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

# Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050

## *Oil Refining Appendices*

MARCH 2015

# INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAP TO 2050 – OIL REFINING

# APPENDIX A - METHODOLOGY

# APPENDIX A METHODOLOGY

The overall methodology used in this project to develop a decarbonisation roadmap for the oil refining sector consists of four stages:

(1) Evidence gathering and processing based on literature, interviews, a workshop and written responses;
(2) Modelling of draft pathways, including scenario testing and sensitivity analysis;
(3) Testing and developing final pathways; and
(4) Creating a sector vision for 2050 with main conclusions and recommendation of next steps.

This methodology is illustrated in Figure 1 and summarised in the report. A detailed description is given in this Appendix.

An important aspect of the methodology has been Stakeholder Engagement to ensure that all implicated parties have been invited to participate and contribute. We have worked closely with UKPIA to identify and invite the right people from the sector. In addition we have worked with Department of Energy and Climate Change (DECC) and the Department for Business Innovation and Skills (BIS) to identify the appropriate academics and other stakeholders, such as financial industry personnel, to participate and contribute.

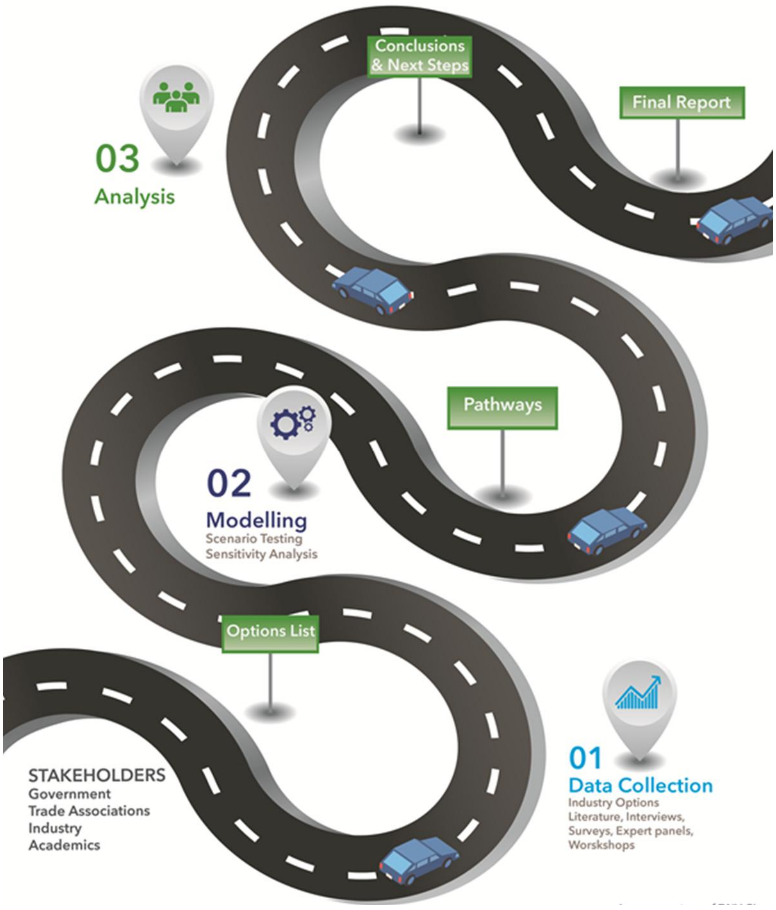


*Figure 1: Roadmap methodology*

# 1. Evidence Gathering

Evidence gathering focused on technical and social and business evidence, and aimed to acquire information about:

- Decarbonisation options (i.e. technologies)
- Barriers and enablers to decarbonisation and energy efficiency
- Background to the sector
- Current state and future changes within the sector
- Business environment and markets
- Potential next steps.

This evidence was required to either answer the principal questions directly, or to inform the development of pathways and the sector vision for 2050. The evidence was developed from the literature review, interviews, site visits, written responses and a workshop. By using these different sources of information, the evidence gathered could be triangulated to improve the overall research. Themes that were identified during the literature review and written responses could subsequently be used as a focus or a starting point during the interviews and the workshop. The data from the literature could be subjected to sensitivity testing by comparing it with information from the interviews and written responses. Similarly, information gaps during the interviews and the workshop could be populated using literature data and written responses.

The different sources of evidence were used to develop a consolidated list of barriers and enablers for decarbonisation, and a register of technical options for the oil refining sector. This information was subsequently used to inform the development of a set of pathways to illustrate the decarbonisation potential of the oil refining industry in the UK.

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

The evidence gathering exercise was subject to inherent limitations based upon the scale of activities and sample sizes that could be conducted within the time and resources available. The literature review was not intended to be exhaustive and aimed to capture key documentation that applied to the UK. The companies interviewed or providing a written response represented 50% of carbon emissions produced in the UK oil refining sector and captured UK decision makers and technical specialists in the oil refining sector. These interviews were conducted to provide greater depth and insight to the issues faced by companies. However, because many of the companies in the UK are globally owned, it was difficult to involve senior staff at a global corporate level. This also applied to workshop attendees.

The identification of relevant information and data was approached from a global and UK viewpoint. The global outlook examined dominating technologies and process types, global production and $CO_2$ emissions (in the EU27) and the global outlook to 2050, including the implications for oil refining 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 UK oil refining dominant technologies and processes were also reviewed.

## 2. Literature Review

A literature review was undertaken on the oil refining sector. Its aim was to help to identify options, barriers and enablers for implementing carbon reduction throughout the sector. It seeks to answer the principal questions, determine the barriers and enablers for implementing carbon reduction and identify what are the necessary conditions for companies to invest and consider carbon management as a strategic issue to determine appropriate technical options for the sector.

The literature review covered over 42 documents. This was not a thorough literature review or rapid evidence assessment (REA) but a desktop research exercise deemed sufficient by the project team[1] in its breadth and depth to capture the evidence required for the purpose of this project. Based on the table of contents and a quick assessment (10 to 30 minutes per document), criteria were defined to identify which documents were to be used for the detailed analysis and evidence gathering (see Section 3 of Appendix A). Where literature was deemed significant and of good quality, it was read and results were gathered on the principal questions.

The review has drawn on a range of literature (published after 2000), that examines energy efficiency and decarbonisation of the sector and also wider reviews, studies and reports deemed relevant to energy-intensive industries overall. Sector-based and academic literature was also added. The documents are listed in section 6 of the main report.

The literature review was conducted in the following phases:

- Broad literature review and information/data collection
- Detailed literature analysis on technical points of note
- Identification of decarbonisation options and associated drivers/barriers
- Information on adoption rate, applicability, improvement potential, ease of implementation, capex, Return on Investment (ROI) and the saving potential for all options where available
- Construction of decarbonisation options list for short (2015-2020), medium (2020-2030) and long term (2030-2050)
- Provision of information on strengths, weaknesses, opportunities, threats, enablers and barriers. This information was used in the information gathering workshop as a starting point for discussion. It provided evidence to support the development of a consolidated list of enablers and barriers for decarbonisation and, subsequently, to inform the list of the possible technological options and pathways that would lead to decarbonisation.

| | Details |
|---|---|
| **Main focus (all in the oil refining sector)** | Energy efficiency improvements<br>$CO_2$ and carbon reduction<br>Fuel switching |
| **Secondary focus** | Drivers, barriers, policy<br>Carbon capture and storage (CCS) |
| **Excluded** | Carbon offsetting<br>Non-$CO_2$ emissions<br>Technologies not applicable to the UK oil refining sector |

*Table 1: Scope of review*

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

## 3. Criteria for Including Literature

As described earlier, the literature review followed a quick assessment process. General criteria used for including or excluding literature are shown in Table 2.

| | Considerations | Final criteria |
|---|---|---|
| **Literature value** | Preference was given to official publications, such as academic papers or governmental publications. Information from general sources (grey literature) was interesting as sector-related info. However, as there is no objective standard with which to compare this information, no extensive search in this domain was executed. The grey literature was used as input to the workshops. | Preference was given to published papers: the main source was ScienceDirect and published official reports. |
| **Time period to be covered** | Given the fact that the European Energy Directive (end 2012) is a recent factor in the energy-related political landscape, preference was given to information which was (very) recently published. Some valuable, but older, information was included, as technology penetration is conducted at different speeds throughout the oil refining sector. | No constraint was set on the date of the publication, but older information was given a lower quality rating, due to its lower relevance. |
| **Geographical area** | Preference was given to the UK industry, with a broader look to Europe as the technology competition in this area is the most prominent. | No geographical exclusion criteria were used, but information on the UK oil refining was given a higher quality rating, due to its higher relevance. |
| **Language** | As the majority of information is in English, no special attention was given to publications in other languages. | The search was limited to papers in English, but where easily obtainable qualitative information was found in other languages, this was included. |

*Table 2: High level selection criteria*

For academic literature, the primary source was ScienceDirect. Of the documents that came on top in the search result (typically the first 25 papers), a skim-read of the abstract decided on the relevance of the paper.

A total of more than 90 papers, official publications and grey literature experts on oil refining were collected using this search methodology. The quality, source and objectivity of each document was analysed by reading the abstract (where present), followed by a skim-read of the document.

Each document was given a score on different aspects of relevance:

- Category: is the content of the document focusing on technology, drivers/barriers or policy-related aspects;
- Affiliation: what is the source of the document: academia, governance or is it sector-based;
- Financial-technical evaluation criteria present (YES/NO);
- Overall quality of the document (+/++/+++);
- Relevance for the UK oil refining sector (0/+/++/+++);

- Information on technological aspects (0/+/++/+++);
- Information on drivers and barriers (0/+/++/+++);
- Information on policy/legislation (0/+/++/+++); and
- Document relevant for developing scenarios (0/+/++/+++).

Based on all these aspects, the document was given a relevance classification: “high”, “medium high”, “medium low” or “low”.

The approach to selecting and categorising literature is depicted in Figure 2.

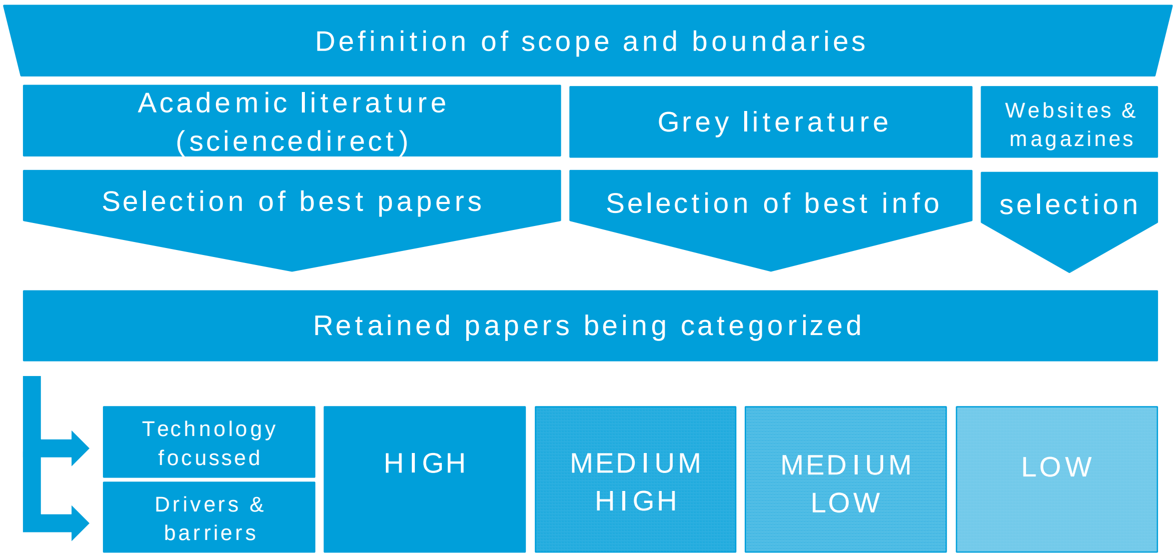


*Figure 2: Diagram of the selecting and categorising process*

All documents categorised as “high” and “medium high” were read in detail, assessed and then included in the literature review process. The documents categorised as “medium low” and “low” were read and assessed in part and only included if a significant reason for inclusion was found.

Energy saving measures (if present) were listed from each document included in the review process and this list was used to construct a decarbonisation options list for short- (2015-2020), medium- (2020-2030) and long-term (2030-2050) timelines.

NOTE: Additional and specific information/data was added to the overall review process from e.g. stakeholder input datasheets and as a result of following citation trails, expert knowledge and further targeted searches and recommendations.

## Method of Analysing Literature

The following method was used to go through the selected literature:

1. Reading and noting of the abstract (or summary) followed by review of the document in detail to extract any relevant information on sector description/outlook and information/data on energy savings and carbon reduction measures.
2. Relevant information (if appropriate) was extracted from other sources (or referred to) and document citation trails (if appropriate) were checked for further relevant information/data.
3. Incorporation of the documents into the literature review and collating of the most relevant information/data on energy saving and carbon reduction measures.

4. Energy savings, where possible, were preferably extracted as a percentage, or as a specific energy saving per relevant unit.
5. For financial savings, the amounts were kept in their original currency.

## 4. Technical Literature Review

### Identifying literature

The primary aim of the literature review has been to gather evidence on technical potential and options (under different timelines) in order to inform the opportunities and challenges associated with the decarbonisation of energy use and improved energy efficiency for the oil refining sector in the UK.

In parallel to the above review process, a number of key academics were identified to participate and provide perspectives on current research and to provide additional input and feedback. This was to ensure that the appropriate literature and research had been identified, screened and included.

### Research Questions

The evidence review addressed the following research questions:

**TECHNICAL POTENTIAL:** What existing research is there on the technical potential for improving the energy efficiency and lowering the carbon footprint of the oil refining Industry to 2050? What generic and specific technical measures exist and what is their potential?

**TECHNOLOGY COSTS:** What research is available on the costs of these technical measures, and what does it tell us?

**DRIVERS/ENABLERS:** What does research tell us about the drivers/enablers for organisations in the oil refining sector to decarbonise their energy use? What are the perceived benefits for industrial organisations to decarbonise their heat use?

**BARRIERS:** What does research tell us about the barriers for organisations limiting effective decarbonisation of their energy use?

**PRINCIPAL QUESTIONS**: Check for other links to issues raised by principal questions.

**SWOT analysis**: Check for any information using terms strengths, weaknesses, threats and opportunities.

### Information Found by the Consortium during Technical Literature Review

A number of additional documents were identified during the course of the literature review. These documents were identified through Google / ScienceDirect[2] and through the oil refining sector team. The search terms used in ScienceDirect and Google were:

- "refining"
- "oil refining"
- "oil refining" AND "UK"
- "oil refining" AND "energy case study"
- "oil refining" AND "energy (savings)"
- "oil refining" AND "carbon capture / CCS"
- "oil refining" AND "energy/energy consumption"
- "oil refining" AND "CHP / cogen (eration)"
- "oil refining" AND "driver(s)/barrier(s)"

[2] http://www.sciencedirect.com/

- “oil refining” AND “policy/politics”

Other documents in ScienceDirect were found by checking the references of the papers found by the above searches.

The results of the technical literature review are summarised in Figure 3.

| Summary of strength of evidence on energy efficiency in oil refining sector | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Division | Number of information sources reviewed | | | | | Strength of the evidence | | | |
| | Academic searches | Direct website searches | expert reviewer | grey literature | Total | HIGH | MEDIUM HIGH | MEDIUM LOW | LOW |
| General | 1 | 4 | 1 | 0 | 6 | 4 | 1 | 1 | 0 |
| Technologies | 11 | 12 | 1 | 4 | 28 | 12 | 9 | 6 | 1 |
| CO2 & CCS | 5 | 5 | 2 | 0 | 12 | 6 | 5 | 1 | 0 |
| Enablers/barriers | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| Social and business | 15 | 12 | 2 | 8 | 37 | 5 | 8 | 13 | 11 |
| Market | 0 | 7 | 1 | 0 | 8 | 4 | 3 | 1 | 0 |

*Figure 3: Overview of literature review*

A complete reference list is available in section 6 of the main report.

## 5. Social and Business Literature Review

In addition to the work and processes described in the technical literature review, the social and business literature review key points and additions are:

- We reviewed over 42 documents (some of them the same as the technical literature review) to create a broad overview of the sector SWOT and identification of drivers and barriers to energy efficiency improvement and decarbonisation, and identification of main uncertainties in generic and business environment.
- The literature review included documents listed in the ITT (invitation to tender) as well as grey literature from trade associations, companies, DECC and BIS. Specific search terms were used which were agreed with DECC to identify the key enablers and barriers.
- We used a systematic and structured approach to the literature review. The criteria for assessing the relevance of the literature were defined to determine whether they address the key principal questions. The literature identified was analysed using a quick assessment process to identify the most relevant information on SWOT, enablers and barriers to decarbonisation.
- Based on table of contents and a quick assessment, we presented the results in a table as below. The analysis resulted in the identification of documents to be used for detailed analysis and information gathering. Where literature was deemed significant and of good quality (three stars or above), the literature was read and reviewed and results were gathered on the principal question areas.

| | Year | Relevance | Quality | Characteristics | SWOT, Drivers and Barriers | Uncertainties future trends | options | pathways |
|---|---|---|---|---|---|---|---|---|
| **Title 1** | | +++ | ++ | 0 | ++++ | ++ | 0 | ++++ |
| **…** | | ++ | +++ | ++ | 0 | +++ | + | + |
| **…** | | + | ++ | + | 0 | ++++ | ++ | 0 |
| **Title 10** | | ++ | ++++ | +++ | ++ | +++ | +++ | ++ |

*Table 3: Literature review assessment process*

*0= very low, ++++ very high*

The outcome of the literature review was a comprehensive list of strengths, weaknesses, opportunities, threats, enablers and barriers which were used in the evidence gathering as a starting point for discussion and voted on to check which ones were most important.

## 6. Interviews

The evidence gathering stage of the project also involved a series of interviews and written responses to the interview questions. These aimed to obtain further details within the oil refining sector and to gain a deeper understanding of the principal questions, including how companies make investment decisions, how advanced technologies are financed, what a company's strategic priorities are and where climate change sits within this.

In liaison with UKPIA, DECC and BIS, nine oil refinery companies were invited to participate in the social and business interviews. In July 2014, when the refining sector study was initiated, there were seven operating major refineries in the UK: Essar Stanlow, Esso Fawley, Murco Milford Haven, PetroIneos Grangemouth, Phillips 66 Humber, Total Lindsey and Valero Pembroke and one specialised bitumen refinery, the Eastham Refinery. This is owned by a Nynas/Shell joint venture and operated by Nynas AB. The Murco Milford haven refinery has subsequently ceased refining operations. BP and Shell were also invited to participate in the study. Although Nynas were not invited to take part in the study, emissions from the Eastham and Dundee refineries have been included in the reference trend emissions projections (the Nynas Dundee refinery ceased refining operations in Q1 2014). The seven major refineries accounted for over 99% of sector emissions in 2012. The social and business team were unable to interview any of the refineries, as refineries declined to participate due to reservations regarding Competition Law. Interviews were also conducted with the Environment, Health and Safety Director of UKPIA as well as a part-time Lecturer at the University of Surrey who is retired oil refining specialist. One site visit was also completed at a refinery.

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

The sector has no subsectors or sub-categories therefore the sources are representative of the sector. This has allowed generalisation during the rest of the report including the following areas: decision-making, barriers, conclusions.

Comments collated via UKPIA and subsequent email correspondence was also used as part of the evidence gathering process.

Interviewees were interviewed using the 'Interview Protocol' template, developed in liaison with DECC and BIS. The Interview Protocol was used to ensure consistency across interviews, to ensure that the interviews could be used to fill gaps in the literature review, identify key success stories of decarbonisation, and extract the key social and business barriers of moving to low-carbon technologies. The "Interview Protocol" can be found further in this Section.

### Evidence Gap

UK refineries declined to participate in the interview process so the information was triangulated from the sources that were made available to the team.

### Assumptions

Going into each interview, a number of assumptions were made to refine the approach being taken:

1. Results from the literature review are available and partially well covered. Well covered areas are not addressed during the interview. Results may include:
    a. Options register of technical options
    b. Sector and subsector characteristic
    c. Sector SWOT analysis
    d. Main trends and drivers
    e. Some hurdles to and barriers for change and/or energy or carbon reduction

2. Preparation of interviews includes rapid review of website and annual reports information related to business and energy and emissions reduction strategies.
3. The technical review covered any gaps in data or information (e.g. specifically related to that company's data) which may be appropriate to obtain during the interview process.
4. Interviewee role is reviewed prior to conducting the interview.
5. All interviews are conducted by interviewers in their own proficient way of dealing with issues around openness, consent, and follow-up.
6. Interviews are conducted by PB or DNV GL consultants (representatives from both technical and social and business disciplines), with their own proficient way of dealing with issues around openness, issues of consent, encouraging openness, and follow-up.
7. There might be follow-up with interviewees to obtain additional information discussed during the interview.

## Interview Template

We identified the proposed interviewees in liaison with UKPIA, DECC and BIS in order to achieve a good coverage of the sector. The methodology for identifying the appropriate number of interviews was the following:

- Identify the number of subsectors by the SIC (Standard Industrial Classification) codes listed in the ITT or another appropriate subsector division;
- Look at ways to combine subsectors based on similarities in products or production techniques to potentially reduce the number of subsectors; and
- Cross validate the subsectors according to the following criteria:
    - Size: medium or large – there are no SME's in the group of companies that covers 80% of the emissions in the sectors;
    - Innovation level of companies such as front runners or laggards;
    - Whether headquarter is in UK or abroad; and
    - The level of integration of the production units in the supply chain (non-integrated, somewhat integrated, fully integrated).

**Interview protocol**

**Preparation:** Interviewers/technical/social leads

**Browsing public information to have an overview with:**
- Company strategy;
- ONS (office of national statistics) data and IBIS;
- Ambitions/plans of the companies with regards to energy and carbon reduction;
- Successes;
- Challenges/issues; and
- Reduction option in place and planned.

**Draft value chain/stakeholder map on sector (or even subsector level) /SWOT/options list (sector specific)**

**Introduction:** project context (what, why, who) setting, goals, agenda interview
**Interviewer explains first four goals outlined below**

**Goals:**

1. Better insight in the (importance of the) current state, ambitions/plans, successes and problems/challenges and way of working of your organisation with regard to energy use, energy reduction and carbon reduction. We will do this by:
    a. Identifying and analysing one or two examples of implementation of energy and carbon reduction stories to get a specific insight in the problems and hurdles on company level;
    b. Understand decision-making processes and responsibilities; and
    c. Understand the relation of energy related strategies with the business strategy.
2. Better insight in energy and carbon reduction options for the company and their potential:
    a. Already in place plus realised potential for your company; and
    b. Considered/planned plus expected potential for your company.
3. Understanding of the main drivers and hurdles for change in general and with regard to energy and carbon reduction in the sector; and
4. Get better insight in the specific characteristics of a subsector (if needed to clarify results or to finish the whole picture).

**Current state and plans for energy and carbon reduction within your company**

1. What is your strategy/plan regarding energy and carbon reduction? (If the plan is clear, we summarise it and ask for confirmation). If we have no plan, we ask if there is one (if we can have a copy) and cover the following questions:
    a What are the main elements of the plans;
    b How far in advance are you planning the company's energy efficiency;
    c What are in your opinion the easy and/or difficult parts; and
    d Why:
        i. *Constrained finance for funding for investments internally or externally*
        ii. ….
2. Do you consider your company as a front runner (innovator/early adopter) or as follower (early, late majority) on sustainability/ energy and carbon reduction:
    a. Can you give one or more example(s) of behaviour of your organization that fits within this role;
    b. Do you expect the company's position/role with regard to energy and carbon reduction will change; and
    c. Why/why not.
3. What options did you implement the last five years and why did you implement these options? For options not considered, why was that?
   Tip for interviewer: use structure of the prepared options register (prepared by technical lead and sector team) to identify options. For parts of the list that are not covered, challenge the interviewee: can you identify options that could be valuable for your company and ask for applicability. With front runners we will emphasise on less mature/more innovative options. With laggards we will emphasize on mature easy wins. Remember that the technical lead is present in the interview.
4. How important is energy and carbon reduction as a subject in your company? This should address how the carbon and energy strategy fits into wider strategy and to what extent it is embedded into the wider business strategy.

**Stories:** on a specific energy or carbon reduction option (measurement)

**A story that worked well and one that has not worked well. Options that have not worked well include options that have been considered but are not (fully) implemented and why.**

**Innovators with long track record will be asked, for most innovative and complex success:**

1. What options were implemented, why, when and where;
2. Can you tell the story preferably from the first idea generation until now? → Timeline of the story. Ensure this covers how ideas were generated (i.e. the step before any appraisal of options takes place):
   a. What was the timeline, sequence of events;
   b. Cover idea generations, feasibility study (tech, finance, and organisation), decision-making, board presentation, and implementation;
   c. What was your process to make a case for an investment and who were involved? Probing into areas such as: key factors in deciding, required payback, main perceived/actual risks, how influenced by alternative options for investment, financial and non-financial factors;
   d. What were the critical moments (breakthroughs, hurdles)?
3. What were the contribution, attitude of the main stakeholders/what were their motivators at these critical moments. Did their attitudes towards the subject change? How;
4. Why do you consider this story as a success or an area for improvement;
5. What are the main conclusions you can draw from this story - positive and negative:
   a. Lessons for future action;
   b. Main drivers and hurdles for energy and carbon reduction in your company;
   c. Lessons for the way of organising energy and carbon reduction options within you company;
   d. Conclusions regarding potential reduction targets on short-, medium- and long-term; and
   e. How well did the carbon reduction option work in practice, in relation to the anticipated performance.
6. Any reports/presentations on this innovation we can use.

**Value chain/business environment and innovation power of the sector (probably only needed in interview before workshop)**

1. What do you consider to be the main drivers for energy and carbon reduction in this sector:
   a. What are main characteristics of the main functions in the production process ( following the structure of the option list):
      i. Ask specific questions on elements not covered after desk research; and
      ii. Important specific characteristics of the subsector (input, process, output, energy use, value chain, competitive forces).
   b. What are the main strong and weak points of the different parts of the value chain;
   c. What were the main changes in the value chain the last 10 years;
   d. What are possible important innovations in the value chain the coming 10/20/30 years; and
   e. What are possible game changers for the value chain/ sector?
2. Main innovators/early adopters in the sector:
   a. The main influential (whom or what are they listening to, why):
      i. Companies and people within companies ( role/function); and
      ii. Within and outside the sector (other sectors, academics, non-government organisations, politicians etc.).
3. Questions on several innovations dimensions[3] . These questions will be on a multiple choice list (answer categories strongly disagree, disagree, neither agree or not agree, agree, strongly

[3] Questions are asked to get a better (and broad overview of space/possibilities for change (not only including investments but also the change that potential of option will materialise.

agree[4]). After filling the list, we ask for clarifications of the answers and examples that underpin these and experiences within the company that contradict these:

   a. technical: networks with other companies, academics, knowledge of competitive and emerging technologies, participation in R&D, pilots, experiments;
   b. Human capital: improvement projects, multi-disciplinary teams, training on innovation/change/improvement;
   c. Organisation: horizontal communication lines, clear goals/responsibilities, customer focus; and
   d. Management: clear performance criteria for projects, structural follow up of main improvement projects in management meeting, clear status information on projects

4. (Optional) characteristic story of a (successful) sector and subsector change/innovation, on energy or carbon reduction. Question is only asked if consortia/sector teams feel a need to get a better overview of success stories. This is relevant because in most business environments managers are influenced most by fellow business men.

**Drivers and hurdles for sector change (partly done to test text for survey)**

**Please lets step back and summarise main drivers and hurdles for sector change (general and or specific for energy and carbon reduction):**

1. What do you consider the main drivers for change in the sector:
   a. Ask for specific drivers in the following fields: social, policy, technical regulatory factors; and
   b. Show the prepared list and check need to elaborate list so far anything not clear in the list.
2. What do you consider the main hurdles for change in the sector:
   a. Ask for specific hurdles in the following fields: social, policy, technical regulatory factors;
   b. Show the prepared list and check need to elaborate the list; and
   c. Anything not clear in the list.

**Closure:**

- Reviewing concept minutes, plus identify key points;
- Remind for reports and other information to be sent;
- Involved in follow up; and
- Thanks.

Function of Interview Template and Protocol:

The interview template was designed to collect, build upon and collaborate specific answers to principal questions which are not covered by results of desk research. The general timeline of one interview is illustrated below:

[4] This way of working is chosen to be able to just cover the field quickly and get a quick first idea what they consider the important aspects so we can spend as much time as possible on this. We normally don't use the survey results to collect quantitative answers to these.

| | |
|---|---|
| Intro | 5-10 minutes |
| Current state and plans energy and carbon reduction | 20-30 minutes |
| Stories of energy/carbon reduction | 30-45 minutes |
| Business environment and innovation power | 15-20 minutes |
| Drivers and hurdles for sector change (to test workshop questionnaire) | If time left |

*Table 4: General interview timeline*

# 7. Pathways

A pathway is a combination of different decarbonisation options, deployed under the assumed constraints of each scenario that would achieve a decarbonisation level that falls into one of the following decarbonisation bands:

- 20-40% $CO_2$ reduction pathway
- 40-60% $CO_2$ reduction pathway
- 60-80% $CO_2$ reduction pathway

In addition, two purely technology-driven pathways were developed: a business as usual (BAU) pathway and a maximum technical (Max Tech) pathway. The BAU pathway consisted of the continued deployment of technologies that are presently being deployed across the sector. Under all scenarios, the BAU pathway reached more than 20% decarbonisation, making it unnecessary to develop additional 20-40% $CO_2$ reduction pathways. The Max Tech pathway included a technology or technology combination that would achieve the maximum $CO_2$ reduction possible within the sector, given constraints of deployment rates and interaction. Additionally, two alternative pathways have been created in which a new refinery is built using BAT (best available technology) to replace an old plant, one without CCS and one with CCS. The pathways have not been optimised to achieve a certain decarbonisation level. The model, which is available through DECC/BIS, is described in Section 9.

# 8. Pathways Development and Analysis

## Overview

Pathways were developed in an iterative manual process in order to facilitate the exploration of uncertain relationships that would be difficult to express analytically. This process started with the data collected in the evidence gathering phase. This data was then challenged and enriched through discussions with the sector team.

Logical reasoning (largely driven by option interaction and scenario constraints), sector knowledge and technical expertise were applied when selecting options for the different pathways under each scenario. For example, incremental options with lower costs and higher levels of technical readiness were selected for the lower decarbonisation bands, whereas more ‘disruptive’ options were selected for the higher decarbonisation bands in order to reach the desired levels of decarbonisation. These pathways were challenged by the sector team, modelled and assessed under the three scenarios and finally challenged by the stakeholders participating in the workshop. This feedback was then taken into account and final pathways were developed. All quantitative data and references were detailed in the options register and relevant worksheets of the model.

It is important to keep in mind that the pathways results are the outcome of a model. As with all models, the accuracy of the results is based on the quality of the input data. There are uncertainties associated with the input data and the output should therefore be seen as indicative and used to support the vision and next steps, not necessarily to drive it. Also the model was a simplification of reality, and there are likely to be other conditions which are not modelled.

The analysis only produced results (pathways) which were iterative inputs of the model operator, without any optimisation.

## Process

1. The gathered evidence (from literature review, sector team discussions, stakeholder feedback and judgement) was consolidated into a condensed list of options.
2. Timing and readiness of options was developed by the sector team, based on evidence from literature, sector knowledge and technical expertise.
3. Options were classified as incremental, major or disruptive.
4. BAU and Max Tech options were chosen and deployed to the maximum level and rate allowable under the current trends scenario.
5. Options were added to the BAU pathway or reduced or taken out of the Max Tech pathway until each intermediary pathway band was reached.
6. Technical constraints and interactions across the list of options were taken into account when selecting options and deployment.
7. The deployment was adjusted to account for the output of the social and business research as well as current investment cycles.
8. Pathways were modelled under the current trends scenario, accounting for changes in production and the carbon emissions of the electricity grid.
9. The results were reviewed and modifications made to the deployment, applicability and reduction potential for any options that appeared to be giving an unexpected or unusual result.
10. Further changes to option choices were made as required through iterations of points 5-9.
11. Revised pathways under current trends were produced for presentation at the workshop.
12. Feedback on pathways was used to make any further necessary adjustments to the pathways under current trends.
13. The final pathways developed under current trends were used as a basis for the development of pathways under challenging world and collaborative growth scenarios.
14. Deployment of each option under challenging world and collaborative growth was adjusted according to the constraints of each scenario, including the removal of options that would not be likely under challenging world and the deployment of additional options that would become feasible under collaborative growth.
15. Deployment for each option was adjusted within the technical and scenario constraints in order to reach each pathway band where possible. Note that not all pathway bands are possible under some scenarios.

The options are listed in Appendix C.

## Deployment of Options

For each pathway, options were selected and deployed over time according to their readiness level, timing constraints, and those most likely to allow the pathway band to be achieved. This process occurred iteratively, involving the sector team, trade association and other stakeholders (who contributed via the second workshop). The sector lead provided an expert view on whether the options identified in each pathway produced a feasible pathway.

As described within the pathways section of the report, the technologies included within each banded pathway under each scenario may differ in order to meet the pathway band under each scenario.

The selection and deployment of options accounted for evidence from the social and business research, for example which options could be deployed without any changes to policy and where the deployment of options may be slowed or curtailed by identified barriers or accelerated by enablers.

### Option Interaction

There were a number of possible ways in which options could interact with each other. These interaction types, and how they were dealt with in the development of pathways, are described below:

- **One option excludes another:** This is taken into account by the user in the deployment inputs in the option selector by ensuring that no exclusive options are deployed out to a conflicting level in the same time period. An example of this is that savings from the use of new technology on specific equipment cannot be applied if the new refinery option is used.
- **One option depends upon another being adopted:** This is taken into account by the user in the deployment section of the option selector by ensuring that if any option requires a precursor that this precursor is deployed to the appropriate level.
- **Options are independent and act in parallel:** The 'minimum interaction' pathway curve assumes that all options are independent and their effect on energy or emissions are therefore incremental; and
- **Options improve a common energy or emission stream and act in series:** The 'maximum interaction' pathway curve assumes that the saving from each option reduces the remaining energy or emissions for downstream options to act upon.

The pathways curves included a 'maximum interaction' and a 'minimum interaction' curve. The actual pathway curve would lie between these two extremes.

### Evidence Not Used in Pathways Modelling

Specific energy use of processes was considered constant in the modelling, whereas they are actually dependent on the load factor (production level) of the equipment. Increasing the production level of existing equipment would increase efficiency, which should be taken into account when calculating emissions. However, a full bottom-up model would be needed, which was beyond the scope of this work.

The options were modelled with a fixed $CO_2$ and fuel saving as input values. As technologies mature, it is likely that these values would increase. This was not taken into account in the model, as the uncertainty of that development is high.

The adoption rates and applicability rates were used to inform deployment, but without a full bottom-up model implemented on a site-by-site basis, it was difficult to link these parameters directly to investment cycles.

## 9. Pathways Modelling

### Scenarios

Modelling pathways starts with the development of scenarios. A scenario is a specific set of conditions external to the sector that would directly or indirectly affect the ability of the sector to decarbonise. An example of a condition in a scenario was the emissions factor of the electricity grid. Where appropriate, conditions were described qualitatively through annual trends. The scenarios analysis also included qualitative descriptions of exogenous drivers which were difficult to quantify, or for which analytical relationships to quantitative factors were indefinable.

For each pathway, the following three scenarios were tested: current trends, challenging world and collaborative growth. Scenario parameters are shown in

| | challenging world | current trends |
|---|---|---|
| **International consensus** | National self-interest | Modest |
| **International economic context** | More limited growth, some unstable markets, weakening of international trade in commodities | Slow growth in EU, stronger in world, relatively stable markets |
| **Resource availability and prices** | Strong competition, High Volatility<br>High price trends. | Competitive pressure on resources. Some volatile prices<br>Central price trends. |
| **International agreements on climate change** | No new agreements. Compliance with some agreements delayed | Slow progress on new agreements on emission reductions, all existing agreements adhered to. |
| **General Technical Innovation** | Slow innovation and limited application | Modest innovation, incidental breakthroughs |
| **Attitude of end consumers to sustainability and energy efficiency** | Consumer interest in green products only if price competitive. Limited interest in energy efficiency. | Limited consumer demand for green products, efficiency efforts limited to economically viable improvements |
| **Collaboration between sectors and organisations** | Minimal joint effort, opportunistic, defensive | Only incidental, opportunistic, short term cooperation |
| **Demographics (world outlook)** | Declining slowly in the west<br>Higher growth elsewhere | Declining slowly in the west<br>Modest growth elsewhere |
| **World energy demand and supply outlook** | Significant growth in demand with strong competition for resources. High dependence on imported fossil fuels | Balanced but demand growth dependent on supplies of fossil fuels from new fields. |
| **UK Economic outlook** | Weaker OBR growth assumption. | Current OBR growth assumption |
| **Carbon intensity of electricity** | Weakest trend of electricity carbon intensity reduction<br>200g/kWh at 2030 | Stronger trend of electricity carbon intensity reduction<br>100g/kWh at 2030 |
| **CCS availability** | Technology develops slowly, only becoming established by 2040 | Technology does not become established until 2030 |

| | challenging world | current trends |
|---|---|---|
| **Low carbon process technology** | New technology viability delayed by ten years | New technology economically viable as expected |

Table 5 below.

## Current Trends

The current trends scenario projected moderate UK and global growth. Alongside this, international policies on climate change were assumed to develop, gradually but effectively driving down emissions.

The oil refining sector production was assumed to decrease by 0.14%. A reduction occurs in the reference sector emissions from 2012 to 2014 due to refinery closures, but with a small bounce-back by 2015 due to increased utilisation of other refineries. Production and reference emissions are then assumed flat over the remaining period to 2050.

## Challenging World

The challenging world scenario was characterised by lower global growth rates. Climate change was assumed to have a lower profile than at present, so that there would be less effective action to reduce emissions.

The oil refining sector production was assumed to decrease by 0.18%. Reference emissions were assumed to regrow to 98% of 2012's emissions, by 2020, after the plant closures have occurred in the intervening period. Indirect $CO_2$ emissions from electricity were assumed to reduce to 200 g $CO_2$ per kWh by 2030, then to 150 g $CO_2$ per kWh by 2050.

## Collaborative Growth

The collaborative growth scenario was represented by higher levels of global growth and concerted action to reduce carbon emissions.

The oil refining sector production was assumed to decrease by 0.1%. A stronger regrowth of sector emissions was assumed from 2014 to 2030: the reference trend reaches around 106% in 2030, compared to 2012. Indirect $CO_2$ emissions from electricity were assumed to reduce to 50 g $CO_2$ per kWh by 2030, and then reach 26 g $CO_2$ per kWh by 2050

| | challenging world | current trends | collaborative growth |
|---|---|---|---|
| **International consensus** | National self-interest | Modest | Consistent, coordinated efforts |
| **International economic context** | More limited growth, some unstable markets, weakening of international trade in commodities | Slow growth in EU, stronger in world, relatively stable markets | Stronger growth in EU, stable markets, strong international trade. |
| **Resource availability and prices** | Strong competition, High Volatility<br>High price trends. | Competitive pressure on resources. Some volatile prices<br>Central price trends. | Competitive pressure on resources. Some Volatile prices<br>Central price trends. |
| **International agreements on climate change** | No new agreements. Compliance with some agreements delayed | Slow progress on new agreements on emission reductions, all existing agreements adhered to. | Stronger worldwide agreements on emission reductions, consistent targets for all countries |
| **General Technical Innovation** | Slow innovation and limited application | Modest innovation, incidental breakthroughs | Concerted efforts lead to broad range of early breakthroughs on<br>Nano, bio, green and ICT technologies. |
| **Attitude of end consumers to sustainability and energy efficiency** | Consumer interest in green products only if price competitive. Limited interest in energy efficiency. | Limited consumer demand for green products, efficiency efforts limited to economically viable improvements | Consumer willing to pay extra for sustainable, low carbon products. Strong efforts to energy efficiency even where not cost effective. |
| **Collaboration between sectors and organisations** | Minimal joint effort, opportunistic, defensive | Only incidental, opportunistic, short term cooperation | Well supported shared and symbiotic relationships |
| **Demographics (world outlook)** | Declining slowly in the west<br>Higher growth elsewhere | Declining slowly in the west<br>Modest growth elsewhere | Stable in the west<br>Slowing growth elsewhere |

| | challenging world | current trends | collaborative growth |
|---|---|---|---|
| **World energy demand and supply outlook** | Significant growth in demand with strong competition for resources. High dependence on imported fossil fuels | Balanced but demand growth dependent on supplies of fossil fuels from new fields. | Growing demands balanced by strong growth in supply of renewable energy, slowly declining importance of fossil fuels. |
| **UK Economic outlook** | Weaker OBR growth assumption. | Current OBR growth assumption | High OBR growth assumptions |
| **Carbon intensity of electricity** | Weakest trend of electricity carbon intensity reduction<br>200g/kWh at 2030 | Stronger trend of electricity carbon intensity reduction<br>100g/kWh at 2030 | Rapid decline in electricity carbon intensity<br>50g/kWh at 2030 |
| **CCS availability** | Technology develops slowly, only becoming established by 2040 | Technology does not become established until 2030 | Technology becomes proven and economic by 2020 |
| **Low carbon process technology** | New technology viability delayed by ten years | New technology economically viable as expected | New technology viability achieved early |

*Table 5: Summary of scenario context and specific assumptions applicable to the scenarios*

# 10. Options

## Classification and Readiness of Options

The options were divided into three groups reflecting the likely timing of their deployment:

- Incremental
- Major
- Disruptive.

**Incremental** improvements extending known solutions, such as optimising process controls, improving maintenance, and plant retrofits.

**Major** improvements reducing carbon emissions, including: design improvements, upgrading process units such as by using Best Available Technologies (BAT), fuel switch (from fuel oil to natural gas), and new Combined Heat and Power (CHP) on remaining sites.

**Disruptive** technology shifts consisting of Carbon Capture and Storage (CCS) and waste heat and energy recovery. Additionally, an alternative disruptive option includes a new refinery rebuild, using the most efficient European refinery as a benchmark (sensitivities with and without CCS).

## Options Processing

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 and through receiving detailed information packs from members of UKPIA. The technical team drafted the first list of options. However, each option had strengths, weaknesses, enablers, and barriers which needed to be taken into account to develop and refine the options register to feed into the model.

A comprehensive list of enablers and barriers identified from the literature review was refined and triangulated with the stakeholder workshop and written responses. To find the most relevant enablers and barriers for incorporating into the options register and pathways, enablers and barriers that were not supported by the information gathering workshop and interviews were removed from the list.

The impact of social and business research was captured in the options register, under the individual technologies (where possible) and in the subsequent pathways selected.

We have used the decision tree below to determine whether the social and business findings should impact upon the options and pathways. The pathways represent a selection of options, and this determines when and to what extent the options become active.

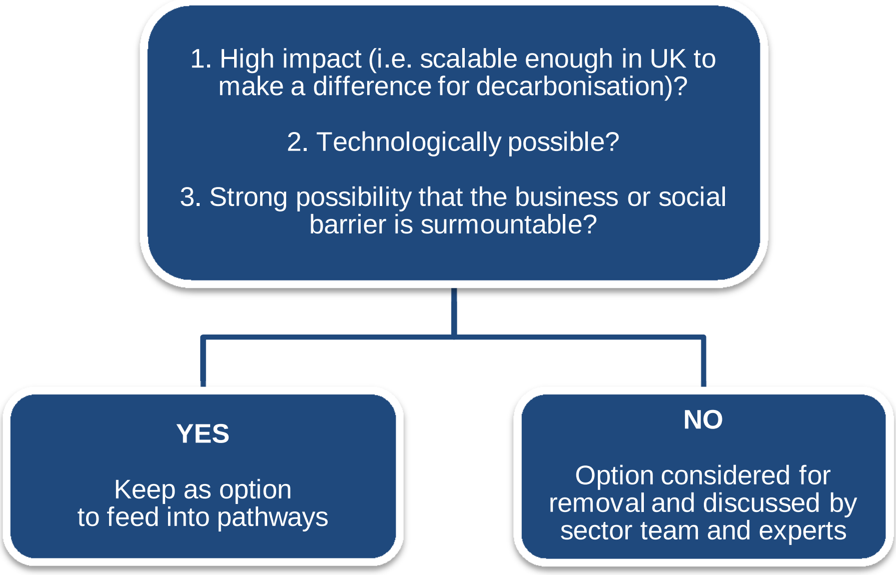


*Figure 4: Social and business pathways impact tree*

## 11. Stakeholder Workshop

The purpose of this workshop was to improve the awareness of the decarbonisation and energy efficiency challenges for the sector together with the evidence base collected during evidence gathering.

It was organised to inform the sector on policy decisions for 2020-2050, to inform all stakeholders on available options for decarbonisation, and to establish a shared evidence base upon which a more constructive relationship between government and industry can be built to deliver emissions reduction.

This workshop aimed to develop conclusions and potential next steps, based on stakeholder engagement, and the research and analysis undertaken in this project.

The workshop was divided into two key activities. The first activity focused on reviewing the modelled technological options (that were identified from literature and interviews) for decarbonisation and the proposed pathways towards decarbonisation of the sector.

It included identifying adoption rate, applicability, saving potential and timeline for implementation. This was done by presenting the options and the pathways that were previously developed, followed by a breakout session allowing facilitated discussions of options and pathways, improvements to the model, interdependencies between options, sensitivities and scenarios. The second activity involved a presentation and discussion of the barriers and enablers that had been identified by the social and business research. Based on these group discussions, potential next steps were identified for the sector.

Based on the feedback from stakeholders during this workshop, pathways were adapted where required and potential next steps were identified.

# 12. Next Steps

The output of the pathway development and social and business research included identification of barriers to and enablers for:

- Implementation of the pathways
- Decarbonisation and energy efficiency in the oil refining sector more generally.

To draw conclusions, the analysis of barriers and enablers is taken further by describing a list of possible next steps to be implemented by a combination of industry, government and other organisations. These actions can take the form of strategic conclusions which are high-level and/or longer term, or more specific, discrete activities which can lead to tangible benefits.

The development of conclusions and next steps has considered the following:

- Actions from other oil refining decarbonisation projects
- Necessary changes in future markets, product features, business environment to enable the different pathways
- The outputs of the workshop held as part of this project covering decarbonisation pathways and action plans
- Actions that help maximise the success of a pathway under a range of scenarios
- Options within the pathways that are necessary for success e.g. if a particular technology option is necessary for the success of a number of pathways, or an option has a very high decarbonisation potential, actions to implement this option are included
- Policy and regulations that contribute to the removal of barriers and/or enhancement of enablers.

The possible next steps can be divided into three main groups: strategy, opportunity and analysis, and tools and resources.

# INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAP TO 2050 – OIL REFINING

# APPENDIX B – FULL SOCIAL AND BUSINESS FINDINGS

# APPENDIX B FULL SOCIAL AND BUSINESS FINDINGS

## 1. SWOT Outcomes

The info-graphic below highlights the top strengths, weaknesses, opportunities and threats in relation to decarbonising the oil refining sector in the UK.

| STRENGTHS | WEAKNESSES | OPPORTUNITIES | THREATS |
|---|---|---|---|
| Some refineries have large RD&D funds for energy efficiency | Highly vulnerable to what happens in the rest of the world | Cogeneration | Rising energy prices |
| Some oil refiners have corporate strategies and energy management systems in place to reduce greenhouse gas emissions and improve energy efficiency | refining is energy intensive | CCS | Regulatory complexity and uncertainty |
| Oil refining supplies over 30% of the energy used in the UK and important feedstock for other industrial sectors and processes | EU refining margins have been and continue to be depressed | | Increasingly competitive market with low margins#<br><br>Market is increasingly competitive market which is reducing margins which impacts on investment |
| Senior management buy-in | Sector is mature and in decline | | Declining total demand: gradual erosion of demand for heavy fuels and concomitant development of markets for light products |
| | | | Additional costs from EU-only policy (e.g. carbon costs) |

*Table 6: SWOT analysis for oil refining sector*

A **SWOT analysis** is a different lens to examine the enablers and barriers and reinforce conclusions and linkages between evidence sources. It identifies how internal strengths mitigate external threats and can be used to create new opportunities, and how new opportunities can help overcome weaknesses. By clustering the various possibilities, we identified key stories from the SWOT analysis which enabled us to describe the business and market story in which companies operate. In order to understand the inter-linkages between the SWOT analysis for the Sector and the key enablers and barriers we identified from the literature review, interviews, and workshop, we analysed the root causes of the enablers and barriers and linked it back to the market environment and internal decision-making. The top SWOT outcomes were identified from the literature review, reinforced in the interviews and voted on by workshop participants as the most important.

Other social and business research methods used include elements of system analysis, root cause analysis, causal mapping, Porter’s Five Forces analysis, and storytelling. **System analysis** can be used to help decision makers identify a better course of actions and make better decisions. It is a process of studying a procedure or business in order to identify goals and purposes, and to create systems and procedures that will achieve those goals most efficiently. It uses an experimental approach to understand the behaviour of an economy, market or other complex phenomenon. **Root cause analysis** is a method of problem solving that tries to identify the root causes of a problem. A root cause is a cause that - once removed from the problem - prevents the final undesirable event from recurring. **Causal mapping** is a visual representation, showing causalities or influences as links between different nodes. These maps can be used to aid strategic planning and thinking. **Porter’s Five Forces** is a framework to analyse the level of competition within an industry and business strategy development. **Storytelling** is a technique that uses a clear and compelling narrative to convey a message or provide context to a conversation with the aim to engage the interviewee and encourage openness.

## 2. Assessing Barriers and Enablers

The first stage in our 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 evidence and whether the findings were validated via more than one information source. If the strength of the evidence was deemed high or medium high, then for the social and business research the enabler and/or barrier was included and information was used to support the answer to the principal question '*What are the main business enablers and barriers to decarbonisation?'*. If the strength of the evidence was deemed high or medium high for the technical options, the uncertainties in the modelling were reduced. The evidence was given a relevance classification of: 'high', 'medium high', 'medium low' or 'low'. The classifications are defined in Table 7 below.

It should be noted that the nature of the interview and workshop discussion process means that these represent the opinions and perceptions of the interviewees and workshop participants which could not always be backed up with evidence from other information sources.

The evidence was analysed and interpreted using a variety of analytical techniques such as SWOT analysis, system analysis and root cause analysis/causal mapping where possible.

| Classification | Definition |
|---|---|
| **High** | High relevance for the UK oil refining sector<br>Good financial-economic decarbonisation data<br>Recent information (after 2000[5])<br>Provides a good example/story of decarbonisation<br>Validated across all evidence gathering methods |
| **Medium high** | Relevance for the UK oil refining sector<br>Financial-economic data not always complete or clear-cut and only generic decarbonisation data<br>Provides a good example/story of decarbonisation<br>Validated by more than one evidence gathering method |
| **Medium low** | Information that is or too general or too specific<br>Relevant grey literature<br>Old information but still relevant<br>Only mentioned via one information gathering method |
| **Low** | Background information<br>No or low applicability for the UK oil refining sector<br>Grey literature of limited value<br>Old information<br>Lack of relevance and/or only mentioned once |

*Table 7: Evidence classification definition*

The following tables provide a summary of raw data collected relating to barriers and enablers.

[5] Two publications older than 2000 were included in the high quality documents

# 3. Detailed Analysis of Enablers and Barriers

## Enablers

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| 1 | **Market** | Cost savings from energy saving (threat of increasing energy costs) - refinery fuel is about 50% of refinery cash costs. | **8 Literature Sources**<br>Ricardo AEA (2013) found that: "The EU refining sector is very competitive in energy efficiency, although many competing regions have significantly lower non-energy cash costs. Additional costs from EU-only policy (e.g. carbon costs) will further aggravate these competitive disadvantages…the key drivers are cost and threat of rising energy prices and willingness of top management to make climate change a priority."<br><br>EUROPIA (2011) found that: "Refinery fuel is about 50% of refining cash costs, which drives efficient use of energy in refining and the EU ETS will further incentivise economic | **5 Industry sources**<br>"Energy efficiency is always considered for KIT replacement as energy costs are the second most important cost after feedstock."<br><br>"Energy costs represent a substantial operating expense for our refining and chemical facilities Successfully improving energy efficiency is therefore a major driver for cost reduction and industrial competitiveness."<br><br>"Refineries are trying to minimize costs and push oil through the refinery. As margins are being squeezed refineries are looking at energy (cost) savings."<br><br>"Energy costs are a driver. Only if the investment is affordable."<br><br>"Energy costs represent a substantial operating expense for our refining | **4 tables out of 4** listed cost savings related to energy efficiency as one of the top 5 enablers. | As refinery fuel is around 50% of cash costs, increases in energy costs impact oil refineries margins. As energy is a core cost to the business, most refineries have robust energy management systems in place, and look to improve energy efficiency when upgrading process equipment. Energy costs are both a driver and a barrier as UK energy prices are higher than in other parts of the world placing UK refiners at a competitive disadvantage. |

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | | efficiency measures."<br><br>IPIECA found that: "The oil and gas industry will continue to support policymakers in formulating cost-effective strategies and measures to promote the rational use of energy for the benefit of all."<br><br>CONCAWE (2008) identified that: "Energy efficiency improvement, a constant theme for many years in refineries, still presents opportunities and these will undoubtedly be grasped especially in the current "expensive energy" environment."<br><br>CONCAWE (2012) found that: "The consumption of energy within EU refineries plays a crucial role in determining refinery operating costs and emissions and has therefore long been a | operations. Successfully improving energy efficiency is therefore a major driver for cost reduction and industrial competitiveness and as such is of high importance to us." | | |

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | | focus of attention by refinery operators."<br><br>Total (2014) discusses its top priorities of its Technological Roadmap Defined for refining and Chemicals in which it states: "Using resources efficiently, especially by enhancing process energy efficiency, and managing and recycling end-of-life plastics." Total aims to produce less but more efficiently.<br><br>Valero (2003) discusses how energy efficiency helps its U.S. based refineries: "With cost-shared funding from the DOE, the Valero Houston refinery also began a plant-wide energy assessment, which included the development of a refinery Energy Optimization and Management System (EOMS). Valero Houston refinery expects significant | | | |

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | | economic benefits from refinery-wide implementation of the EOMS. Benefits will be realized through improved energy purchasing with lower contract prices, better adherence to contract terms to reduce penalties, maximized use of the most efficient equipment, accurate selection of fuel type, reduction of standby equipment and steam venting, and faster responses to problems. Typical cost savings at comparable refineries are in the range of 2 to 8% of energy expenditures. If the EOMS performs as expected in all 12 refineries, it has the potential to save Valero \$7 to \$27 million per year company-wide."<br><br>Worrell et al. (2009) found that in the USA "Petroleum industry operations consume up to 15% to 20% of the energy in crude oil or 5% to 7% of world | | | |

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | | primary energy, with refineries consuming most of that energy (EIDT 2004). Based on a survey of US refinery operations, researchers found that most petroleum refineries can economically improve energy efficiency by 10–20% and provided a list of over 100 potential energy-saving steps.<br>The petroleum industry has had long-standing energy efficiency programs for refineries and the chemical plants with which they are often integrated. These efforts have yielded significant results. Exxon Mobil reported over 35% reduction in energy use in its refineries and chemical plants from 1974 to 1999 and in 2000 instituted a program whose goal was a further 15% reduction. Chevron reported a 24% reduction in its index of energy use between 1992 and | | | |

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
| --- | --- | --- | --- | --- | --- | --- |
| | | | 2004."<br><br>Neelis, Worrell, and Masanet (2008) found that: "There are a variety of opportunities available at individual plants in the U.S. petrochemical industry to reduce energy consumption in a cost-effective manner." | | | |
| **2** | **Production/ Operational** | Oil refineries are energy inefficient, thus there is an opportunity to improve energy efficiency through improved energy monitoring and process control systems. | **3 Literature Sources**<br>Milosevic, Zoran, Cowart, and Wade (2002) found that: "the refining industry as a whole can be classified as energy inefficient."<br><br>Hodges and Hawkes (2013) found that: "there are a number of actions that can be carried out to bring UK refineries up to the efficiencies of top EU refineries of the Benelux and Scandinavian countries. These actions are estimated to improve energy efficiency across the board in refinery operations by 20%. | **3 Industry Sources**<br>"Invested a total of $330 million to help improve energy efficiency, reduce flaring and decrease GHG emissions."<br><br>"We are the oldest refinery in the UK. Much of our crude oil processes are from the 50s. Thus, there are lots of good opportunities to improve energy efficiency."<br><br>"There is a lot that refineries can do to improve energy efficiency such as improving energy monitoring and process controls, but that requires management focus and resources." | **0 out of 4 tables** listed oil refineries are inefficient creating an opportunity to improve through energy monitoring and process control systems as their top five enablers.<br><br>The lack of capital due to negative margins and the lack of management focus or prioritisation of basic energy efficiency projects were seen as key barriers to this enabler. | Process and control improvements are a medium term option for decarbonising the oil refinery sector. Many refineries already have these systems in place, but basic actions such as: reducing flaring, fixing leaky valves, reducing steam leaks, ensuring flue gas expanders are working, for example, are not taken as the focus is on increasing throughput whilst minimising costs given the unfavourable market conditions. |

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | | These include: improving the use of energy monitoring and process control systems, elimination of flaring, improved operation of process and elimination of steam leaks, improved condensate recovery, improved integration and operation of preheaters for process fired heaters and Improved operation of process fired heaters are actions with mostly short lead times."<br><br>Worrell et al. (2009) found that in the USA: "Petroleum industry operations consume up to 15% to 20% of the energy in crude oil or 5% to 7% of world primary energy, with refineries consuming most of that energy (EIDT 2004). Based on a survey of US refinery operations, researchers found that most petroleum refineries can economically improve energy efficiency by | | | |

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | | 10–20% and provided a list of over 100 potential energy-saving steps.<br>The petroleum industry has had long-standing energy efficiency programs for refineries and the chemical plants with which they are often integrated. These efforts have yielded significant results. ExxonMobil reported over 35% reduction in energy use in its refineries and chemical plants from 1974 to 1999 and in 2000 instituted a program whose goal was a further 15% reduction. Chevron reported a 24% reduction in its index of energy use between 1992 and 2004." | | | |
| **3** | **Organisation** | Management focus- corporate targets and long-term energy strategy and willingness of top management to make climate change a priority. | **2 Literature Sources**<br>Ricardo AEA (2013) found that: "Ricardo AEA (2013) found that one of the drivers was the "willingness of top management to make climate change a priority and having a | **6 Industry Sources**<br>"Management focus, resources, and funds are needed for refineries to prioritise basic energy efficiency improvements"<br><br>"Their projects compete globally and their manufacturing strategy | **3 tables out of 4** listed management focus as one of their top 5 enablers.<br><br>At the workshop Solomon EII (a refinery benchmarking tool for improvement, which | Across the information gathered, it is clear that currently oil refinery management is mainly focused on business survival. Energy is part of business improvement but does not always way up against other business improvement options, such as increasing output and yield.<br>Companies such as Total and ExxonMobil that do have energy efficiency or overall efficiency strategies and management |

| # | Category | Enablers | Literature review | Interviews | Workshops | Analysis and Interpretation |
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| | | | long term energy strategy."<br><br>Total (2014) stated that: "Total is pursuing a targeted investment strategy in refining and petrochemicals in Europe. Despite weaker markets, we believe that we have an industrial future in Europe, as long as we can produce less, more efficiently." | and focus may be on investments in large complex refineries in growing markets. The strategies do not currently focus on the UK market and refineries, except for one company."<br><br>"Improving throughput and increasing yield enhancements are the key focus, with energy as a side benefit."<br><br>"One company uses a Global Energy Management System (GEMS) to monitor each facility on a fairly wide range of parameters and benchmark facilities against each other. The company uses the benchmarking to identify improvement projects, and as a result have implemented energy efficiency projects. They have a very particular focus on energy management."<br><br>"Energy costs represent a substantial operating expense for their chemical facilities. Successfully improving energy efficiency is | assesses energy as one criterion and is conducted every two years by all refineries) was highlighted as a driver for improving energy performance. | systems such as GEMS are more likely to prioritise energy efficiency projects. |

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| | | | | therefore a major driver for cost reduction and industrial competitiveness and as such is of high importance to the company. The company has a clear strategy and well developed approaches to improve energy efficiency, which have been successful in achieving significant reductions."<br><br>"Solomon EII league table name and shame approach acts as a driver for refineries to improve their energy efficiency performance." | | |
| 4 | **Regulation / Policy** | Government actions that encourage investments in decarbonisation such as:<br>• Predictable policy and legislative framework<br>• Long-term stable regulatory and fiscal environment for CHP and CCS<br>• Implementation of a level playing field with other regions<br>• Reduce overall cumulative regulatory costs | **3 Literature Sources**<br>EUROPIA (2011) found that: "the continued need for oil products to 2050 indicates that it is in the EU's interest to implement policy and legislation that maintains the viability of the EU domestic refining sector throughout the transition to a competitive low-carbon economy."<br><br>Ricardo AEA (2013) found that: "The | **8 Industry Sources**<br>"Key enablers of energy efficiency and carbon reduction projects include: implementation of a level playing field with competing regions (both in terms of relevant policies and overall cumulative regulatory burden); elimination of technology specific subsidies and; a stable and predictable policy and legislative framework."<br><br>"We support managing GHG emissions on a | **4 out of 4 tables** listed one or more types of government actions that encourage investments in decarbonisation as one of their top 5 enablers.<br><br>One table indicated that having more support for community use of waste heat for district heating would be beneficial for decarbonisation. | Across the information sources gathered, stakeholders called for a level playing field (both in terms of energy prices and overall cumulative regulatory costs) and a stable regulatory environment in order to create an environment that is conducive to refineries investing in decarbonisation technologies. Stakeholders suggested a number of government actions that could encourage investment such as taxing carbon refinery imports or enhancing corporate level capital allowances. |

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| | | on refineries<br>• Targeted use of enhance corporate level capital allowances- allow companies to write off the cost of investments for specific energy efficiency projects from their taxes<br>• Carbon tax on refinery imports<br>• Carbon price support mechanism to help incentivise investments in low-carbon electricity<br>• Elimination of technology specific subsidies - support an array of technologies not just one as can lead to a misallocation of resources<br>• Support for investment in use of waste heat for community heating | evidence suggests that the CO2 price required to make refinery owners invest in CO2 mitigation is quite high.”<br><br>UKPIA found that a key driver for decarbonisation is to: “Introduce a carbon price support mechanism to help increase incentives for investment in low-carbon electricity.” | global basis, using pragmatic, science-based solutions that encourage the full array of energy solutions. Duplicative policies should be avoided and policies should not pick winners and losers…We believe than rather than developing specific pathways, a technology neutral approach is the most cost-effective.”<br><br>“UK refineries are mid to low performers in terms of competitiveness with the EU. Investment and resources are needed to compete with more attractive large-scale projects of parent companies in other parts of the world.”<br><br>“Enhance capital allowance schemes – available in the upstream industry. Government should consider this for specific projects in oil refining and other sectors to improve energy efficiency and improve air quality, emissions abatement, and investment.” | | |

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| | | | | "Legislative drivers for industrial energy efficiency include: EU Emissions Trading Scheme, Pollution Prevention and Control, and Climate Change Agreements."<br><br>"The introduction of a suitable policy as part of a stable, long-term regulatory and fiscal environment for CHP could act as an enabler for further investment in this effective, proven energy efficient technology."<br><br>"…the UK to focus on ensuring that the EU adopt a single, cost effective, long term trajectory for carbon abatement, which is shared economy-wide and transparent to society."<br><br>"In the UK, investment in existing and future cogeneration is impacted by the regulatory and fiscal environment for CHP. As an example, whilst the company welcomes the Budget 2014 announcement that | | |

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| | | | | fuel inputs used to generate electricity via CHP will be exempt from the Carbon Floor Price (CPF), earlier removal of the support mechanism for UK CHP investment (the Levy Exemption Certificates, LECs) created uncertainty in the regulatory regime – acting as a barrier to investment.” | | |
| **5** | **Regulation / Policy** | Regulatory compliance is a driver of energy efficiency investments. | **3 Literature Sources**<br>House of Commons Energy and Climate Change Committee (2013) found that: “There is considerable investment in the refining industry, although much of it is primarily directed at compliance with legislative and regulatory requirements.”<br><br>Milosevic, Zoran, Cowart, and Wade (2002) found that: “Stringent environmental limits being imposed on the quality of fuels that refineries can burn is increasing the cost of refinery marginal | **3 Industry Sources**<br>“Regulatory compliance is a driver.”<br><br>“Legislative compliance is an enabler to a point. There is a tension between this being an enabler and barrier. Move operations elsewhere if compliance burden too high.”<br><br>“Regulatory compliance is an enabler and barrier.” | **2 out of 4 tables** listed regulatory compliance as their top 5 enablers. | Regulatory compliance was seen as both a barrier and an enabler. IHS Purvin and Gertz concluded that the cost impacts from existing legislation would impose a serious challenge to future refining margins. However, across the information sources stakeholders indicated that regulatory compliance is a driver of energy efficiency improvements, but that a balance must be struck between regulatory compliance as a barrier and as an enabler. |

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| | | | fuels, which prompts an additional incentive to save energy."<br><br>IHS Purvin and Gertz (2012) identified: "We believe that no industry would bear such an investment burden for no return." | | | |
| **6** | **Strategy** | Government recognition of the strategic importance of the oil refining sector. | **-** | **1 Industry Source**<br>"Government objectives for refining are not clear. What refinery structure should there be?" | **1 table out of 4** listed Government recognition of strategic importance of the oil refining sector as a 'missing' enabler.<br><br>This enabler was also discussed and highlighted by a keynote speaker at the workshop. | Although not highlighted in the literature, one industry source and a key note speaker as well as one table at the workshop identified the need for government to determine the strategic importance of the oil refining sector to the UK going forward for energy security as well as employment and tax revenue. By communicating its importance, this would help oil refineries to overcome the uncertainties regarding the market and help them to make future investment decisions related to decarbonisation. |
| **7** | **Market** | Enhance certainty over market for more efficient and greener products and fuels and implement regulations to support these changes. This would create demand for oil refinery products and create more revenues to be able to invest in decarbonisation technologies. | **-** | **1 Industry Source**<br>"Uncertainty is the biggest barrier. Up to 2025 there is a short term uncertainty due to very low margins." | **2 tables out of 4** listed enhance certainty over new more efficient and greener products and fuels as a 'missing' enabler.<br><br>New products to be used in new engines would help create market demand for oil refinery products.<br><br>Certainty about | Market uncertainty and demand destruction were highlighted as key barriers across all information sources. At the workshop two tables indicated that building greater certainty regarding the transport sector, especially greener products and fuels required, would help overcome these barriers by building confidence in future product demand, which can increase revenues and management's willingness to invest in longer term decarbonisation projects. |

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| | | | | | market for more efficient and greener product fuels may improve the market and regulatory changes should be implemented to support these changes. | |
| **8** | **Value chain** | Enhance collaboration between industry, government, trade associations, and academia to deploy and invest in decarbonisation projects. | **-** | **2 Industry Sources**<br>“Research and money are required for CCS... A national effort would be needed but no incentive for government to enhance collaboration.”<br><br>“There is no mechanism for cross collaboration. The current research mechanisms act as a barrier to cross sector collaboration. Research is conducted by specific companies. Collaboration led by single companies. Government does not drive any collaboration.” | **1 table out of 4** listed the following enablers as ‘missing’ regarding research and collaboration :<br>-Research grants in new chemical technologies<br>-Simplify state aid rules to allow easier government help to enable industry.<br>- Find a mechanism to ‘fast-track’ research to be deployed in industry.<br>-Link and join up research between refineries and academia.<br>-Consider government secondees to refineries. | Competition was seen as a key barrier to collaboration on research and development across the information sources. Two industry sources and one table indicated that there were opportunities to develop multi-stakeholder research projects to help invest and deploy new decarbonisation technologies. |

*Table 8: Raw data - enablers for the oil refining sector*

## Barriers

| # | Category | Barriers | Literature review | Interviews | Workshops | Analysis and Interpretation |
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| **1** | **Market** | Unfavourable market conditions- demand destruction, negative cash-flow and uncertainty limiting the availability of funds available to invest in decarbonisation. | **5 Literature Sources** CONCAWE (2008) found that: "In the last decade the oil product market in Europe has undergone very significant changes. This will continue through the coming decade and towards the 2020 time horizon considered in this study. The changes stem both from the evolution of demand, particularly with that of road fuels but also the relentless increase in the proportion of diesel and jet fuel, and from product quality changes brought about chiefly by environmental legislation across the spectrum of fuel grades. Slow rate of growth of total demand:<br>• Gradual erosion of demand for heavy fuels and concomitant development of markets for light products,<br>• Within the light | **6 Industry Sources** "Economics is a key barrier…... Up to 2025 there is short term uncertainty with very low margins. The focus is on survival. In the medium term there is a major investment challenge for regulatory compliance bringing us to 2025 to 2030. Between 2030 and 2050 there is the challenge of demand destruction. It is a very uncertain world with refining."<br><br>"Key barriers include: market conditions and negative cash flow."<br><br>"The industry suffers from cyclical profitability, as it is greatly affected by the price of crude oil (set by suppliers and international events) and energy demand (set by national economy and market forces) over which the sector has no controls."<br><br>"Financial uncertainty regarding ability to pull through with low margins | **4 out of 4 tables listed** unfavourable market conditions / demand destruction/ uncertainty about product and the future of the business as their top 5 barriers.<br><br>A keynote speaker at the workshop indicated that the challenges faced by the sector are bleak as less oil products are being demanded as there is an oversupply of product and negative margins. The current focus of the refineries is on survival, with only one refinery being cash positive. | All of the information sources reaffirm that oil refineries are currently experiencing demand destruction, and the majority are faced by negative cash flows. The sector is in decline. |

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| | | | products market, a relentless increase of demand for "middle distillates" particularly automotive diesel and jet fuel, and a slow erosion of motor gasoline demand."<br><br>Purvin and Gertz (2013) found that: "The downstream oil market in the UK is going through a process of change characterised by weak overall petroleum demand, growth in the aviation sector, increasing numbers of diesel vehicles and a reduction in the use of oil for power generation. The profile of companies and investors in the market is also changing, with a more diverse ownership profile in the refining sector, a steadily increasing supermarket presence in the retail sector, continuing pressure on margins and sustained levels of competition; these | in the short term, in the long term there is uncertainty regarding demand destruction and the future of the sector."<br><br>"Decisions are made on the amount of income refineries are earning. EU refiners aren't making any income, thus; shareholders don't want to invest."<br><br>"Economic and financial position of the company investing in decarbonisation is a key barrier." | | |

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| | | | trends are likely to continue in the future."<br><br>European Commission (2012) found that: "EU refining margins have been and continue to be depressed, while EU demand has been and continues to be declining. It is principally falling demand, coupled with excess capacity (leading to low utilisation rates), which have depressed margins. In addition, projections for future EU petroleum demand point towards continuing decline, with the exception of growth in middle distillates which will however continue to be positive only for a few more years (even taking into account future demand from the shipping industry for very low sulphur fuel). The response of a number of EU refining companies to the current market | | | |

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| | | | situation and future prospects has been to put refinery units up for sale or to halt operations, sometimes for indefinite periods of time. However, actual complete closures of refineries are not occurring, due to the large, and costly, site remediation clean-up which owners would have to incur. Altogether, some eight refineries have ceased operation since 2009, amounting to around 6% of total EU refining capacity… The EU refining industry also needs continuous access to funds in order to carry out operational improvements in line with the regulatory requirements imposed on the industry (fuel quality, industrial emissions, CO2 emissions etc…);<br>As exemplified by what is being experienced by Petroplus, EU refiners | | | |

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| | | | have however been having great difficulties accessing funds lately (not least, due to the bleak current and future market expectations mentioned previously). A situation which is likely to be compounded, given the change in ownership profile of the EU refining industry."<br><br>IEA (2014) found that: "The economic recovery buys demand, but the dynamics of demand growth undergo a structural shift - efficiency gains and fuel switching increasingly balance income and population impacts. Asia is by far the largest magnet for global crude exports as North America grows into a net oil exporter The refining industry faces a new round of restructuring and a potential glut of light products." | | | |

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| | | | Breeze 2014 found that: “Petroleum refiners faced extremely tough market conditions over the five years through 2013-14. Most refineries in the United Kingdom are geared towards petrol production. Demand for petrol tailed off considerably during the five year period, leading to an oversupply in the industry. At the same time, crude oil prices exhibited volatility combined with an overall increase. These higher input costs and the excess supply led to a severe squeeze on industry profitability. As a result some refineries closed, while others had to work hard to find markets for their excess petrol. The demand shift away from petrol has left a damaging context of oversupply in the domestic petrol market.” | | | |

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| **2** | **Market** | High and increasing energy costs | **4 Literature Sources**<br>Neelis, Worrell, and Masanet (2008) found that "energy is the most important cost factor in the U.S petrochemical industry"<br><br>Ricardo AEA (2013) concluded "it is difficult to determine the exact scope for potential decarbonisation in the UK without detailed knowledge of current heat integration within UK refineries".<br><br>EUROPIA (2011) found that: "Implications for the EU economy of rationalisation in the EU refining, distribution and marketing would include loss of employment, significant loss of EU income, lower supply security, loss of technological leadership by the EU, leakage of investment to other parts of the world without net GHG emissions | **2 Industry sources**<br>"Energy efficiency is always considered for KIT replacement as energy costs are the second most important cost after feedstock."<br><br>"Energy costs represent a substantial operating expense for our refining and chemical facilities. Successfully improving energy efficiency is therefore a major driver for cost reduction and industrial competitiveness." | **2 out of 3 tables** listed high energy prices as one of their top 5 barriers.<br><br>Participants at the workshop discussed that energy costs are higher in the UK than globally leading UK refineries to be at a competitive disadvantage. | High and increasing energy costs act as a barrier as it can minimise margins and therefore a company's ability to invest in disruptive energy efficiency technologies. |

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| | | | reductions."<br><br>CONCAWE (2012) found that: "The consumption of energy within EU refineries plays a crucial role in determining refinery operating costs and emissions and has therefore long been a focus of attention by refinery operators." | | | |
| **3** | **Market** | UK refineries face high competition levels. Competition also acts as a barrier to collaboration on decarbonisation. | **3 Literature Sources**<br>According to Vivid Economics (2014), "Carbon leakage risk in the EU ETS is potentially significant for carbon- and trade-intensive sectors under high carbon prices; a number of measures can tackle leakage but no perfect solution exists."<br><br>Europea (2011) found that: "The EU refining sector is very competitive in energy efficiency, although many competing regions have significantly lower | **5 Industry Sources**<br>"Competition constraints are keenly felt and observed by the UK refiners especially those with American based principals."<br><br>"Competition is keenly felt and observed. Energy efficiency gives refiners a competitive advantage."<br><br>"Competition is a big barrier. Others are rating you on collaboration on fuel prices so you have to be careful."<br><br>"Competition between the two refineries prevented collaboration on CHP." | **1 out of 4 tables** listed high competition levels as their top 5 barriers.<br><br>However, **all** tables listed unleveled playing field as one of their top five barriers, which is linked to the level of competition faced by the sector.<br><br>One key note speaker at the workshop discussed that UK refiners are at a disadvantage in comparison to European refiners and from outside the UK. | A high level of competition was identified across the information sources gathered. Competition was also seen as limiting collaboration amongst refineries preventing large-scale demonstration projects from being implemented. |

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| | | | non-energy cash costs. Additional costs from EU-only policy (e.g. carbon costs) will further aggravate these competitive disadvantages."<br><br>European Commission (2012) found that: "Expectations are therefore of growing global competition - and, therefore, prices - for supplies of such products, which happen to be also the petroleum products which the EU consumes more than it produces." | "UK refineries are mid to low performers in terms of competitiveness within the EU." | | |
| 4 | **Operational** | Due to the long lifespan of oil refineries, and as oil refining is a declining sector; it is unlikely that there will be any new builds, limiting the energy efficiency technologies and techniques that can be applied. | **1 Literature Source**<br>Vivid Economics (2014) found that: "Improved energy efficiency techniques are more likely to be economical in the case of new build refineries but new builds are relatively rare." | **2 Industry Sources**<br>"As an alternative the refinery might consider putting in place a newly designed heat exchange, but it would be working within the space of the unit, limiting improvements."<br><br>"Limited capability for making changes to operation. The nature, size, and time scale of investment projects require certainty of | **1 Table out of 4**<br>listed limited opportunities for investing in energy efficiency technologies due to five year investment cycles as a missing barrier. The participants at that table also pointed out that uncertainty over the five year period regarding refineries future reduces likelihood of | Across the information sources, the lifespan of refineries and the longer investment cycles required, make deployment of advanced technologies less likely, especially new build. |

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| | | | | planning to give acceptable levels of financial risk." | deployment. What's more, the IED four year compliance timetable also does not fit with the 5 year cycle.<br><br>One workshop participant stated that if they had the choice between investing in a new refinery or adding technologies to existing aging infrastructure; they would choose adding to existing infrastructure every time. | |
| **5** | **Organisation** | Management focus is short term and is not focused on decarbonisation in the UK due to companies' corporate structure. Thus, UK decarbonisation projects compete with CAPEX projects Upstream and in other sectors. | **2 Literature Sources**<br>Ricardo AEA (2013) found that one of the key risks was: "lack of resources, both in terms of time and capital; and, closely related, lack of prioritization."<br><br>Neelis, Worrell and Masanet (2008) found that: "Even when energy is a significant cost, many companies still lack a strong commitment to improve energy management… Companies without a | **9 Industry Sources**<br>"Management focus, resources, and funds are needed for refineries to prioritise basic energy efficiency improvements."<br><br>"Their projects compete globally and their manufacturing strategy and focus may be on investments in large complex refineries in growing markets. The strategies do not currently focus on the UK market and refineries, except for one company."<br><br>"Improving throughput | **2 out of 4 tables** listed lack of management focus due to corporate structure and competition from other projects as one of the top 5 barriers. | Multi-national refineries with operations in the UK and elsewhere with comprehensive business strategies compete for investment internally. UK refinery managers may not be able to make investment decisions or may not have their projects approved as return on investment may be better in other countries where returns are better. Management may not prioritise decarbonisation given the unfavourable market conditions in the UK as there are better payback projects on a refinery through yield optimisation than on energy efficiency projects. |

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| | | | clear program in place, opportunities for improvement may be known, but may not be promoted or implemented because of organizational barriers.” | and increasing yield enhancements are the key focus, with energy as a side benefit.”<br><br>“It should be recognised that, within the company, energy efficiency and carbon reduction projects are in internal competition for capital with other investment projects.”<br><br>“All the companies compete with investment opportunities elsewhere.”<br><br>“Larger CAPEX projects get ranked across the world or investments in other sectors such as petrochemicals or upstream production. All the companies compete with investment opportunities elsewhere and compete with investment requirements under current business strategies.”<br><br>“Refineries in the UK are part of a global energy business and so the oil majors may decide to minimize investment or focus their refining interests outside of the UK. | | |

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| | | | | "Energy efficiency improvement projects and programmes have not been pursued to their fullest extent at two refineries due to a lack of funding and an inability to meet the high rate of return required for project approval. There is limited discretionary investment by the oil majors in UK refineries results from the need for, and greater returns obtained from, large scale projects in oil and Gas Exploration and Production."<br><br>"A barrier to implementation is multi-national oil companies focus on getting crude oil and natural gas, replacing reserves, returns on investment (Upstream profit after tax 26%) Downstream (8% return on capital employed 2.5 billion) Chemicals (4%, 1 billion)." | | |
| **6** | **Market** | Major investment challenge to meet regulatory compliance in the medium term. This may tie up capital that could be invested in disruptive | **4 Literature Sources**<br>House of Commons Energy and Climate Change Committee (2013) found that: "There is considerable | **3 Industry Sources**<br>"In the medium term there is a major investment challenge for regulatory compliance bringing us to 2025 to 2030." | **3 out of 4 tables** listed investment challenges linked to regulatory compliance as one of their top five barriers. | Cost of regulatory compliance is increasing and high in the UK. Across the information sources stakeholders were concerned that the costs of regulatory compliance on top of the current unfavourable market conditions could lead to further consolidation in the sector. |

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| | | technologies. The sector faces unleveled playing field in comparison to competitors. | investment in the refining industry, although much of it is primarily directed at compliance with legislative and regulatory requirements."<br><br>Milosevic, Zoran, Cowart, and Wade (2002) found that: "stringent environmental limits being imposed on the quality of fuels that refineries can burn is increasing the cost of refinery marginal fuels, which prompts an additional incentive to save energy."<br><br>UK PIA found that: "Circa £11.4 billion is estimated to be required to comply with UK and EU legislation to 2030. The legislative cost impact is likely to increase further once the impacts from legislation which has yet to be fully defined, such as the Fuels Quality Directive (FQD), are factored | "Key enablers of energy efficiency and carbon reduction projects include: implementation of a level playing field with competing regions (both in terms of relevant policies and overall cumulative regulatory burden); elimination of technology specific subsidies and; a stable and predictable policy and legislative framework."<br><br>"Upcoming cost of legislation will drive us out of business." | A key note speaker at the workshop discussed the cost impacts of legislation and its impacts on the sector. | |

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| | | | in… No industry would bear such an investment burden for no return. It would be highly likely that, when faced with such a large mandatory capital expenditure requirement that provides no return on investment, UK refiners could be forced to close more UK refineries.”<br><br>Purvin and Gertz (2013) found that: “In order to remain competitive in the future, UK refineries would need to invest £1.5 to £2.3 billion over the next 20 years. We believe that no industry would bear such an investment burden for no return. It would be highly likely that when faced with such a large mandatory capital expenditure requirement that provides no return on investment, UK refiners could be forced to close more UK refineries. Firstly some may not have | | | |

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| | | | access to adequate finance to undertake such expenditure. Secondly, those refiners fortunate to have access to adequate finance would still be likely to conclude that operating in the UK (or EU) would not provide adequate return on investment compared to other regions and would voluntarily decide to close UK and European operations. Since most of the legislative items are European legislation, and would also severely impact EU refineries significant closures of EU refineries could also be expected. This would leave the UK (and EU) very exposed to the international refined product markets, and dependent on refineries located outside the region for refined product supply." | | | |
| **7** | **Investment/** | Advanced | **1 Literature Source** | **3 Industry Sources** | **1 Table out of 4** | Given current unfavourable market |

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| | **Finance** | technologies have long paybacks, whereas decision makers in oil refineries require shorter payback periods as low as six months in order to be invested in. Advanced technologies with additional risks have higher required rates of return. | Ricardo AEA (2013) found that "continuity of production is of primary importance to firms. This is one of the reasons that energy efficiency technologies tend to have more stringent economic criteria compared to investments that are more closely related to the core business." | "For CAPEX projects- all projects have a threshold that they have to meet for the payback period; it can be as low as 6 months to warrant investment."<br><br>"Energy efficiency projects, as with all capital investment projects, are typically only undertaken if they are economically viable and satisfy internal investment criteria and return rates."<br><br>"Hurdle rates would be 15 to 20% cost improvements. If there is a lot of risk then hurdle risks are made higher." | listed payback as one of the top 5 barriers to decarbonisation. | conditions, investors and internal decision makers demand quick payback in some cases as short as 6 months, limiting the energy efficiency technologies implemented to incremental technologies rather than disruptive technologies which have longer paybacks of 6 to 7 years. |
| **8** | **Investment/ Finance** | Energy efficiency projects are not usually singled out as an individual project. Thus, energy efficiency improvements are likely to be incremental. | - | **2 Industry Sources**<br>"Energy efficiency projects are not singled out as an individual project. Energy efficiency is one factor that is considered usually during KIT replacements or technology upgrades."<br><br>"Oil majors are self-financing and only have a certain pot of money. They invest where they get biggest returns. They have a long list of projects, and thus energy efficiency isn't necessarily | - | Industry sources identified that energy efficiency is seen as one of the many criteria considered when replacing process equipment, however; unless payback and rates of return criteria are met it is not a main driver as it is not able to compete with other investment options more directly linked to the core business. |

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| | | | | singled out.” | | |
| **9** | **Organisation** | Shortage of staff due to an ageing workforce and sector consolidation | **1 Literature Source**<br>Ricardo AEA (2013) found that a lack of focus on decarbonisation was compounded by the risks of “lack of awareness, heterogeneity, concern for job security, shortage of staff …” | **6 Industry Sources**<br>“Skills are becoming an issue because of the age profile of refinery engineering staff.”<br><br>“Aging workforce and shrinking supply of talented indigenous recruits.”<br><br>“There is a distinct shortage of E and I engineers for process safety work and offshore.”<br><br>“Human resources might be limiting the rate at which the UK refining industry can progress activities to improve operations… as a result of mergers and reorganisations in the industry there has been a general decline in the number of employees. Many employees in the sector also take advantage of early retirement, causing the demographics of the industry to generally be recognised as having limited skilled human resources. A possible skills shortage could possibly limit the scope | - | The industry sources and one piece of literature identified a shortage of staff due to an ageing workforce and consolidating sector as a key barrier to implementing key technologies. Refineries are under-resourced and the pipeline of indigenous engineers is weak. |

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| | | | | and delay the schedule of any energy efficiency projects. "<br><br>"Skills are becoming an issue because of the age profile of refinery engineering staff. But in terms of skills for implementing CCS some of the concerns would be shared with other sectors."<br><br>"Restrictions are a lack of resources." | | |
| **10** | **Organisation** | Lack of authority of UK refinery managers to make investment decisions | - | **1 Industry Source**<br>"Some UK refineries management do not have the authority to make investment decisions." | **1 Table out of 4** listed lack of authority of UK refinery managers to make investment decisions as one of their top 5 barriers. | The lack of authority is due to the fact that many of the oil refineries are large multi-national companies, where corporate headquarters are located elsewhere and make key investment decisions. The level of authority delegated to them in regards to investment spend is also limited. Thus UK refinery managers do not always have the authority to make large investment decisions and have limited discretionary budgets.<br><br>Lack of delegated authority to local management- This is a common issue across many industrial sectors due to the organisational structure of overseas-owned companies in the UK. |
| **11** | **Organisation** | Oil refineries are risk averse, and thus like to be the first followers in regards to | **1 Literature Source**<br>Ricardo AEA (2013) found that for energy efficiency projects: | **1 Industry Source**<br>"Most refiners would describe themselves as followers." | **1 Table out of 4** listed risk aversion as one of its top barriers. This table discussed | Given current unfavourable market conditions, intense competition, and a focus on throughput, oil refiners are risk averse and are wary about implementing |

| # | Category | Barriers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | technology implementation. Risk of production disruption is of primary importance. | "risk of production disruption is of primary importance to refiners when making investment decisions." | | that there is a culture or risk aversion given the current unfavourable market conditions and fear of disrupting production. The table also discussed there was risk aversion in allowing outside suppliers of technology to implement new riskier technologies. It was discussed that oil refineries like to be the first follower not the leader in implementing new technologies. | new technologies that may disrupt production as they prefer to be the first follower rather than a leader. |
| **12** | **Regulation/ Policy** | Absence of government policies | **1 Literature Source** Ricardo AEA (2013) found that for energy efficiency projects "absence of government policies is a narrower." | - | **1 Table out of 4** listed lack of government policy as a top five barrier to decarbonisation.<br><br>1 Table also listed absence of government policies and poor application and interaction between policies as a barrier specifically pointing out the interactions between CCA and EDR. | Lack of government policies was seen as a barrier in the literature and at the workshop and was discussed in the context of newer technologies. |
| **13** | **Cogeneration** | Cogeneration has a number of barriers including: | **1 Literature Source** Milosevic, Zoran, Cowart and Wade | - | - | One literature source identified a range of barriers to the implementation of cogeneration, the main barrier being fuel |

| # | Category | Barriers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | • Cogeneration plants require a minimum size to be economically justifiable, while larger plants often have the potential to be more efficient. This tends to limit practical cogeneration opportunities to large and medium size refineries.<br>• Complicated cogeneration permitting systems that are complex, time-consuming and varied;<br>• Difficult and frequently prohibitive interconnection arrangements with utilities impede the implementation of cogeneration<br>• Regulations currently do not account for system efficiencies of CHP impeding its implementation. | (2002) found that: "fuel and power pricing will continue to be an influential factor in determining cogeneration viability. Rigorous marginal fuel and power pricing, as utilised in current cogeneration feasibility studies, will remain key. In fact, as the other barriers fall away, it will become one of the primary operators."<br>They also found the following:<br>• "Complicated cogeneration permitting systems that are complex, time-consuming and varied act as a barrier to implementation."<br>• "Difficult and frequently prohibitive interconnection arrangements with utilities limit | | | and power pricing. |

| # | Category | Barriers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | • Depreciation schedules that do not reflect the true life of CHP assets. | its implementation."<br>• "Regulations that do not account accurately for the overall system efficiency of CHP, or do not adequately credit displaced emissions and grid losses impede its implementation."<br>• "Depreciation schedules do not reflect the true life of CHP assets and therefore make investment more difficult." | | | |
| **14** | **Regulation/ Policy** | Earlier removal of the support mechanism for UK CHP investment (the Levy Exemption Certificates, LECs) | - | **2 Industry Sources**<br>"Earlier removal of the support mechanism for UK CHP investment (the Levy Exemption Certificates, LECs) | **1 Table out of 4** listed the earlier removal of support for UK CHP investment as one of the top 5 barriers. | Earlier removal of support mechanism for CHP led to greater uncertainty in the marketplace limiting refiners' willingness to invest in further CHP plants. |

| # | Category | Barriers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | created uncertainty in the regulatory regime – acting as a barrier to investment. | | created uncertainty in the regulatory regime – acting as a barrier to investment. "<br><br>"CHP is seen as a risker investment now." | | |
| **15** | **Technology** | Non-availability of disruptive technology and non-availability of technology that is tested and reliable.; suppliers have limited access to refineries to try out new technologies | **1 Literature Source**<br>Ricardo AEA (2013) found that: "The disruptive technologies for decarbonisation are not available acting as a barrier to implementation." | **1 Industry Source**<br>**"**One of the top barriers includes availability and reliability of technology." | **1 Table out of 4** listed non-availability of technology as a top 5 barrier. The table also noted that in the last 20-30 years there has been a shift from new technologies being developed in house to suppliers. Suppliers have less ready access to refineries to test it on the site. Technology providers do not have the scale or facility to test on their own sites. | Across the information sources non-availability of disruptive technologies as well non- availability of reliable and tested technology was found to be a barrier as refiners like to be the first follower rather than the leader. This is compounded by increased outsourcing of new technology developments and limited access of suppliers to refineries to test technologies. |
| **16** | **Technology** | CCS has a number of barriers:<br>• increased operational complexity and risks;<br>• applications not proven at scale;<br>• lack of availability of space;<br>• plant integration risks (hidden costs of additional | **3 Literature sources**<br>CONCAWE (2008) found that: "Some refineries may develop CCS projects based on a combination of favourable local circumstances. In the next 15 years this will be the exception rather than the rule….Although | **5 Industry Sources**<br>"A number of barriers in the application of industrial CCS including: increased operational complexity and risks; applications not proven at scale; plant integration risks (hidden costs of additional downtime, alternative product supplies, technology lock-in etc.); high levels of | During the workshop breakout sessions, CCS was discussed at length including the variety of barriers CCS has. The need for CCS infrastructure and new planning permissions as well as a multi-stakeholder approach to piloting CCS was discussed. | CCS has significant barriers that must be overcome which vary from space availability onsite, plant integration risks, lack of $CO_2$ transport and storage infrastructure, and high and uncertain CAPEX costs to name just a few. |

| # | Category | Barriers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | downtime;<br>• Alternative product supplies, technology lock-in etc.);<br>• high levels of uncertainty regarding costs; health, safety and environmental considerations;<br>• staff familiarity and expertise;<br>• effects on product quality;<br>• challenge of capturing emissions in sites which have multiple, heterogeneous small CO2 streams;<br>• lack of commercial incentives to implement CCS (which has significant up-front and ongoing variable costs);<br>• lack of CO2 transport and storage infrastructure; and limited experience of operational full chain CCS projects with industrial sources; and<br>• scale and significant | refineries are fairly large CO2 emitters as an entire site, these emissions come from a number of discrete sources, often spread over a large area and with different gas compositions. This makes efficient capture more complex and expensive than is the case for single-source sites such as power stations."<br><br>CONCAWE (2011) concludes that: "One important conclusion is that the volumes and unit locations for CO2 production in refineries are not conducive to CCS projects in individual refineries and will require alliances with other large CO2 producers, particularly the power industry, in order to be commercially justified."<br><br>Total 2014 found that: "Research is ongoing to further reduce the high costs of capture | uncertainty regarding costs; health, safety and environmental considerations; staff familiarity and expertise; effects on product quality; and the challenge of capturing emissions in sites which have multiple, heterogeneous small CO2 streams. Further, systemic barriers include: lack of commercial incentives to implement CCS (which has significant up-front and ongoing variable costs); lack of CO2 transport and storage infrastructure; and limited experience of operational full chain CCS projects with industrial sources."<br><br>"Space availability is a constraint. No place to put the clean-up kit. The CO2 recovery and capture KIT and compressor required to storage takes up a lot of space."<br><br>"Systemic barriers include: lack of CO2 transport and storage infrastructure; and limited experience of operational full chain CCS projects | | |

| # | Category | Barriers | Literature review | Interviews | Workshops | Analysis and Interpretation |
|---|---|---|---|---|---|---|
| | | investment is required and remains a potential barrier to widespread deployment of CCS | and an assessment of regional and global carbon storage capacity still needs to be undertaken. We believe that the immediate priority is to replace coal with natural gas wherever possible and to supplement fossil fuels by developing new energies.**”** | with industrial sources.”<br><br>“The scale, significant investment and required new infrastructure cannot be overlooked and these remain potent barriers to widespread deployment of CCS. The concept includes potentially duplicating the oil and gas industry’s infrastructure – which has been built over 100 years – in a third of the time.”<br><br>“CCS is not economically viable. The size of the KIT required for CCS is excessive- landscape, visual pollution, and geography.” | | |

*Table 9: Raw data - barriers for oil refining sector*

# INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAP TO 2050 – OIL REFINING

## APPENDIX C – FULL TECHNOLOGY OPTIONS REGISTER

# APPENDIX C FULL TECHNOLOGY OPTIONS REGISTER

| Whole Refinery Options | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Option** | **Technology Readiness Level**[6] | **Adoption Rate** | **Practical Applicability** | **Capex (per average site)**[7] | **Capex Data Source** | **$CO_2$ (C) or Electricity (E) Reduction** | **Carbon Reduction Data Source** |
| Advanced Control and Improved Monitoring | 7 | 85% | 100% | £4,200,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 10.0% (C) | Expert judgement (PB/DNV GL consortium) with review from industry |
| Carbon Capture and Storage (CCS) - on CHP & $H_2$ plant[8] | 7 | 0% | 100% | £138,000,000 | Factored from data in Element Energy (2014) | 25.6% (C) | Provided by trade association with review by sector team and PB/DNV GL |
| Carbon Capture and Storage (CCS) - on FCC stacks | 7 | 0% | 100% | £125,500,000 | Factored from data in Element Energy (2014) | 23.3% (C) | Provided by trade association with review by sector team and PB/DNV GL |
| Flaring | 8 | 43% | 100% | £14,000,000 | Directly from literature (SNIFFER, 2011) and review by sector team | 0.9% (C) | Directly from literature (SNIFFER, 2011; Holmes, 2008) and review by sector team |
| Fuel Switch (Fuel oil to natural gas) | 9 | 0% | 100% | £26,400,000 | Directly from literature (SNIFFER, 2011) and review by sector team | 0.4% (C) | Directly from literature (SNIFFER, 2011) and review by sector team |

[6] Please note that expert opinion has been used to evaluate the TRL (technology readiness level) – except CCS, which used the Element Energy (2014).

[7] Capex values shown in the table are for a representative site to which that option applies. While cost input data on some options was available on a per site basis, data for others was expressed differently e.g. cost/tonne of production capacity, cost/tonne of emission. Where necessary, these data have been used to derive representative capex estimates per site, as shown in the table. To account for sectors with diverse site sizes, a range of capex values for standard site categories (e.g. small and large sites) have been developed and then multiplied by the relevant proportion of sites in the sector of that category.

[8] These carbon capture costs are applied to a site of nominal emissions 2.3 Mtes $CO_2$ per year. All costs are for $CO_2$ capture alone, including $CO_2$ purification and compression. Costs associated with transport and storage/utilisation are excluded.

| Whole Refinery Options | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Option** | **Technology Readiness Level[6]** | **Adoption Rate** | **Practical Applicability** | **Capex (per average site)[7]** | **Capex Data Source** | **$CO_2$ (C) or Electricity (E) Reduction** | **Carbon Reduction Data Source** |
| Lighting (Sodium lighting to low energy) | 9 | 50% | 100% | £180,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 1.7% (C) | Expert judgement (PB/DNV GL consortium) with review from industry) |
| Maintenance - Fouling control | 7 | 80% | 100% | £300,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 2.5% (C) | Directly from literature (Ricardo AEA, 2010) and review by sector team |
| Motors, Pumps, Compressors, Fans | 8 | 35% | 100% | £9,000,000 | Directly from literature SNIFFER, 2011 and review by sector team | 6.1% (C) | Directly from literature SNIFFER, 2011 and review by sector team |
| New Refinery as replacement | 8 | 0% | 100% | £8,500,000,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 25.0% (C) | Expert judgement (PB/DNV GL consortium) with review from industry |
| Process Heaters and Furnaces | 7 | 43% | 80% | £18,800,000 | Directly from literature (SNIFFER, 2011) and review by sector team | 4.6% (C) | Directly from literature (SNIFFER, 2011; Holmes, 2008) and review by sector team |
| Storage Tanks | 8 | 10% | 100% | £900,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 2.0% (C) | Expert judgement (PB/DNV GL consortium) with review from industry |
| Waste Heat and Energy recovery | 6 | 0% | 100% | £42,500,000 | Directly from literature (SNIFFER, 2011) and review by sector team | 10% (C) | Directly from literature (SNIFFER, 2011; Holmes, 2008) and review by sector team |

*Table 10: Whole refinery full technology options register*

| Sub-Process Options | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Option** | **Technology Readiness Level** | **Adoption Rate** | **Practical Applicability** | **Capex (per average site)** | **Capex Data Source** | **$CO_2$ (C) or Electricity (E) Reduction** | **Reduction Data Source** |
| Crude Unit Upgrades (BAT) | 7 | 29% | 80% | £15,000,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 10.0% (C) | Directly from literature US EPA, 2010 and review by sector team |
| Onsite renewables – e.g. Wind | 8 | 0% | 100% | £9,000,000 | Directly from literature (Siemens, 2011) and review by sector team | 0.7% (E) | Directly from literature (Siemens, 2011) and review by sector team |
| FCC – Design improvements (BAT) | 6 | 50% | 80% | £11,500,000 | Directly from literature (SNIFFER, 2011) and review by sector team | 10.0% (C) | Directly from literature (SNIFFER, 2011) and review by sector team |
| Hydrogen – Recovery / Optimisation | 6 | 60% | 100% | £16,300,000 | Directly from literature (SNIFFER, 2011) and review by sector team | 7.7% (C) | Directly from literature (SNIFFER, 2011) and review by sector team |
| Hydrocracker – Design improvements (BAT) | 5 | 0% | 100% | £300,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 5.0% (C) | Expert judgement (PB/DNV GL consortium) with review from industry |
| Biomass (syngas etc.) | 4 | 0% | 50% | £212,500,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 8.4% (C) | Expert judgement (PB/DNV GL consortium) with review from industry |
| CHP | 8 | 79% | 100% | £75,000,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 30.0% (C) | Directly from literature (CONCAWE, 2011) and review by sector team |

| Sub-Process Options | | | | | | | |
|---|---|---|---|---|---|---|---|
| Option | Technology Readiness Level | Adoption Rate | Practical Applicability | Capex (per average site) | Capex Data Source | $CO_2$ (C) or Electricity (E) Reduction | Reduction Data Source |
| Boiler (retrofit) | 6 | 71% | 100% | £1,500,000 | Directly from literature (SNIFFER, 2011) and review by sector team | 3.0% (C) | Directly from literature (SNIFFER, 2011) and review by sector team |
| Utilities optimisation | 7 | 75% | 100% | £2,600,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 19.0% (C) | Directly from literature (SNIFFER, 2011) and review by sector team |
| VDU – Design improvements (BAT) | 8 | 29% | 100% | £1,000,000 | Expert judgement (PB/DNV GL consortium) with review from industry | 4.3% (C) | Expert judgement (PB/DNV GL consortium) with review from industry |

*Table 11: Sub process full technology options register*

Technology options identified in the above tables come from sources listed in the references in section 6 of the main oil refining roadmap document.

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INDUSTRIAL DECARBONISATION AND ENERGY EFFICIENCY ROADMAP TO 2050 – OIL REFINING

# APPENDIX D – ADDITIONAL PATHWAYS ANALYSIS

# APPENDIX D ADDITIONAL PATHWAYS ANALYSIS

## 1. Option Deployment for Pathways under Different Scenarios

Challenging World

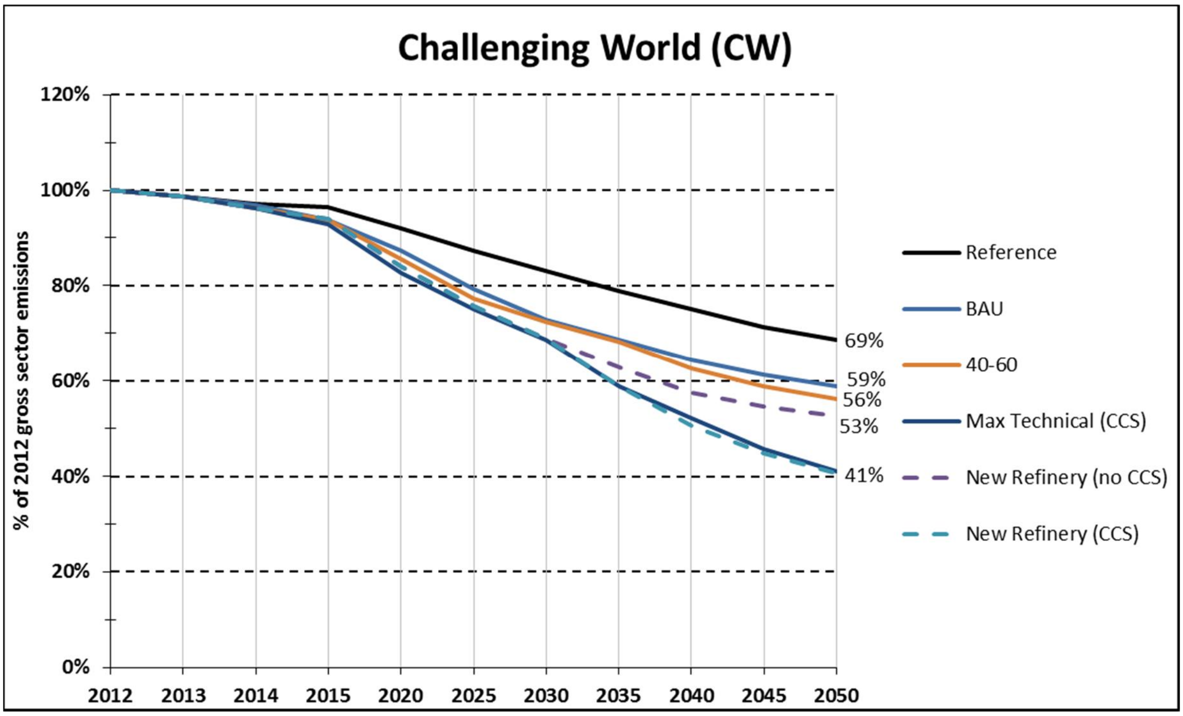


*Figure 5: Pathways, challenging world scenario*

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

*Figure 6: Option deployment for the BAU pathway, challenging world scenario*

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

*Figure 7: Option deployment for the 40-60% CO2 reduction pathway, challenging world scenario*

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

*Figure 8: Option deployment for the Max Tech pathway, challenging world scenario*

## Collaborative Growth

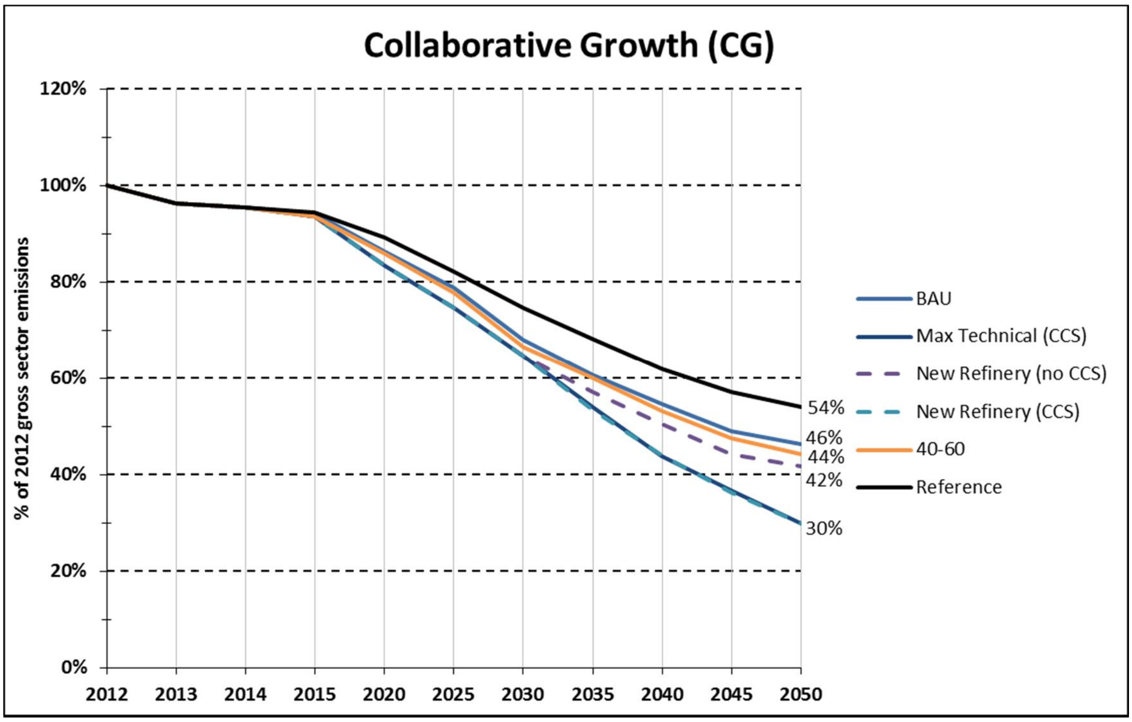


*Figure 9: Pathways, collaborative growth scenario*

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

*Figure 10: Option deployment for the BAU pathway, challenging world scenario*

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

*Figure 11: Option deployment for the 40-60% CO2 Reduction pathway, challenging world scenario*

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

*Figure 12: Option deployment for the Max Tech pathway, challenging world scenario*

## 2. Sensitivity Analysis

### New Refinery without CCS

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

*Figure 13: Option deployment for the new refinery without CCS pathway, current trends scenario*

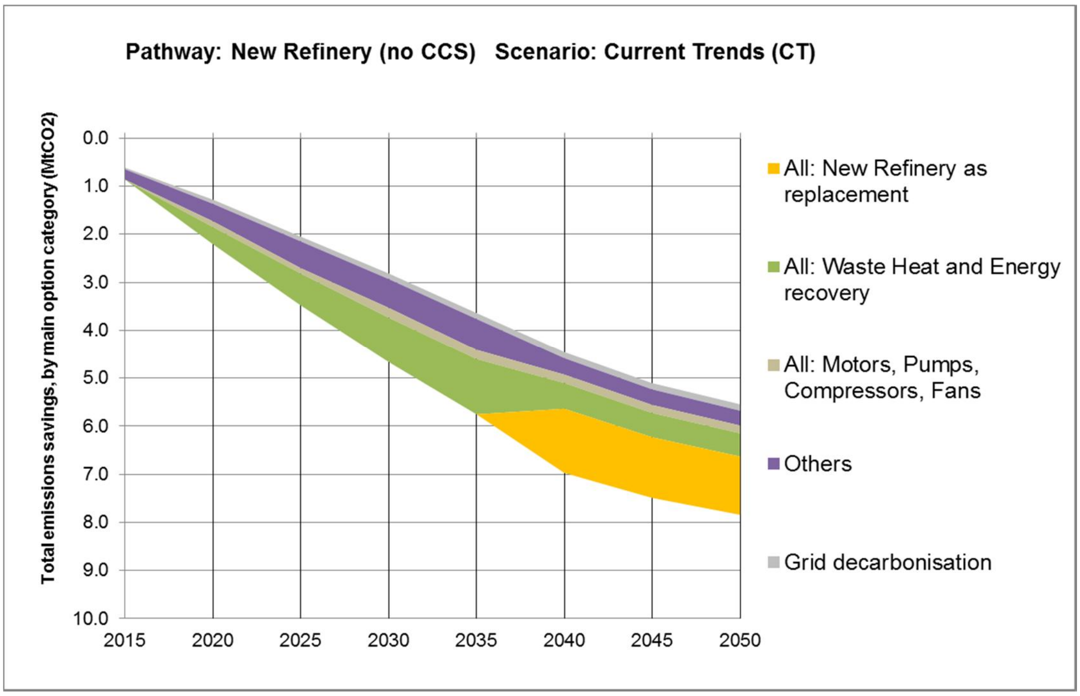


*Figure 14: Contribution of principal options to the absolute emissions savings throughout the study period for the new refinery (no CCS) pathway, current trends scenario*

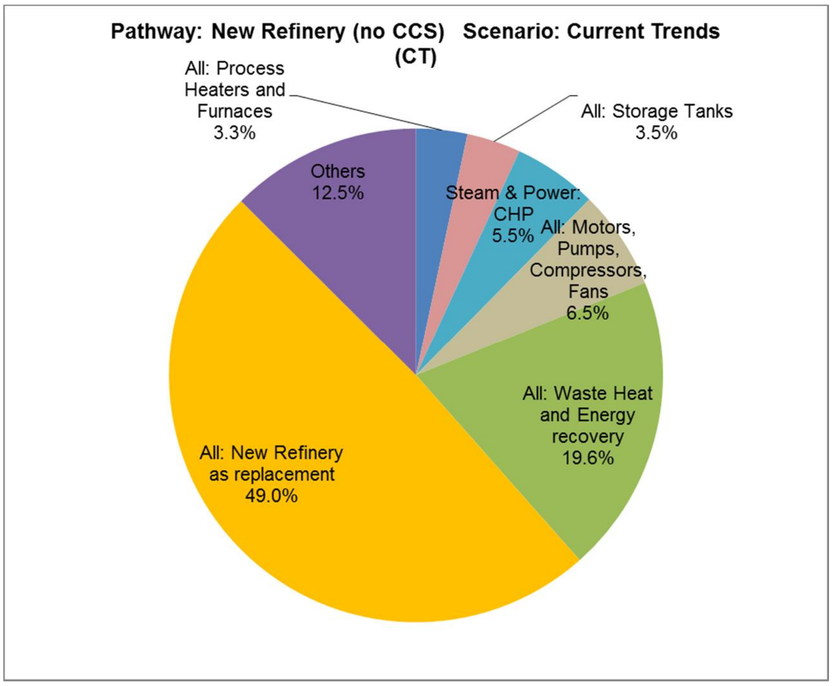


*Figure 15: Breakdown of the 2050 emissions savings for the new refinery (no CCS) pathway, current trends scenario*

## New Refinery with CCS

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

*Figure 16: Option deployment for the new refinery with CCS pathway, current trends scenario*

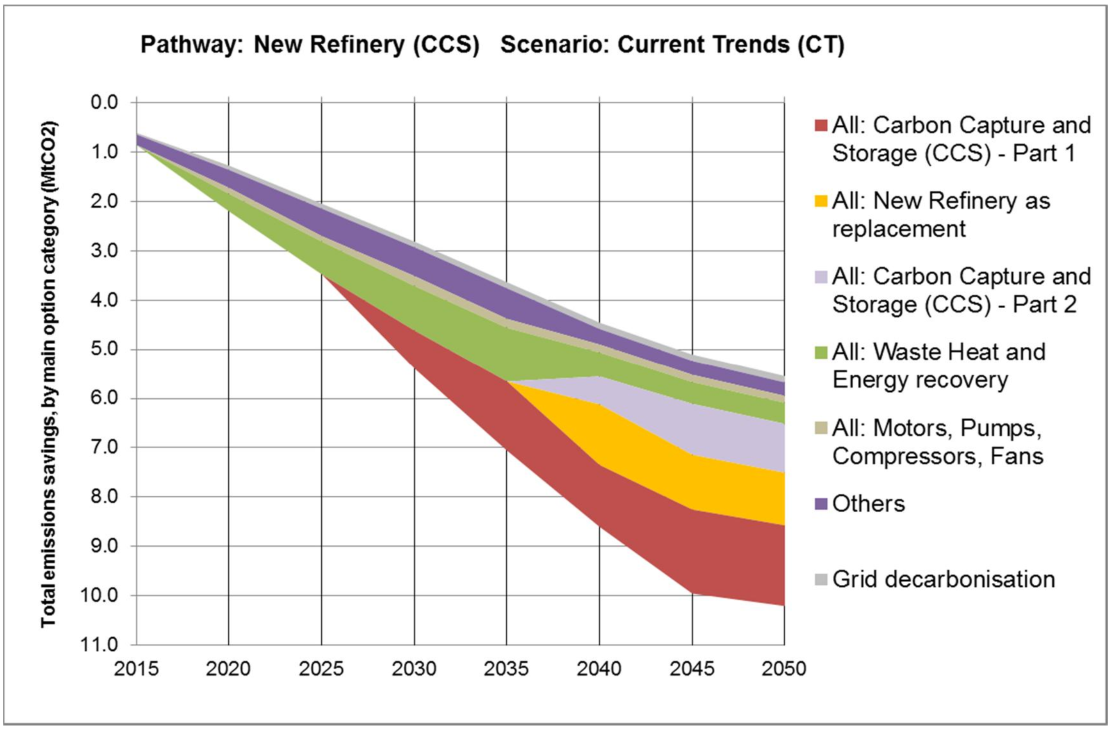


*Figure 17: Contribution of principal options to the absolute emissions savings throughout the study period for the new refinery (with CCS) pathway, current trends scenario*

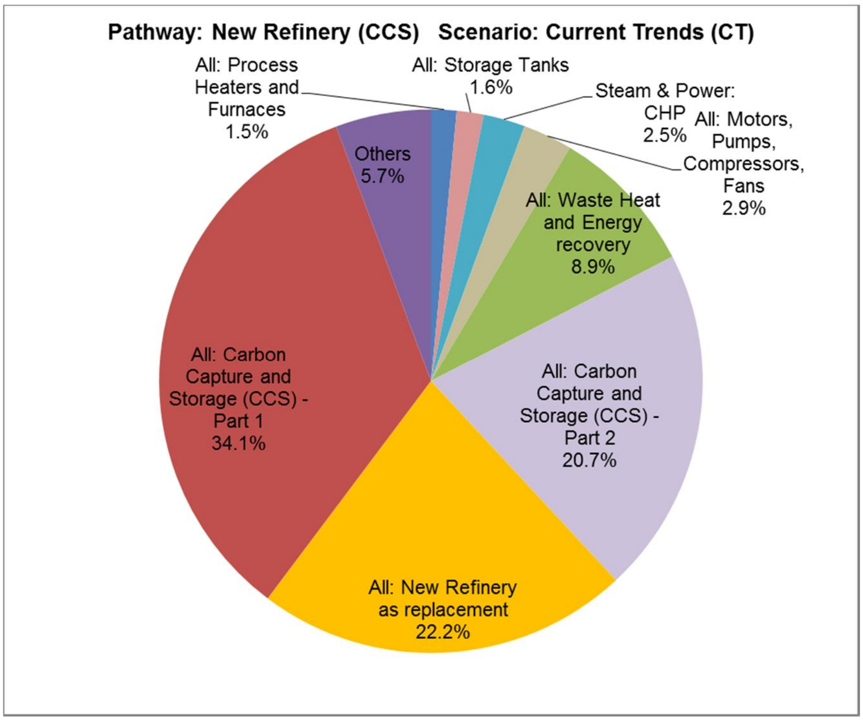


*Figure 18: Breakdown of the 2050 emissions savings for the New Refinery (with CCS) pathway, current trends scenario*

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