effectiveness of the technology through pilot plants is required. In particular, development of bio-refineries has been identified (e.g. CEFIC and Ecofys, 2013) as a solution to optimise feedstock, energy and product mix. This links to the clustering option.

The literature also indicates that processes based on biomass feedstock typically require more energy overall, often due to the need to process the biomass before use e.g. via gasification (IEA, ICCA and DECHEMA, 2012). Even though carbon emissions can be lower (by using bio-based energy sources), this can increase production costs.

Enablers	Bio-refinery approach to optimise feedstock, energy and products
Barriers	Uncertainty on biomass availability Need means to provide appropriate financial credit for emissions reductions Technology development and demonstration required Higher energy requirements vs. current processes

4.8.3 Decarbonised Methane as Fuel

This option is the provision of 'decarbonised' methane, produced from low-carbon sources such as the anaerobic digestion of biomass. It could also be produced by the generation of hydrogen using renewable electricity and subsequent conversion to methane (methanation), although this would only be worthwhile in cases where the hydrogen could not be used directly as a fuel. In such cases, the methanation reaction could make use of CO_2 captured from other processes, as described in the literature (Sprecht et al., 2009), and so could link to the CCS and CCU options described below.

However, decarbonised methane is perceived as costly, raising concerns regarding competitiveness among workshop participants.

Enablers	Direct replacement of existing natural gas fuel Opportunity to use captured CO_2
Barriers	Limited availability of feedstock material for anaerobic digestion Cost competitiveness impacts

4.8.4 Carbon Capture

This option relates to the capture and storage of CO_2 generated by combustion processes. The modelling suggests that CC of the process emissions from ammonia and hydrogen plants, which are identified as separate options, would provide only a small contribution to overall sector decarbonisation due to the size of the emissions from these subsectors relative to the sector as a whole. As noted below, however, these options could be an important enabler for the CCS option – ammonia and hydrogen plants could provide a first step for CCS in the sector as they produce high purity CO_2 process emissions, making the 'capture' element of CCS easier (Ricardo-AEA and Imperial College, 2013).

Workshop participants identified the insufficient scale of plants in the sector as a barrier – it was considered that no individual plant produces sufficient emissions to justify its own CCS network. The Centre for Low Carbon Futures also found that the existing industrial geography is a barrier as *"different parts of processes are dispersed*" and that access to "*…transportation and storage may be limited due to high (pipeline) costs*". As noted in section 3, however, many large emitters in the sector are located in clusters, some of which are on the east cost of the UK, and this can be considered an enabler compared to other sectors. For CCS to be deployed, shared transport and storage networks need to be established. Once in place, these networks would enable individual plants to 'plug in' when their own capture processes were implemented.

Discussions during the workshop and interviews identified the complexity of implementing shared networks among numerous players as another significant barrier, driven by commercial issues. Strong industry commitment, clear leadership, and commercial incentives and/or subsidies were suggested as some of the ways to overcome this barrier identified at the workshops.

The Chemistry Growth Strategy Group also suggests that "*much greater research is urgently required on the potential for commercialisation of CCS*". Combining research with an internationally competitive carbon price and related policy framework would provide some of the key enablers identified by the evidence sources.

A further barrier to CCS implementation is that, in addition to the capital investment required, CCS processes result in higher energy use (GCCSI, Parsons Brinckerhoff experience) which increases operating costs. This extra energy is needed to operate the capture process which is in addition to existing production processes.

Enablers	Once established, networks could allow plants to 'plug in' when ready Existing industry clusters provide a starting point for shared infrastructure Deployment to ammonia and hydrogen subsectors could provide first step for sector
Barriers	Geographical dispersion of sector outside clusters Complexity and commercial issues related to necessary multi-party collaboration Further research required on commercialisation Higher energy requirements vs. current processes

4.8.5 Energy Efficiency Measures

This is a group of options (numbers 16-20 from the options register) based around incremental efficiency improvements using known technology such as improved insulation and process control, more efficient steam systems and equipment (e.g. pumps, drives), and increased heat recovery. They have been grouped together for the purposes of this section as they are likely to have similar enablers and barriers.

One of the key enablers that drives chemical producers to implement incremental energy efficiency measures is the operational cost savings that can be made once such measures are installed. Workshop attendees also perceived these options as low risk due to their relatively low cost and low technical risk (which reduces the risk of operational disruption post-installation).

Barriers identified in the workshops include limitations on deployment rate because measures of this kind are often installed only when equipment needs replacement or during wider plant overhauls – it is generally not considered worthwhile to disrupt production simply to install these measures. It was noted by workshop participants and interviewees that energy efficiency options are often not a priority for limited capital and staff resources, particularly when the benefits are long-term compared with other short-term priorities. Interviewees in particular were concerned about the lack of sufficiently skilled energy specialists that can analyse current energy performance, identify opportunities, and select and implement feasible solutions. The chemicals producers consulted also perceived the abundance of regulatory and compliance requirements (including new EU energy audit requirements) that energy managers have to deal with as a key barrier to identifying and implementing energy efficiency improvements.

Enablers	Operational cost savings Low risk
Barriers	Rate restricted by timing of more major work Low priority for limited resources Limited specialised staff Regulatory requirements divert resources

4.8.6 Clustering

The clustering option refers to optimising the use of energy and materials between plants that are located close together. The UK benefits from a number of 'clusters' of chemicals companies (e.g. Teesside, Runcorn, Humberside) and this option refers to companies taking better advantage of this to increase their efficiency, improve their cost position, and locally source their feedstock and other inputs. This may in some cases involve encouraging inward investment to fill supply chain gaps.

This option was identified in the workshops as a significant opportunity in the longer term, provided the barriers could be overcome. Clustering facilitates energy efficiency and decarbonisation activities such as one plant selling its waste by-product to a neighbouring plant as a feedstock or input (e.g. steam). The Chemistry Growth Strategy Group indicated the need for "*clustering and infrastructure to effect economies of scale and greater efficiency and productivity*". Interviewees favoured the option as it drives cost savings in energy and materials. However, it was suggested that economic incentives are required to support implementation. For example, government policy and support in building the infrastructure (e.g. pipelines, roads) are some of the key enablers identified by interviewees and workshop participants, along with further development of local partnerships and cluster organisations. Workshop attendees concluded that there is also a need for leadership and champions to drive the coordination and trust required for clustering and for a long-term industrial strategy to be in place to give confidence that the industry will be thriving in 20-30 years.

Workshop attendees also identified that, as well as direct energy and material sharing benefits, clustering can reduce costs through the use of shared infrastructure and facilities, and the ability to locate close to key customers and suppliers. This can improve overall economics and so provide the headroom for further investment.

While the potential is understood by the sector and there are no significant technical barriers, the clustering option faces other challenges. The benefits of clustering through shared infrastructure and greater resource efficiency can attract inward investment; however UK clusters compete with clusters abroad which may have lower energy and labour costs or lower regulatory requirements. By taking a lead on clustering, the UK could maximise the resulting business benefits and so improve its attractiveness for investment.

To achieve its full potential, clustering would require re-location of existing production which would involve significant costs and risks a loss of skilled staff. Workshop 2 identified the risk that raising the possibility of re-location within the UK might lead to a wider review within individual companies of production in the UK versus other locations – the implication being that production could re-locate abroad.

Other barriers identified at the workshops include the legacy of contamination at some existing sites, which restricts opportunities for plants to locate and/or expand there, and the need to have confidence that clustering partners will remain in place for the long term. The latter is a security of supply issue – if a process is dependent on energy or materials supplied by a neighbouring site, supply may be affected if that site changes its processes, or ceases to operate. This barrier was also identified in the literature (CEFIC and Ecofys).

With many of the UK sector's parent companies located abroad, inter-company collaboration was perceived by workshop participants and interviewees to be very challenging. Competition and confidentiality concerns also make collaboration more difficult. There is a difficulty in securing long-term arrangements. This is further hindered by management risk aversion related to the concerns over security of supply mentioned above.

Enablers	Potential understood No technical barriers Existence and future development of local partnerships and cluster organisations
Barriers	Risk of reliance on other parties Historical contamination on some sites Difficulty in achieving necessary collaboration Costs and risks of relocation

4.8.7 Other Technologies

Sections 4.8.1 to 4.8.6 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:

- Major innovative technology changes require significant further development before they could be considered for deployment.
- A number of technologies are likely to result in higher overall energy use compared to current processes.

- Long-term stability in carbon pricing is needed in order to make major investments.
- New technologies will require significant upfront investment which is difficult because UK sector sites have difficulty in competing internally for resources and funding in light of UK energy prices and policy costs.

In addition, decarbonised grid electricity, while considered as part of the reference pathway and not under the direct control of the sector, is a major contributor to decarbonisation for many of the pathways.

Many of the principal options described in sections 4.8.1 to 4.8.6 above are either fully or partially outside the control of the sector. Grid decarbonisation and low-carbon biomass supply, for example, are outside the sector's control, while CCS appears unlikely to be an option that the sector can deploy on its own[24], even with collaboration within the sector. Of the seven key options listed at the start of section 4.7, only two – energy efficiency measures and clustering – can be considered within the sector's control (and clustering is likely to need some collaboration outside the sector to be fully effective). To illustrate the most significant options that are within the sector's control, Table 11 below shows all the options considered to be within the sector's control that have the potential to save more than 2% of the sector's direct CO_2 emissions.

Option	Subsector	Direct CO_2 reductions potential (% of sector)	Deployed in any pathways?	Comments
Hydrogen by electrolysis (ammonia)	Ammonia	12.9	Y	Requires significantly more energy than current process and only provides decarbonisation if low-carbon electricity is used. Evidence from literature (e.g. International Energy Agency – International Council of Chemicals Association (IEA-ICCA)) and interviews is that significant cost reductions are needed, and/or major change in the price of electricity relative to natural gas.
Hydrogen by electrolysis (hydrogen)	Hydrogen	2.2	Y	Same process as above.
Recycled plastics - syngas	All	10	Y	Requires higher amounts of energy than current processes and, unless provided by a low-carbon source, this could increase CO_2 emissions. Literature (e.g. CEFIC and Ecofys) and interviews identified that the technology requires significant further development. Other barriers include the high capital and operating costs for this option, and uncertainty of availability of recycled plastics to use as feedstock.
Integrate gas turbines with cracking furnace	Olefins	2.5	Y	Potential as a future retrofit option (interviews, CEFIC and Ecofys (2013)).
CCU	All	8.5	Y	Could apply to a range of processes (CLCF/CO_2Chem) but all require high energy use to convert CO_2 to usable form (CEFIC and Ecofys), implying the need to use low-carbon energy to achieve decarbonisations.
Energy efficiency	All	10.5	Y	See section 4.6.6 above.
Catalytic cracking	Olefins	3.7	Y	Requires technology development beyond pilot scale (IEA-ICCA).

[24] Based on the size of individual chemical sites which are not considered large enough to justify a CO_2 pipeline network on their own, requiring cooperation with other major emitting sectors.

Option	Subsector	Direct CO_2 reductions potential (% of sector)	Deployed in any pathways?	Comments
Methanol-to-olefins	Olefins	2.5	N	Requires significantly more energy than current processes (CEFIC and Ecofys) and does not provide decarbonisation unless low-carbon feedstocks and energy used (IEA-ICCA).
High-temperature steam electrolysis	Ammonia	12.9	N	Currently R&D process only.
Solid state synthesis	Ammonia	12.9	N	Currently R&D process only.
Clustering	All	6.7	Y	See section 4.8.6 above.

Table 11: Main options within sector control

Note that the reductions shown in Table 11 are for each option in isolation with no interaction. For example, options eight and 28 would save the same emissions and so the reductions shown cannot be added together.

4.9 Summary

From the above analysis, there are a number of key themes around enablers and barriers for the sector pathways:

- Strategic Context:
    - The need to provide confidence and incentives to invest in major decarbonisation technologies e.g. via long-term carbon regulation under a global climate agreement.
    - That the high capital costs of major investments will require government support in the form of bankable economic incentives and subsidies.
    - The potentially higher operating costs for some decarbonisation options.
    - The need to understand the carbon impacts through the entire life-cycle from initial feedstock through to final product disposal.
- Supply Chain:
    - The importance of decarbonising external energy sources (electricity).
    - The uncertainty in the availability of alternative fuels and feedstocks such as biomass.
- Collaboration:
    - The need for increased collaboration within the sector and externally to facilitate R&D, technology demonstration, and clustering.
- Internal Resources:
    - The difficulties companies face with respect to availability of capital and internal competition for funding.
    - The need to ensure the availability of skilled resources to implement options.

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:

- Eight 'strategic conclusions' or themes have been developed by analysing the main enablers and barriers. Example next steps and potential actions are also included for each strategic conclusion.
- Six 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 pathways[25]. Example next steps are included to assist with developing, funding, and implementing those technologies. A seventh 'other' group covers technologies which are specific to the chemical sector and/or in the sector's control.

It is intended that government and industry use the roadmap to develop the example actions further in order to achieve their objective of economically competitive decarbonisation of the chemicals 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 4.9. Having identified and explored the enablers and barriers through three different research methods (see section 3.1), we have summarised the points into key themes (strategic conclusions) and key technology groups:

Strategic Conclusions

- Leadership, organisation and strategy
- Business case barriers
- Cost-competitiveness
- Policy and incentives
- Life-cycle carbon accounting
- Value chain collaboration
- Research, development and deployment (RD&D)
- Employees and skills

Key Technology Groups

- Electricity grid decarbonisation
- Electrification of processes
- Fuel and feedstock availability (including biomass)
- Energy efficiency and heat recovery technology
- Clustering
- CCS and CCU
- Other technologies

[25] These six technology groups apply to the chemicals sector and also the other seven sector roadmaps.

5.2 Strategic Conclusions

5.2.1 Strategy, Leadership and Organisation

Leadership is important at plant, company, sector, regional and UK level, and both in industry and government level. It can drive and enable all of the themes below. Leadership is required to drive programmes forward and involves developing solutions in response to evidence and analysis. It means that companies are setting targets for emissions reductions, allocating adequate staff time and funding to explore and implement decarbonisation solutions, and thinking long-term. Leadership across companies is also required to drive cluster-led and nationally-led solutions.

The chemical sector illustrates good practice in relation to strategy through its industry-led council, CGP. This council was formed to enable government and industry to work together over the long term to address the key challenges and opportunities for the sector.

Further good practice has been illustrated in Teesside where the chemical sector has been taking a leading important role in developing the case for the industrial CCS as part of their City Deal project.

5.2.2 Business Case Barriers

A key theme from the evidence in the interviews and workshop is that the R&D, demonstration, and deployment of major, long-term technologies requires significant upfront capital which is not always readily available in the UK sector. The long investment cycles in the industry, combined with ageing plants and the cost of operating in the UK, makes it harder for domestic sites to compete for limited investment funds. In addition, large sites producing commodity chemicals often have low margins, which limits their available funds for investment, and their available resource for exploring and making the case for investment options (e.g. technical staff, management time). A further barrier is internal competition with UK and overseas projects that may have higher business priority or shorter payback times; this applies to varying extents to all projects, from small-scale energy efficiency improvements up to major investments in new or replacement plants. For these reasons, decarbonisation projects that appear to be economically worthwhile may not be implemented, even when a solid and well-justified business case is made (see section 3.1 – enabler four and barriers one, five and seven).

With respect to external financing, the evidence suggests that this is not always available on terms (e.g. interest rates) that allow internal investment criteria to be met. Projects are then unable to progress.

Examples of actions to overcome these issues include:

- Consider using third parties to implement projects in order to avoid capital and other resource limitations. For example, an external company could be employed to install a specific energy efficiency measure (for which they would provide funding and staff resources) in return for a share of the benefits. This is an action for industry and could start now for projects that are already defined and ready to implement.
- Government could consider how to assist in developing external project financing mechanisms (by 2020). These need to take account of the likely long-term nature of energy-saving projects.
- Use the full range of outputs from other actions in this section to make the strongest possible business cases for decarbonisation investments. This would need to be an on-going activity by industry.

5.2.3 Cost-Competitiveness

Some of the key technological options considered and discussed by the pathways in section 4, such as CCS, require higher energy consumption and thus increase overall operating costs for a plant. This was a significant barrier according to workshop participants. This reduction in the overall cost-competitiveness of the sector could diminish the likelihood of future investment into the UK to build energy- or feedstock-intensive production facilities and put the long-term future of such plants at risk. However, the high energy and feedstock costs can also make such options appear more cost-competitive than in other countries, allowing the UK to develop a global lead commercialising these technologies at scale. For example, the UK is a world leader in industrial biotechnology, with numerous applications for the chemicals sector, in part as there is a limited market for developing bio-based alternatives to fossil fuel based feedstocks in countries where crude oil and natural gas prices are low.

Example actions to mitigate this could include:

- Collaboration on technology demonstration to drive down capital and operating costs and ensure performance is demonstrated before mass adoption. This would be ongoing activity as technologies become ready but with the overall approach put in place before 2020 (links to *collaboration* with respect to clustering, CC, and RD&D below). This could be an area for joint action between industry and government.
- Establish a multilateral carbon price under a global CCA (see *industrial energy policy context* below).

It should be noted that in a situation of multilateral climate agreements and rising carbon prices, early adoption of decarbonisation options could be advantageous for UK plants.

5.2.4 Industrial Energy Policy Context

The need for long-term energy and climate change policy was identified as key to investor confidence, according to literature and all other sources (see section 3.4.6– enablers one, two and four and barrier four). Some industry participants suggested a need for incentive schemes to become long-term, bankable commitments, as changes in policy around incentive schemes can be damaging, particularly when the business case for investment is marginal and is highly dependent upon factors such as (fluctuating) energy prices. Industry participants stressed that the business case for investments needs to be strong and a crucial part of this is minimising policy-related risks and demonstrating government support.

Policy and incentives is clearly an area where government is likely to take the lead. Example actions could include:

- Establish a 'level playing field' through a global carbon agreement (with regional breakdowns) before 2020, including establishing a multilateral CO_2 price. This could provide a long-term means to avoid carbon leakage.
- Establish a long-term plan on energy security (2015).
- Evaluate means in the short-to-medium term to prevent climate policy induced product and investment leakage. Ideally, work on this would start as soon as possible (2015) on the assumption that it will take a number of years to implement a global agreement (see above) to avoid leakage in the longer term.
- Explore alternative funding arrangements to recognise mid- to long-term decarbonisation benefits (2015). This would allow the value of these benefits to be taken into account in investment decisions. The CO_2 price noted above would be one means of doing this. This action links to the *business case barriers* theme above.

- Continue with its industrial strategy model of long-term partnership with sector councils to give confidence that the industry will be present and thriving in the UK for many investment cycles to come. This confidence would facilitate future investment in both current and new plants.

Actions above to implement effective long-term carbon pricing would have an impact throughout the supply chain. From the evidence of the workshops, this would be likely to increase demand for low-carbon products by customers of the sector and therefore assist in justifying investment in decarbonisation (see also value chain collaboration, section 5.2.6 below). This also links to the *cost-competitiveness* and *business case barriers* themes above).

5.2.5 Life-Cycle Accounting

Workshop participants identified the need to standardise the tools and methodologies for carbon accounting, to ensure comparability and full understanding of the impacts across the product value chain. The sector uses raw materials from and provides its products to other parts of the economy, and there needs to be a common and quantifiable means of understanding the overall carbon impact of the entire product life-cycle. The interactions involved are complex – for example, producing biomass absorbs carbon; if this carbon is then 'sequestered' in a plastic derived from this biomass there might be a long-term societal carbon benefit, but this will depend on factors such as how the biomass is produced, the end-of-life disposal or re-use of the plastic and the alternative materials that the plastic may be replacing. There are also interactions with products from other sectors that need to be taken into account. There needs to be a means for this benefit to be measured and allocated in order to for it to be valued appropriately by industry and customers. This would overcome a number of barriers, including a lack of knowledge in the sector on how best to compare the value of different technological options. If an appropriate value can be put on life-cycle (carbon) benefits which better aligns the industry incentives for generating revenue and maintaining competitiveness with societal incentives for decarbonisation, investment in decarbonisation becomes easier to justify.

This accounting would also help to determine, for example, to compare the uses of a limited resource such as biomass (i.e. as a feedstock or a fuel) by assessing the overall life cycle carbon impact compared to that of alternatives (e.g. the continued use of fossil hydrocarbons).

Example actions include:

- Wider dissemination of knowledge on carbon benefits of existing technologies. This would help remove the barriers identified by some workshop participants of not having the expertise to understand the potential of these technologies and how to operate them most effectively (2015/16). This could be an action for industry bodies and equipment manufacturers to take forward, with government assistance, to help build knowledge and capability across the sector.
- Develop standard tools for evaluating life-cycle 'cradle-to-grave' carbon impacts, from original raw material and feedstock through to final product disposal (2015/16). These should include defined, consistent boundary conditions to ensure results can be compared across sectors. This could be carried out in academia, with industry and government support. This would need to include means to account for the benefits of re-use and recycling within product lifetimes. It may also need to include elements of life cycle accounting for wider resources e.g. materials, water.
- Implement policies and incentives that allow the value of carbon benefits to be realised at the appropriate point in the supply chain (by 2020). For example, if carbon is captured in biomass and then 'stored' by converting it into a plastic with a long lifetime, the carbon benefit needs to have a commensurate financial value that passes this benefit to the producer, which will support the supply chain and help justify investment decisions to implement this business model. A global climate agreement would be one way to allow the market to price in these carbon benefits.

5.2.6 Value Chain Collaboration

Collaboration between different parties in the value chain can provide opportunities for decarbonisation beyond those related to individual sites. For the chemical sector, this could include clustering, collaborative RD&D, and the development of comprehensive carbon accounting (which could incentivise decarbonisation throughout the value chain). A description of the enablers, barriers and potential actions in these areas is provided elsewhere in this conclusions section.

5.2.7 Research, Development and Deployment

Many of the options identified in this roadmap require development of new technologies and processes. The interviews and workshops have identified that progressing the necessary RD&D into decarbonisation technologies is not straightforward for the sector. In particular, there are issues in moving from smaller-scale, initial R&D to the kind of full-scale commercial demonstration that is required to de-risk new processes and accelerate wider deployment. Commercialisation is an inherently risky process which requires significant time and resources, which companies may not be able or willing to provide. A further barrier includes the challenge of knowledge-sharing and collaboration across the complex landscape of organisations and companies involved in R&D activities. Participants highlighted a need to provide support and funding for these activities (links to the *industrial energy policy* and *business case barriers* themes).

Deployment of options once proven will require close collaboration between companies and innovators, and will need to address the technical and financial risk involved with making potentially major modifications to operational plants.

Potential actions include:

- Increased collaboration in order to join up industry needs and academic research. This could start with an inventory of current activities which are already in the public domain. Government could develop incentives to encourage this increased collaboration.
- Industry and government to further develop and support centres of excellence and technology, such as the 'catapult centres' network in the UK.
- Identify areas of possible RD&D collaboration between companies, potentially via existing local industry groups. Key areas for research could include the development of processes to use captured carbon as a feedstock (CCU), which could create additional value from CC. These processes were identified in section 4 which have significant potential to contribute to decarbonisation.
- As identified at the second sector workshop, relevant industry, trade association, academic and government parties should work together to further develop existing knowledge transfer networks.
- Incentivise early adoption of new technologies in order to drive down costs and demonstrate performance. Successful technology demonstration would reduce risks and encourage wider deployment. Technologies should be selected through a collaborative process between industry, academia and technology providers.

All these actions should be deployed in the near future (before 2020) in order to maximise longer-term decarbonisation benefits.

5.2.8 People and Skills

As identified in the workshops, there is a limited number of staff with specialised skills in energy and heat engineering in the sector. The priorities of those staff tend to be on ensuring compliance with regulations which diverts attention and effort away from identification and implementation of energy-efficiency activities.

Some examples of actions to overcome this barrier include:

- Investment in training and recruitment by industry to make the necessary skills available (2015 onwards).
- Government could consider support for skills development in this area at a national level (2015 onwards). This could take place through the Science Industry Partnership, which helps to fund employer-led skills programmes in the chemicals and life sciences sectors.
- Collaboration between industry groups, trade associations and third party providers to provide knowledge of, and access to, external support where expertise is not available in-house.

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

As shown in the pathway modelling (section 4), the decarbonisation of electricity supply has an important contribution to make to overall sector decarbonisation. Trends for electricity decarbonisation in particular are assumed in the pathways model (through the use of the scenarios) and these will need to be achieved to deliver the levels of emission reduction in the pathways. This is not within the direct control of the sector and so actions here are more likely to lie with government to continue with the on-going process of decarbonising the grid. The Government's reforms of the electricity market are already driving electricity grid decarbonisation, and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with Government methodology and modelling.

Grid decarbonisation would provide a further opportunity to decarbonise the sector by the electrification of processes, as noted in section 4.

Example actions include:

- Continue incentives for electricity decarbonisation. These will need to be ongoing to deliver the grid decarbonisation on which the pathways are based.
- Put in place measures to mitigate any negative cost impact of electricity grid decarbonisation measures on the sector (links to *policy* theme above).

5.3.2 Electrification of Processes

As noted above, grid decarbonisation would provide a further opportunity to decarbonise the sector through the electrification of processes. This will only provide overall emissions reductions where the use of electricity is a lower carbon option than the current energy source i.e. as the grid becomes decarbonised, more processes could have a reduced carbon impact simply through electrification.

Example actions include:

- There may be a difficult trade off calculation to be made by both industry and government as to whether it is more cost effective to invest in the costs of converting from fossil fuel to electrical process, versus continuing with existing processes by using industrial CC. The analysis in this report can provide a basis from which to develop this analysis.

- Identify those processes where process electrification would be feasible, quantify how much potential energy use this represents, and at what level of grid decarbonisation conversion to electricity would provide a carbon reduction. Industry could take the lead here, in collaboration with academic and other partners, to identify suitable processes and at what level of grid decarbonisation each could be deployed.
- Government could have a role in providing financial support to companies making the capital investment required for process electrification and/or bridging an ongoing gap in costs, should the operating costs of electrification prove to be higher (e.g. due to the price of electricity versus the previous energy source). Industry and government may need to assess whether it is more cost effective to invest in converting processes to use electricity, compared to alternatives such as applying CCS to existing processes.

5.3.3 Fuel and Feedstock Availability (Including Biomass)

Understanding how much low-carbon fuel and feedstock will be available to the sector is an important first step in delivering the pathways. At present, as identified in the sector workshops, 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) and waste or recycled materials. It will also be necessary to understand, within the chemicals sector, other industries, and across the wider economy, where these fuels and feedstocks can be used to achieve the greatest decarbonisation impact.

To achieve these pathways, 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 and feedstock to the UK as a whole. This would need to be established before 2020 in order to maximise the availability of, for example, biomass fuel from 2020s onwards when it becomes a major contributor to decarbonisation under many of the pathways.
- Industry and academia could collaborate to examine different uses of low-carbon fuels and feedstock 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. This links to the *life-cycle carbon accounting theme* above and feeds into the action below.
- 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. This should happen in the near future (2015/16) to allow future focus on the right options. This also links to the *life-cycle carbon accounting theme* above.
- 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.

5.3.4 Energy Efficiency and Heat Recovery

Energy efficiency and heat recovery technologies have been identified in the roadmap as a significant potential contributor to decarbonisation. This option covers a group of technologies which are generally well-established and so there is a relatively low technical risk with their implementation. By reducing energy use, these options can provide operational cost savings.

The barriers to further deployment of this option relate to the availability of resources (both financial and personnel) to implement them. Example actions to overcome these barriers would be similar to those identified above under *business case barriers* and *people and skills*. Development of *clustering* would allow some of these options (e.g. waste heat recovery) to be applied between sites as well as within them.

5.3.5 Clustering

The literature, sector workshops, and interviews have all highlighted the potential of clustering to reduce emissions. Clustering can reduce emissions by optimising the use of resources e.g. waste heat or by-products from site A being used by site B nearby. By making use of these resources (which would otherwise be wasted), site B avoids having to generate its own energy or raw materials or transport them in, thus avoiding the emissions associated with doing so. In addition, site A avoids the financial and environmental costs of generating wastes and instead generates extra revenue, helping to strengthen its viability within the cluster. Clustering typically involves a degree of co-location in order to make energy- and/or resource-sharing practical.

The barriers to clustering are generally related to organisational collaboration and include the perceived risk of becoming reliant on a partner or partners who may not be present in the long term. The diverse foreign ownership of much of the sector in the UK makes collaboration of this kind more difficult. These barriers were highlighted specifically at Workshop 2. Clustering does not have to be limited to the chemical sector, and both the literature and workshops identified cross-sector clustering as having potential to contribute to decarbonisation. As noted at the workshops, clustering is a long-term, gradual option that requires new or replacement plants to be encouraged to locate where clustering benefits can be realised, and existing plants to maximise local opportunities.

Potential actions to assist in deploying clustering:

- Research risk mitigation measures for clustering. Academia and industry could work together jointly on this.
- Planning and incentive policies could be considered by the Governments to provide strong signals to encourage clustering.
- Increase local collaboration and partnerships to identify and advertise clustering opportunities. Local industry bodies would have a key role here.
- Explore infrastructure investments (e.g. road, ports, pipelines etc.) that would strengthen existing clusters or enable new ones to develop. This is an action for local industry bodies.
- Work on a cross-sector basis to ensure clustering opportunities are encouraged outside the sector. This should be in coordination with organisations that already operate existing clusters, or may be interested in developing new ones.
- Recognise clustering benefits in internal decision-making processes. Individual companies in the sector could consider how clustering benefits are taken into account in these processes.

All these actions should be put in place in the near future (before 2020) to maximise the potential for clustering as future investment decisions are made.

5.3.6 Carbon Capture

As identified in the sector workshops and the literature, there are barriers to the deployment of CCS related to the size of individual emitting sector sites and the fact that, individually, they are not considered of sufficient size to justify a CO_2 pipeline and storage network. Collaboration between sites (both within and outside the sector) is needed to overcome this as the costs of building and operating a network would need to be shared between a number of parties. The CO_2 pipeline and storage network would be 'shared' infrastructure – in the same way that, for example, the electricity grid is shared infrastructure – and appropriate funding will need to be established. The presence of industrial clusters, especially those near possible storage sites, may have less barriers to eventual development of this technology than sectors with distributed sites and emissions.

Example actions could include:

- Industry bodies and government could consider how to facilitate the development of cross-sector networks, for example via joint venture or independent 'pipeline companies'. Networks would need to be in place for the major sector hubs (e.g. Teesside, northwest England, Grangemouth, Humberside) in the early 2030s to allow the significant deployment of this option under many of the pathways during the 2030s and 2040s.
- Assist in funding initial CCS network infrastructure during the 2020s. This could, for example, be through initial support to pipeline companies to allow them to establish networks and so provide confidence to industry to invest in CO_2 capture (in the knowledge that there will be a CCS network to connect to). Government could consider possible means of providing this initial funding support.
- Development of demonstration CC projects during the 2020s in order to allow deployment during the 2030s. These would ideally cover a range of different processes and would need to be located to match with the initial pipeline networks developed above. This would be likely to be led by industry, with government support.

There are other actions related to policy, technology demonstration and cost which apply to CCS which are reflected in other themes in this section.

The comments above would also apply to CCU. This option would also be likely to need a shared pipeline network, although with no need for storage the network could be more limited and could initially connect a small number of CO_2 producer and consumer sites.

5.3.7 Other Technologies

Other decarbonisation technologies have been identified during the development of this roadmap such as generating hydrogen by electrolysis and the recycling of plastics to generate syngas feedstock. The enablers and barriers for these technologies are similar to those identified above such as the need for further *RD&D* and *cost-competitiveness*.

5.4 Closing Statement

This roadmap report is intended to provide an evidence-based foundation upon which future policy can be implemented and actions delivered. The way in which the report has been compiled is designed to ensure it has credibility with industry, 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 chemicals sector are able to build on the its evidence, analysis, and strategic conclusions to deliver significant reductions in carbon emissions, increased energy efficiency, and a strong competitive position for the UK chemical industry in the decades to come.

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7. GLOSSARY

Adoption

The percentage of sector production capacity to which a decarbonisation 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 decarbonisation 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 energy 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 CO_2 emissions reduction and improved energy efficiency. In general, emissions of other GHGs, relative to those of CO_2, are very low.

Decarbonisation 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.

Decarbonisation 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 overcome a barrier.

Feedstock

Raw material used in a chemical process.

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

A combination of carbon abatement options and energy 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 decarbonisation 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 evidence 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 decarbonisation 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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