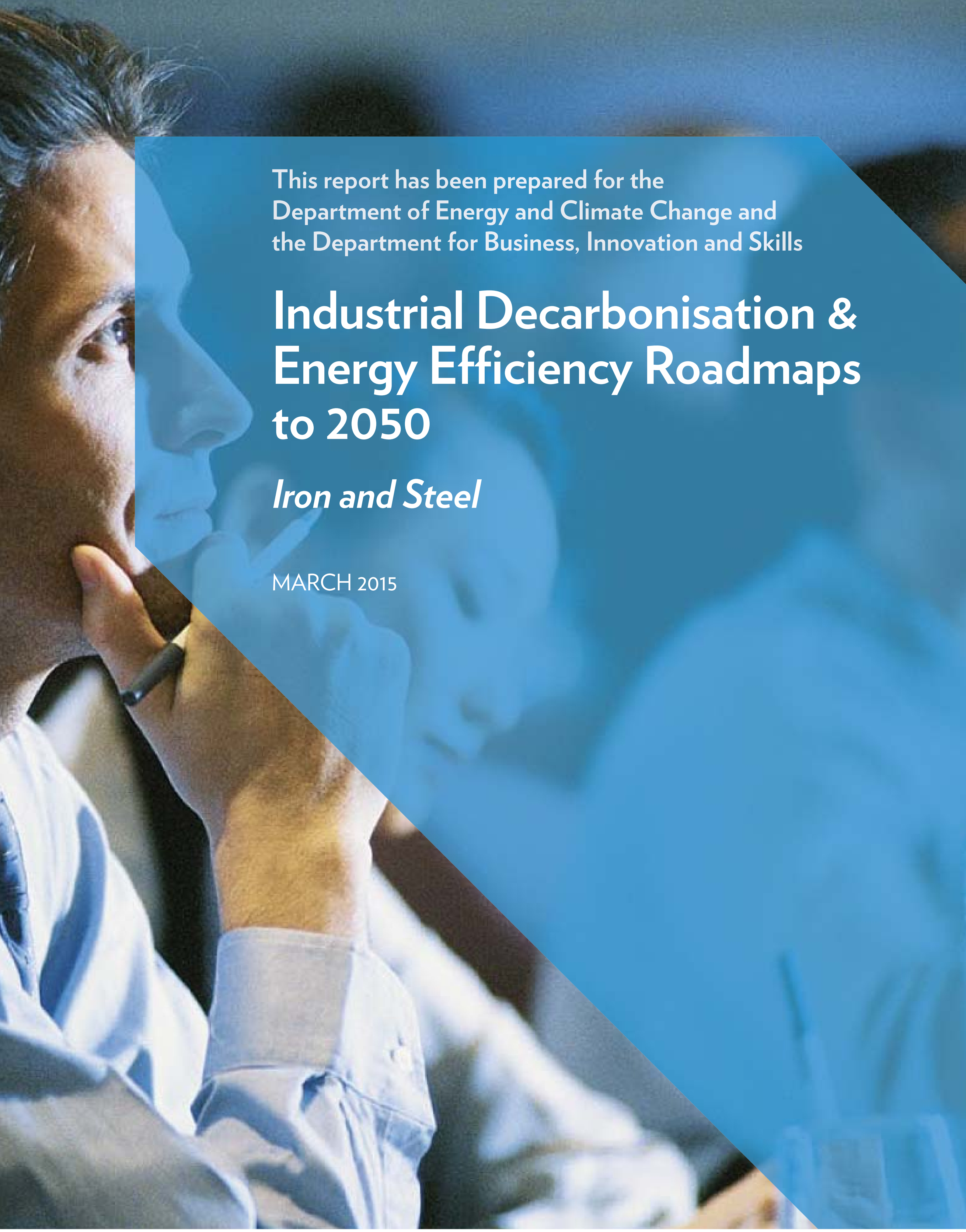

This report has been prepared for the Department of Energy and Climate Change and the Department for Business, Innovation and Skills

Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050

Iron and Steel

MARCH 2015

WSP | PARSONS BRINCKERHOFF
DNV·GL

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ACRONYMS

AC	Alternating Current
AOD	Argon Oxygen Decarburising
BAT	Best Available Technology
BAU	Business as Usual
BF	Blast Furnace(s)
BF-BOF	Blast Furnace(s) – Basic Oxygen Furnace(s)
BF-TGR	Blast Furnace(s) – Top Gas Recycling
BIS	Department for Business, Innovation and Skills
BLT	Bell-Less Top (charging)
BOF	Basic Oxygen Furnace
BOS	Basic Oxygen Steelmaking
BTT	Breakthrough Technologies and Techniques
capex	capital expenditure
CC	Carbon Capture
CCB	Carbon Composite Agglomerates
CCL	Climate Change Levy
CCS	Carbon Capture and Storage
CDQ	Coke Dry Quenching
CEO	Chief Executive Officer
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COG	Coke Oven Gas
COURSE	CO_2 Ultimate Reduction in Steelmaking process by innovative technology for cool Earth
CPF	Carbon Price Floor
CPS	Carbon Price Support
DC	Direct Current
DECC	Department of Energy and Climate Change
DRI	Direct Reduced Iron
DRI-EAF	Direct Reduced Iron – Electric Arc Furnace
EAF	Electric Arc Furnace(s)
EEF	Engineering Employers' Federation
EII	Energy Intensive Industries
EOS	Emissions Optimised Sintering
EPOSINT	Environmentally Process Optimised SINTering
EPSRC	Engineering and Physical Sciences Research Council
ERC	European Research Council
ERDF	European Regional Development Funding
ESCO	Energy Service Company
EU ETS	European Emissions Trading System
GDP	Gross Domestic Product
GIB	Green Investment Bank
HBI	Hot Briquetted Iron
HSE	Health, Safety and Environment
HVAC	Heating, Ventilation and Air Conditioning
INDEMAND	Industrial Energy and Material Demand
ITT	Invitation to Tender
LAF	Ladle Arc Furnace

LCA	Life Cycle Assessment
Max Tech	Maximum Technical
NAEI	National Atmospheric Emissions Inventory
NO_x	Nitric Oxide (NO) and Nitrogen Dioxide (NO_2)
OEM	Original Equipment Manufacturer
OHF	Open Hearth Furnace
ORC	Organic Rankine Cycle
PCI	Pulverised Coal Injection
POSCO	Pohang iron and Steel Company
R&D	Research and Development
RD&D	Research, Development and Demonstration
REA	Rapid Evidence Assessments
RHF	Rotary Hearth Furnace
ROI	Return on Investment
SAT	State-of-the-Art Technologies
SIC	Standard Industrial Classification
SR	Smelting Reduction
SR-BOF	Smelting Reduction – Basic Oxygen Furnace
SWOT	Strengths, Weaknesses, Opportunities and Threats
TRL	Technology Readiness Level
ULCOS	Ultra Low CO_2 Steelmaking
VSD	Variable Speed Drive

1. EXECUTIVE SUMMARY

1.1 What is the 'Decarbonisation and Energy Efficiency Roadmap' for the Iron and Steel Sector?

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

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

The roadmap project aims to:

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

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

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

1.2 Developing the Iron and Steel Sector Roadmap

The development of the iron and steel sector roadmap consisted of three main phases:

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

A sector team comprising representatives from the iron and steel industry and its trade association (UK Steel), the government, Imperial College London and the University of Cambridge has acted as a steering group as well as contributing evidence and reviewing draft project outputs. It should be noted that the findings from the interviews and workshops represent the opinions and perceptions of particular industrial stakeholders, and may not therefore be representative of the entire sector. Where possible we have tried to include alternative findings or viewpoints, but this has not always been possible; this needs to be taken into account when reading this report.

1.3 Sector Findings

Steel can be manufactured either by the primary BF-BOF (blast furnace – basic oxygen furnace) or by the secondary EAF (electric arc furnace) route. The primary BF-BOF route accounts for 79% of crude steel production in the UK, and includes coke production, sintering, BF, BOS, casting and rolling. The secondary EAF route accounts for the remainder of UK crude steel production, and includes scrap preparation, electric arc furnaces, casting and rolling. The iron and steel sector produced over nine million tonnes of diverse products in 2012: slabs, plates, coils, sheets, pipe products, coated steel products, bars, wire rods, sections, rails, sheet piles, seamless tubes, drawn wires, etc. used in automotive, heavy machinery, pipes and tubes, construction, packaging and appliances, construction, mechanical engineering, and energy applications. The sector contributed to the UK economy with revenues of nearly £10 billion in 2013. In that year, it was estimated to emit 16.45 million tonnes/year of carbon dioxide, with a further 1.95 million tonnes/year emitted in electricity production for use within the sector (EEF, 2014).

More than two-thirds of the sector's energy consumption is used to provide heat (often at very high temperatures over 1,000°C), mainly by burning fossil fuels (coal and natural gas) (UK Steel, 2014). The reliance on carbon as a chemical reductant (resulting in significant amounts of process emissions for integrated sites), together with the combustion of fossil fuels, and the indirect emissions from electricity consumption (mainly for EAF sites) make up the iron and steel sector carbon footprint shown in Table 1.

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

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

The iron and steel sector is dominated by large international companies with five big steelmakers. The industry is highly mature and consolidated. Steel is globally traded and highly price sensitive. The sector faces high barriers to entry and low technological changes. After several years of revenue contraction due to the recession, the gradual economic recovery of the automotive and construction sectors is holding a promise of resurgent global demand and increasing sales volumes. Competition in this sector is high and global, with UK industry competing with industry both in Europe and further afield.

1.4 Enablers and Barriers for Decarbonisation in the Iron and Steel Sector

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

- Access to growing markets
- Improved policy framework
- Cost of carbon
- Location near to CCS infrastructure
- Increased demand for materials used in renewable energy and energy efficiency
- Link between environmental and safety issues in investment projects

The main barriers to decarbonisation have been identified as:

- Global competition from lower-cost producers
- Shareholders demand quick payback
- Availability of capital or competition for funds

[1] For the iron and steel sector, the reference year used is 2013. This was chosen due to the large production increase from the re-commissioning of SSI Teesside steelworks in 2012.
[2] For the cement sector, the 2012 actual production levels where adversely affected by the recession. Therefore we have assumed production of 10 million tonnes (rather than the actual production in 2012) and normalised emissions to this production level.

- Increasing electricity and gas prices
- Slow rate of capital stock turnover
- Steel customers primarily make decisions on costs, not on carbon emissions
- Regulatory uncertainty
- Increasing cost of carbon and uneven playing field

1.5 Analysis of Decarbonisation Potential in the Iron and Steel Sector

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

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

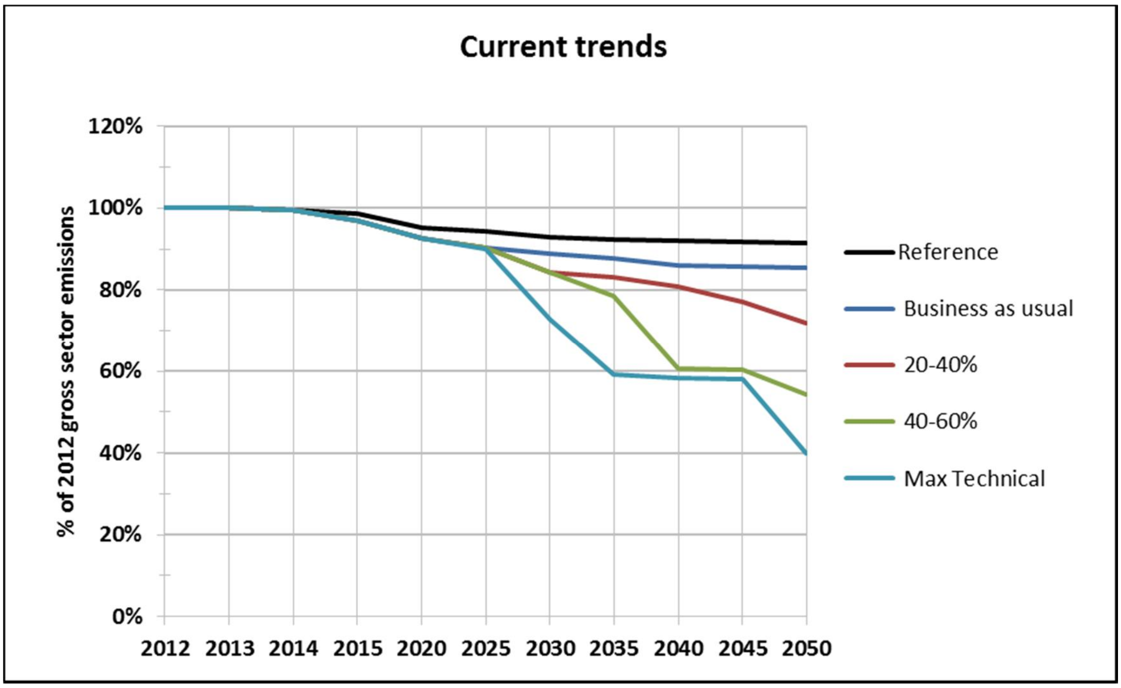

Figure 1: Overview of the different decarbonisation and energy efficiency pathways

Analysis of the costs of the pathways used order of magnitude estimates to add up the capital cost of each pathway. As an indication, the net present capital cost for the pathways, discounted at 3.5%, falls within an estimated range of £400 million[3] to £600 million[4]. There is a large degree of uncertainty attached to the cost

[3] For the BAU pathway in the current trends scenario

analysis, especially for options which are still in the research and development stage. Also, costs of operation, energy use, research, development, demonstration, civil works, modifications to plant and costs to other stakeholders are significant for some options, but not included here. The costs presented are for the study period and are adjusted to exclude residual value after 2050, thus a proportion of the costs of high capex items deployed close to 2050 is excluded. Great care must be taken in how these costs are interpreted. While implementation of some of the options within the pathways may reduce energy costs due to increased efficiency, the scale of the investments associated with the pathways must be considered by stakeholders when planning the next steps in the sector.

1.6 Conclusions and Key Technology Groups

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

Strategy, Leadership and Organisation

The scale of change and investment required to meet the carbon reduction challenge require a strategy to be developed and pursued through leadership and organisation. This links to all other conclusions below, including research, development and demonstration (RD&D), energy supply and business case barriers.

Business Case Barriers

One of the most important barriers to decarbonisation and energy efficiency, based on the literature, interviews and workshops, is lack of funding for investments as the return of investment is not attractive enough or there is a lack of capital available.

Future energy costs, energy supply security, market structure and competition

The UK energy supply system will influence company decisions to invest in the sector. In the absence of a global price on carbon, it is important that competitiveness risks to UK industry are assessed and managed when designing approaches to reduce emissions.

Industrial Energy Policy Context

Given the highly competitive market for steel, and international ownership of many UK sites, along with the significant investment challenge facing the sector to reduce emissions, the policy context needs to carefully balance industrial regulation and investment support. Many in the sector have emphasised that a long-term energy and climate change policy framework alongside policy support for industrial competitiveness is key to investor confidence.

Life-Cycle Accounting

Improvements in standardised carbon accounting methodologies enable measurement, valuation and comparison of steel products, and facilitate the iron and steel sector to differentiate their products produced using low carbon options. Work to develop standardised methodologies will benefit from involving academia, industry and government, as well as the value chain.

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

Value Chain Collaboration

Steel customers primarily make purchasing decisions based on cost for service delivery, rather than on carbon emissions. Many of the technology combinations illustrated by the pathways analysis are likely to incur additional production costs for the steel manufacturers. In addition there is potential for steel services to be delivered with enhanced material efficiency. A viable business model could be developed to assist with decarbonisation through value chain collaboration.

Research, Development and Demonstration

In order to realise significant decarbonisation in the sector, deployment of medium to longer term technology is needed. Some of the decarbonisation options identified in this work require further technology innovation and development before commercial scale demonstration can be considered.

People and Skills

This strategic conclusion supports a number of themes, for example, people need the right skills to develop the investment business case for new projects, to deploy options and also to research and develop new technologies. The iron and steel sector's carbon reduction will be dependent on a skilled and knowledgeable workforce in the UK.

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

Electricity Grid Decarbonisation

As shown in this work, the decarbonisation of electricity supply has an important contribution to make to overall sector decarbonisation. The government's reforms of the electricity market are already driving electricity grid decarbonisation, and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with government methodology and modelling.

Electrification of Heat

Electrification of heat can deliver emissions reductions in the iron and steel sector through an increased proportion of steel production via the EAF route. The potential for emissions reductions by increasing the share of EAF produced steel, has been assessed through a sensitivity analysis. The extent to which this option can be utilised is also highly dependent on the costs and availability of scrap as well as the demand for the types of steel produced by EAFs. The level of decarbonisation from these options is also dependent on the level to which the grid is decarbonised.

Fuel and Feedstock Availability (including biomass)

Biomass provides a possible opportunity for the iron and steel industry to decarbonise, as illustrated in the biomass sensitivity analysis. However, at present, the use of biomass as a significant decarbonisation option is considered to be a low priority, given uncertainty about cost, availability of biomass and the need for further technical demonstration in the UK.

Energy Efficiency and Heat Recovery

The sector has already achieved significant improvements in energy efficiency (a 40% reduction in energy consumed per tonne of steel produced over a 40-year period). As identified in this work, shorter term options are only partly implemented to date. Accelerated deployment of energy efficiency options can bring operational benefits including life cycle cost savings, however their investment continues to compete with other investment opportunities as companies are capital constrained.

Clustering

Improved site and sector integration could deliver significant emissions reductions in the iron and steel sector. Many of these technical options could be enabled by further industrial clustering around existing iron and steel sites.

Carbon Capture

As the pathways and sensitivity analyses show, CC technologies could play a key role in a decarbonised iron and steel sector. There are a range of specific technologies which could deliver the emissions reductions, the best technology will need to be identified through research, development and demonstration.

Next Steps

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

2. INTRODUCTION, INCLUDING METHODOLOGY

2.1 Project Aims and Research Questions

2.1.1 Introduction

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

Overall, industry is responsible for nearly a quarter of the UK's total emissions (DECC, 2011)[5]. By 2050, the government expects industry to have delivered a proportionate share of emissions cuts, achieving reductions of up to 70% from 2009 levels (DECC, 2011). Nonetheless, the government recognises the risk of 'carbon leakage' and 'investment leakage' arising from the need to decarbonise and is committed to ensuring that energy-intensive industries are able to remain competitive during the transition to a low-carbon economy.

The Department of Energy and Climate Change (DECC) and the Department for Business, Innovation and Skills (BIS) have set up a joint project focusing on the eight industrial sectors which use the greatest amount of energy[6]. The project aims to improve the understanding of technical options available to sectors to reduce carbon emissions and increase energy efficiency while remaining competitive. This includes include investigating the costs involved, the related business environment, and how investment decisions are made in sector firms. This will provide the industry and government with a better understanding of the technical and economic abatement potential, set in the relevant business context, with the aim to agree measures that both the government and these industries can take to reduce emissions while maintaining sector competitiveness.

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

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

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

Table 2: Industrial sectors evaluated in this project

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

2.1.2 Aims of the Project

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

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

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

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

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

2.1.3 What is a Roadmap?

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

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

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

Table 3: Inputs and outputs for the industrial decarbonisation and energy efficiency roadmap to 2050

<u>The views of contributing organisations</u>

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

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

2.2 Overall Methodology

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

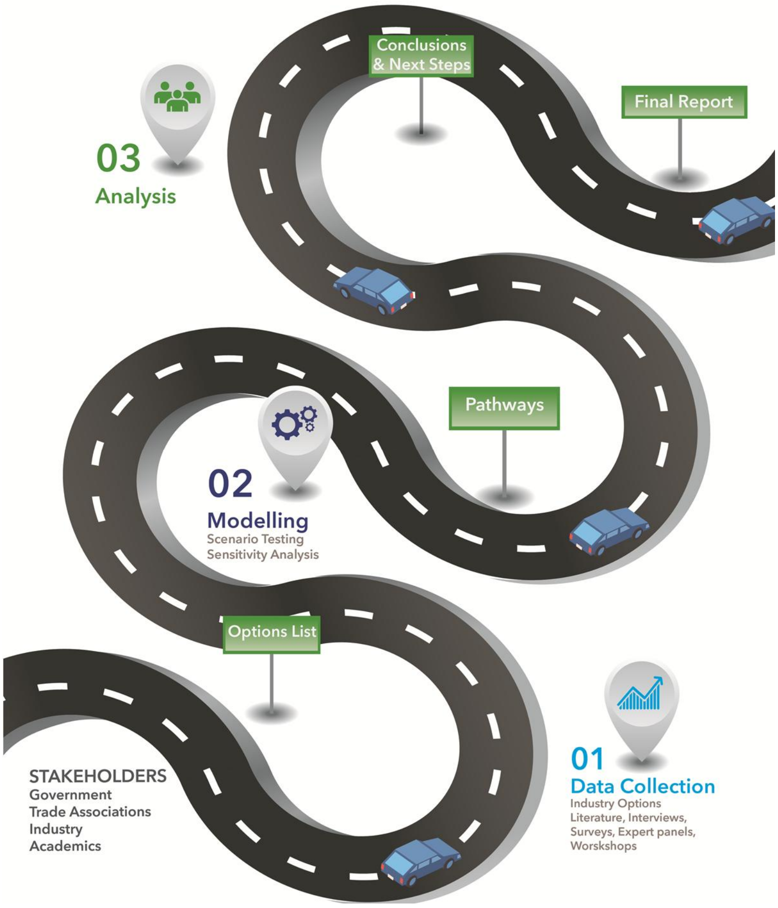

Figure 2: Roadmap methodology

Evidence was gathered for covering technical, and social and business aspects from literature reviews, interviews, and workshops with relevant stakeholders. These different sources of information allowed evidence triangulation to improve the overall research. The data was then used to develop a consolidated list of Enablers and Barriers for decarbonisation, and a register of technical options for the industry. This was subsequently used to develop a set of decarbonisation and energy efficiency pathways to evaluate the decarbonisation potential of the UK iron and steel sector and the main technical options required within each pathway.

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

2.2.1 Findings

Evidence Gathering

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

- Decarbonisation options (i.e. technologies)
- Enablers and Barriers to decarbonisation and energy efficiency

- Background to the sector
- Current state of the sector and possible future changes within the sector
- Business environment and markets
- Potential next steps

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

- **Literature review:** A short, focussed review of over 130 documents all published after 2000 was completed. The documents were either related to energy efficiency and decarbonisation of the sector or to energy-intensive industries in general. This was not a thorough literature review or rapid evidence assessment (REA) but a desktop research exercise deemed sufficient by the project team[7] in its breadth and depth to capture the evidence required for the purpose of this project. The literature review was not intended to be exhaustive and aimed to capture key documentation that applied to the UK. This included the sector structure, recent history and context including consumption, demand patterns and emissions, the business environment, organisational and decision-making structures and the impacts of UK policy and regulation. Further details are provided in appendix A.
- **Interviews:** In liaison with UK Steel, DECC and BIS, seven semi-structured interviews were conducted with key players in the iron and steel sector. This included five iron and steel manufacturers, one member of UK Steel and one equipment manufacturer. The purpose of the interviews was to obtain further details on the different subsectors within the iron and steel sector and gain a deeper understanding of the principal questions, including details of decision-making processes and how companies make investment decisions, how advanced technologies are financed, what a company's strategic priorities are and where climate change sits within this. The interviewees were interviewed using an 'interview protocol' template, developed in liaison with DECC and BIS. This template was used to ensure consistency across interviews, fill gaps in the literature review, identify key success stories and extract key barriers to investment in low-carbon technologies. The interview protocol can be found in appendix A. Interviewees were selected to maximise coverage across subsectors and emissions and also take into account company headquarters location, production processes and company size.
- **Workshops:** Two workshops were held, attendees for which were identified in consultation with UK Steel, DECC and BIS. The first workshop focused on reviewing potential technological decarbonisation and energy efficiency options (that had been provisionally generated from the literature review) and discussing adoption rate, applicability, improvement potential, ease of implementation, capex, return on investment (ROI), savings potential and timeline for the different options. This was done through two breakout sessions: one focused on collecting more data and the other one on timelines under different scenarios. The second activity involved group discussions on enablers and barriers to energy efficiency and decarbonisation investment, and how to overcome them. The second workshop focused on reviewing the draft pathways and identifying potential actions for delivering them. The workshop participants included the relevant trade associations, large companies with the aim of achieving representation of key companies or subsectors and academics with expert knowledge of the sector, PB and DNV GL consultants, DECC and BIS project managers and senior civil servants. The average size of a workshop was 40 people.

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

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

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

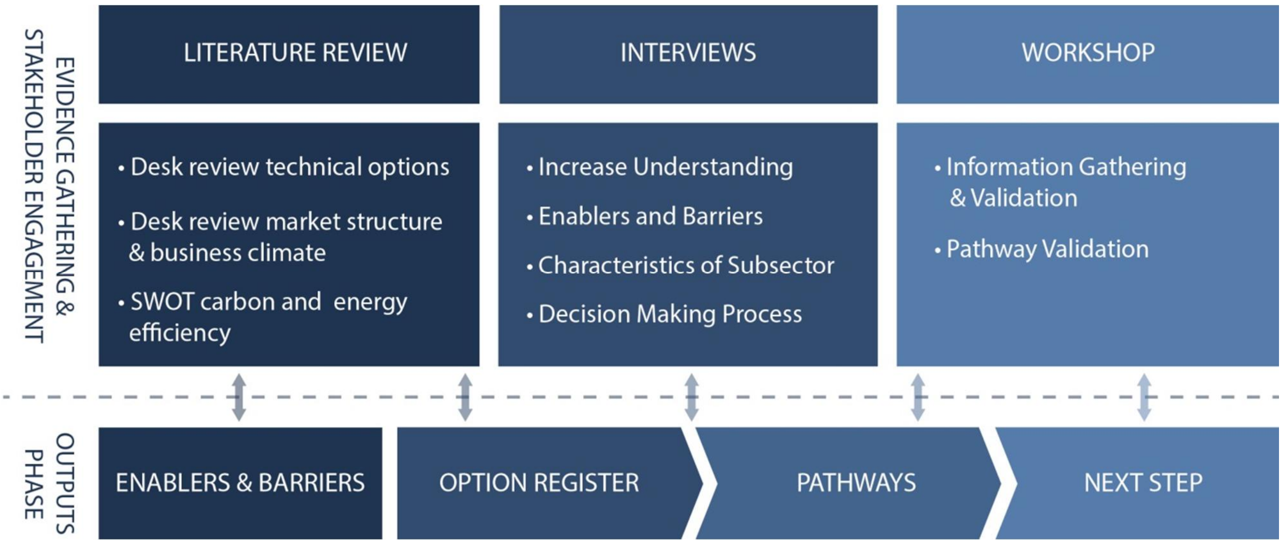

Figure 3: Evidence gathering process

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

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

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 staff fromf DECC and BIS.

The evidence gathering exercise (see appendix A for details) was subject to inherent limitations based upon the scale of activities and sample sizes that could be conducted within the time and resources available. The iron and steel companies interviewed represented over 90% of carbon emissions produced in the UK sector, and included UK decision-makers and technical specialists in the iron and steel sector as well as some senior staff at global corporate level. These interviews were conducted to provide greater depth and insight to the issues faced by companies.

The identification of relevant information was approached from a 'global' and UK viewpoint. The global outlook examined dominating technologies and process types, global production, CO_2 emissions (in the EU-27), and the global outlook to 2050, including the implications for iron and steel producers and consumers. The UK outlook examined the sector structure, recent history and context including consumption, demand patterns, emissions, the business environment, organisational and decision-making structures and the impacts of UK policy and regulation.

Options examined (see appendix C) were relevant to various parts of the production process, i.e. coke making, sintering, BF (blast furnace), BOF (basic oxygen furnace), EAF (electric arc furnace), and secondary processes. Disruptive options such as rebuild or retrofit of integrated sites with advanced technologies, including HIsarna, Corex, Finex and CC (carbon capture) were also included.

Evidence Analysis

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

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

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

Limitations of these Findings

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

2.2.2 Pathways

The pathways analysis is an illustration of how the iron and steel industry could potentially decarbonise from the base year 2013 to 2050. Together the set of pathways developed in the study help give a view of the range of technology mixes that the sector could deploy over coming decades. Each pathway consists of different technology options that are implemented over time at different levels. Each technology option included a number of key input parameters including carbon dioxide saving, cost, fuel use change, applicability, current adoption (in the base year), and deployment (both rate and extent). A 'pathway' represents a particular selection and deployment of options from 2014[8] to 2050 chosen to achieve reductions falling into a specific decarbonisation band.

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

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

Two further pathways - with specific definitions - were also created, assessing (i) what would happen if no additional interventions were taken to accelerate decarbonisation (business as usual, BAU) or (ii) the maximum possible technical potential for decarbonisation in the sector (maximum technical, Max Tech)[9].

The BAU pathway consisted of the continued deployment of technologies that are presently being deployed across the sector as each plant or site reaches the appropriate point to implement the technology. For the iron and steel sector, the 60-80% CO_2 reduction pathway is the same as the Max Tech pathway.

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

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

Scenario Testing

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

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

- **Current trends**: This would represent a future world very similar to our world today with low continuous growth of the industry in the UK.
- **Challenging world**: This would represent a future world with a more challenging economic climate and where decarbonisation is not a priority and the industry is declining in the UK.
- **Collaborative growth**: This would represent a future world with a positive economic climate and where there is collaboration across the globe to decarbonise and where the industry has a higher growth rate in the UK.

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

Key Assumptions and Limitations

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

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

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

In this report, when we report carbon dioxide, this represents CO_2 equivalent. However, other greenhouse gases were not the focus of the study which centred on both decarbonisation and improving energy efficiency in processes, combustion and indirect emissions from electricity used on site but generated off site.

Also, technical options assessed in this work result primarily in CO_2 emissions reduction and improved energy efficiency. In general, emissions of other greenhouse gases, relative to those of CO_2, are very low.

Assumptions in relation to the maximum technical pathway

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

The following assumptions apply:

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

Option Interaction Calculation

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

Cumulative Emissions

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

Scope of Emissions Considered

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

Complexity of the Model

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

Material Efficiency

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

Base Year (2013)

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

In this project for the analytical work, we have set 2012 as the base year for all sectors. This is the most recent dataset available to the project, and was considered to be a suitable date to assess how sectors (as they currently are) can reduce emissions to 2050. This separates the illustrative pathways exercise from national targets, which are based on 1990 emissions. However, to allow for the re-commissioning of SSI Teesside, the CO_2 emissions reference level for iron and steel are the emissions from 2013, and therefore 2013 is used as the base year for this sector.

2.2.3 Conclusions and Next Steps

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

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

The main technology groups as presented in section 5 are:

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

3. FINDINGS

3.1 Key Points

The iron and steel industry is one of the biggest industrial emitters of CO_2 in the UK due to the energy intensity of iron and steel production, its reliance on carbon as a chemical reductant (resulting in significant amounts of process-related carbon emissions for integrated sites), and the large volumes of steel produced. The emissions (sum of direct and indirect) in 2012 totalled 18.4 million tonnes of CO_2 for a production of 9.5 million tonnes of crude steel. In 2013, production went up steeply to 12.0 million tonnes due to the re-commissioning of the former Tata Steel BF (now SSI UK) at Teesside, resulting in a total of 22.8 million tonnes of CO_2 emissions for the UK iron and steel sector. To allow for the re-commissioning of SSI Teesside, the CO_2 emissions reference level in this work are the emissions from 2013. BOF accounted for 79% of 2012 UK steel production and the other 21% came from EAF. In 2013, BOF steel production increased to 83% (UK Steel, 2014).

The largest sources of CO_2 emissions are the process-related emissions from coal combustion, the direct emissions from on-site combustion of fossil fuels and the indirect emissions from electricity consumed during the production process (IEA Clean Coal Centre, 2012). The use of energy sources in the sector is dominated by coal and coke (77.8%) with 9.7% of the energy sources used being natural gas, 6.8% coke oven gas and 5.5% purchased electricity[10] (UK Steel, 2014).

Over time, the sector has achieved significant improvements in energy efficiency (a 40% reduction in energy consumed per tonne of steel produced over a 40-year period) through investment in technologies which are today considered standard for any state-of-the-art steel plant. In more recent years, the technological opportunities have become more limited, with only relatively small incremental improvements in energy consumption realised.

Seven sites in the UK cover the majority (more than 90%) of the emissions of the sector, divided into three integrated steel plants and four EAF sites. The industry is dominated by large international companies: Tata Steel Europe Limited had nearly 45% of the UK market share in 2013, while SSI, Outokumpu, Sheffield Forgemasters and Celsa Steel UK Ltd are the remaining big steelmakers (UK Steel, 2014).

Decarbonisation and energy efficiency are considered as mechanisms for saving costs, especially if energy and carbon prices increase over the long term. Smaller-scale energy efficiency projects are being implemented, as these are likely to have shorter payback periods and represent immediate cost savings. However, evidence (from interviews) indicated that decarbonisation and energy efficiency are not considered as strategic and high-priority business goals in their own right. In the absence of breakthrough technologies and the right policy mechanisms from government, it is difficult for decarbonisation to become a strategic issue at individual company level, beyond trying to manage the current policy costs.

The main enablers for decarbonisation of the iron and steel sector are:

- Access to growing markets
- Improved policy framework

[10] Note: on BF-BOF sites, gases arising from the coke ovens, BF and BOF are collected and used for other purposes on site, including electricity generation. The energy source consumption figures are quoted on a net basis to avoid double-counting. Thus, self-generated electricity for example is excluded.

- Cost of carbon
- Location near to CCS infrastructure
- Increased demand for materials used in renewable energy and energy efficiency
- Link between environmental and safety issues in investment projects

The main barriers to decarbonisation have been identified as:

- Global competition from lower-cost producers
- Shareholders demand quick payback
- Availability of capital or competition for funds
- Increasing electricity and gas prices
- Slow rate of capital stock turnover
- Steel customers primarily make decisions on costs, not on carbon emissions
- Regulatory uncertainty
- Increasing cost of carbon and uneven playing field

After several years of revenue contraction due to the recession, the gradual economic recovery of and demand from UK and European automotive and construction sectors is holding a promise of resurgent demand and increasing sales volumes, whilst increasing competition for steel producers (Scotton, 2013). According to industry (from workshops and interviews), the current business environment is not conducive to large-scale demonstration projects (which are needed to decarbonise the sector), as there is limited capital available, and companies are focusing on business continuity and cost savings. In this work, depending on the scenario, the overall sector is estimated to decline or grow by -1.5%, 0% and 1.5% in absolute terms for the challenging world, current trends and collaborative growth scenarios, respectively.

The energy and CO_2 reduction opportunities for the iron and steel sector distilled from the literature review, interviews, workshops, discussions with the trade association and input from academia were classified into short-, medium- and long-term perspective, but also into two types: incremental and disruptive. The disruptive options fall into the medium-/medium-long-term group of options and the incremental options in the short- or short-medium-term categories. Incremental options are characterised by smaller incremental energy or CO_2 reductions to various parts of the production process: generic options, coke making, sintering, BF, BOF, EAF, casting, and secondary processes. Disruptive options, in contrast, are breakthrough technologies such as rebuild or retrofit of integrated sites with advanced technologies, including HIsarna, Corex, Finex and CC. CC could potentially be added with minimal outage requirements if it is an 'end-of-pipe' type CC solution. As investment cycles are long, typically 25-40 years, then 2050 is only one – or at most two – investment cycles away (EC, 2013 and Rootzén and Johnsson, 2013).

3.2 Iron and Steel Processes

3.2.1 Iron and Steel Production

Steel plays an essential role in our everyday life, due to its characteristics and wide versatility. Annually, more than 1.3 billion tonnes of crude steel are produced globally, with China the largest producer. According to IEA projections (2012), global steel demand could reach 3 billion tonnes per annum by 2050 (IEA, 2012).

As can be seen from Table 4, the share of the UK in the world production of crude steel is quite small: in 2013 the UK provided around 0.8% of global crude steel and 7.1% of EU-27 crude steel respectively (WorldSteel, 2013).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Global	130,043	124,249	135,121	132,587	136,337	131,263	132,532	131,05	132,429	134,262
China	63,622	61,83	66,293	65,65	67,034	64,664	65,472	66,277	65,424	65,081
EU-27	13,429	13,249	14,377	14,112	14,633	14,081	13,549	11,997	14,279	14,699
UK	824	878	1,018	960	988	1,051	1,011	1,002	1,075	1,054

Table 4: Monthly crude steel production during 2013 (thousand tonnes) across geographic regions (adapted from data in WorldSteel, 2013)

Figure 4 shows UK crude steel production levels from 1993 to 2013 and the split by production route (basic oxygen steelmaking BOS in black, EAF in pink). As can be seen from this graph, there has been a long-term decline in the steel produced in the UK via both routes: 52% decrease in basic oxygen and 39% decrease in EAF steelmaking from 1993 to 2012. The impact of the global financial crisis of 2008 and the financial restructuring that took place globally can also be seen. In 2012, crude steel production in the UK stood at 9.5 million tonnes, the lowest output since 1934 (UK Steel and EEF, 2012). In 2009, production greatly decreased due to the mothballing of Tata Steel Teesside. In 2013, however, production went up again due to the re-commissioning of the same plant (now SSI UK), increasing BOS by 32% compared to 2012 (UK Steel, 2014). To allow for the re-commissioning of SSI Teesside, the production reference level in this work is the production from 2013.

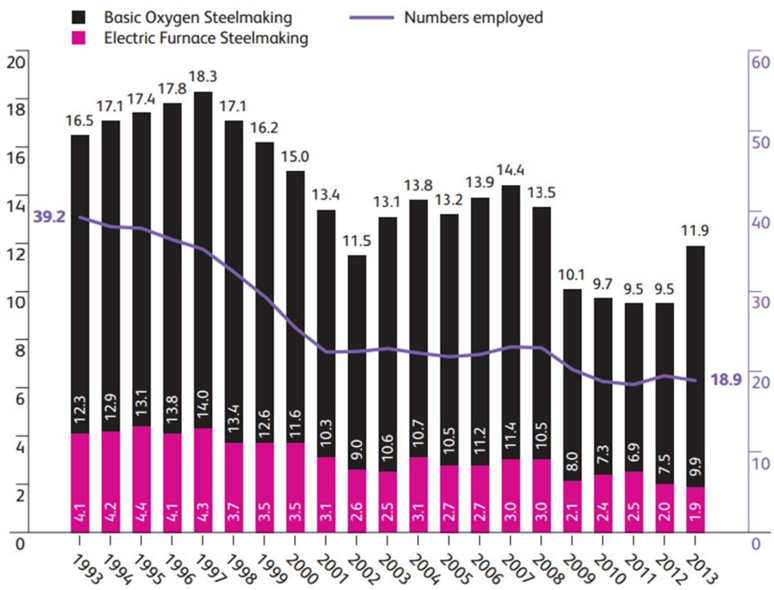

Figure 4: Crude steel production (in million tonnes) in the UK during 1993-2013 (UK Steel, 2014)

3.2.2 Primary and Secondary Production of Iron and Steel

Before discussing the different production routes in the iron and steel sector, it is instructive to consolidate the terminology used and provide descriptions of each term in order to clearly define the terms and their boundaries:

- Primary production route: BF-BOF
- Secondary production route: scrap-EAF
- Primary processes: BOF and EAF, making steel from either pig iron or scrap
- Secondary processes: the treatment(s) after the molten metal is tapped into a ladle from the BOF or EAF; the treatment varies depending upon the grade of steel required
- Steel manufacturing: the combination of primary and secondary manufacturing processes

The primary BF-BOF route, which accounts for most of the crude steel production in the UK (79% in 2012 as shown in Figure 4), has a number of stages that include primary processes such as the production of coke, sinter plant, BF, BOS and casting plant, and subsequent secondary processes such as rolling in various mill set-ups. The secondary EAF route, which accounts for the remainder of crude steel production in the UK, consists of stages that include primary processes such as the preparation of scrap, the EAF processes, and secondary casting and rolling processes.

The different secondary process routes are shown in Figure 5. Note that near-net-shape casting frequently requires hot rolling as a subsequent stage, though with fewer rolling stages than for continuous casting and that there is no near net shape casting in the UK at the moment. The ultimate aim of near-net-shape casting is to eliminate this subsequent rolling stage.

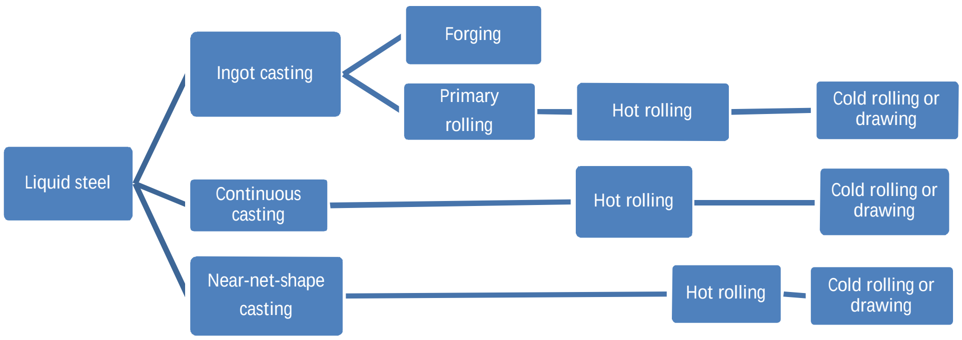

Figure 5: Iron and steel secondary process routes

3.2.3 Different Stages in Iron and Steel Production

The different stages presented below are generic descriptions and not necessarily how steel is made in the UK.

Coke making. Coking coal is converted to coke by driving off impurities to leave almost pure carbon. The coking process consists of heating coking coal, using coke oven gas, to 1,000-1,100°C in the absence of oxygen (pyrolysis) to drive off the volatile compounds. The coking process takes place over long periods of time (12-36 hours) in the coke ovens, after which the hot coke is quenched with water or air to cool it before transferring it to the BF. The volatile compounds driven off constitute the coke oven gas. The coke oven gas is cleaned and used as a fuel in the coke making but also other parts of an integrated iron and steel plant. Coke acts as a reducing agent and a source of thermal energy in integrated iron and steel plants using the BF-BOF route. Coke consumption can be less than 300 kg per tonne of hot metal in modern BF with supplementary fuel injection (IIP, 2014).

Sintering. Sinter plants produce coarse-grained iron ore sinter from small particles of ore, ferrous-containing material and fine coke particles. The process takes place at high temperature (1,300-1,500°C), fuelled by the coke particles that are ignited by gas burners. The gas used can be coke oven gas, BF gas or natural gas. It is a critical path process, continuously providing feedstock to the BF (EPA 1995).

Blast Furnace (BF). During the iron-making process, a BF is fed with sinter, coke and small quantities of fluxes (minerals such as limestone, used to collect impurities). Pressurised air is heated to 1,200°C, typically by BF off-gases in a hot blast oven and then blown into the furnace through nozzles in the lower section.

This causes the coke to react and the iron ore to melt. The carbon monoxide that is produced by combustion of the coke reacts with the iron ore to reduce it to iron. Finally, the tap hole at the bottom of the furnace is opened and molten iron and slag (impurities) are drained off (EPA 1995).

Basic Oxygen Furnace (BOF). In the BOF, the molten iron is combined with varying amounts of steel scrap (less than 30%) and small amounts of additives to give steel the required properties (World Coal, 2014). In the furnace, high-purity oxygen (99%) is introduced onto the surface of the iron bath through a water-cooled lance. Carbon and silicon dissolved in the steel is oxidised, liberating great quantities of heat, melting the added steel scrap. Temperatures can reach 1,700°C. By this process, steel with the required carbon content is formed (EC, 2012). Fluxes of burnt lime or dolomite are fed into the furnace to remove impurities, form slag and maintain basicity.

Electric Arc Furnace (EAF). The secondary steel production route uses steel scrap that is melted down and processed to produce new (recycled) steel. In this secondary production, an EAF is used, applying a very high current through the scrap and melting it with O_2 injection or oxy-fuel burners, fired by natural gas (EC 2013). The power is supplied through the electrodes placed in the furnace, producing an arc of electricity through the scrap steel and raising the temperature to 1,600°C, melting the scrap. Impurities can be removed by the use of additives and draining off slag through the tap hole. The availability and quality of scrap place an upper capacity limit on this process path (EPA 1995).

Secondary steelmaking. Liquid steel is tapped into ladles (or a secondary argon oxygen decarburising vessel in the case of stainless steel), in which it may undergo further processing or the addition of alloys to fine-tune the steel's metallurgical properties.

Casting. Once the steel has been made, it must be cast into a useable shape and size using moulds. Traditionally, crude steel is first cast into ingots by pouring molten metal into moulds, which are then further rolled or shaped into the desired semi-finished product (blooms, billets or slabs). Today, ingot casting has largely been replaced by continuous casting, continuously pouring molten metal into the top of a long mould in which it is simultaneously cooled to produce a bloom, billet or slab, which is cut to the desired length as it exits the other end. Over the last 50-60 years, continuous casting has become the most popular method, accounting for around 90% of produced steel (BCG and VDEh, 2013).

Rolling. Rolling mills are used following the continuous casting process, and its production of an intermediate product, to produce a finished shape and dimension. Natural-gas-fired furnaces are often used to reheat blooms, billets or slabs to above their recrystallisation temperature. These semi-finished products are then rolled to produce the shape and dimensions required for the finished product. Hot-rolled finished products may subsequently be cold rolled or cold drawn to further change the product's dimensions and mechanical properties. Steel products, particularly flat steel products, may also undergo additional processes, such as metallic or organic coating.

3.2.4 Technologies for Delivering Heat and Power

Next to coke ovens, the UK iron and steel industry has a mix of technologies for delivering heat, including burners, boilers and turbines. The term 'integrated steel plant' is used because of the way that the separate processes are integrated together, by-product gases from one process being used in others. Boilers at integrated plants are predominantly fired by by-product gases, particularly BF gas. A significant quantity of the steam produced is used to drive turbines that generate a high proportion of the electricity required on the site. This utilises a low calorific value gas to provide high-grade energy. Steam passed out of the turbine at low pressure will be used as process steam.

Boilers at EAF plants and secondary process plants (not at integrated sites), where there are no by-product gases, are generally used simply to provide process steam. They are usually fired on natural gas or oil, although oil is used rarely now. Burners used as direct process heaters such as ladle driers or preheaters, in reheating furnaces etc. are traditionally air or fuel-fired. At integrated sites, the fuel may be coke oven or BOS gas or a mixture, supplemented by natural gas if required. At other sites it will be usually natural gas.

Oxygen enrichment can be used to increase output from burners and hence the process, but this has the disadvantage of increasing NO_x formation. There is an increasing use of recuperative, regenerative and oxy-fuel burners to give energy savings. Recuperative burners are limited in output due to the physical size of the recuperator. Regenerative burners, particularly those employing flameless oxidation now give very low NO_x levels and are comparable in NO_x levels and efficiency with oxy-fuel, without the additional cost of the oxygen and boilers.

Turbines are used to generate power, complementing electricity purchased from the grid. In primary steel production, except for the BF, most processes are heated by burners. These burners are generally fired by natural gas or process gas, but occasionally could also be fired by oil (stand-by fuel). Traditional burners are air-fuel fired; an increased use of oxygen will increase fuel efficiency but also increase NO_x formation. Air can therefore be enriched with oxygen, or burners could theoretically be 100% oxygen-fuel fired (Ziebik and Gladysz, 2014).

The primary energy source in the EAF melting process is electricity. Electric arcs (generated between the electrodes, between the electrodes and the scrap charge in an AC furnace, or between the single electrode and via the scrap to the anodes in the hearth for a DC furnace), create very high temperatures which melt the scrap. Oxy-fuel burners can be used (where steel quality allows) to supplement the heat input into EAFs. Oxygen injection is also used and the reaction with materials in the charge releases supplementary chemical energy as well as driving the process reactions.

At all steel plants, waste heat is generated. It is frequently low grade and hence difficult to use directly. Where there are no appropriate heat sinks on site, it is possible to pass it for outside use such as district heating, provided there is a demand close by and the infrastructure can be provided (DECC, 2013). To increase energy efficiency, modern BOF furnaces are equipped with regenerators for heat recovery. Potential on-site heat recovery measures include heat recovery from coke oven gas cooling, from water quenching of cokes, from exhaust gases in reheating furnaces, from sinter plants, from the blast stove exhaust to preheat combustion air and gas, from BF slag, from steel slab, from ladle preheat off-gases, from hot strip mill furnaces or from continuous annealing process lines (DECC, 2013).

Plants have significantly reduced gas flaring, and instead capture the gases arising from coke ovens, BF and BOF, using them to replace natural gas elsewhere, such as at reheating furnaces, to produce steam and to generate electricity.

3.3 Current Emissions and Energy Use – Principal Question 1

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

3.3.1 Evolution of Energy Consumption and CO_2 Emissions

Over time, the UK iron and steel sector has achieved significant improvements in energy efficiency. Figure 6 shows the evolution of the specific energy consumption, from 31.7 GJ per tonne steel produced in 1973 to 18.8 GJ per tonne in 2013, which is a reduction of ca. 40% over a period of 40 years. These improvements have been realised through investment in technologies that are today considered standard for any state-of-the-art steel plant (EEF, 2014). In more recent years, the technological opportunities have become more limited, with only relatively small incremental improvements in energy consumption.

Figure 6: Evolution of specific energy consumption (in GJ/tonne steel produced) for the UK iron and steel sector since 1973 (EEF, 2014)

3.3.2 Emissions

The iron and steel industry is one of the biggest industrial emitters of CO_2 in the UK due to the energy intensity of steel production, its reliance on carbon-based raw materials and fuels, and the large volumes of steel produced. The largest sources of CO_2 emissions are the process-related emissions, the direct emissions from on-site combustion of fossil fuels, and the indirect emissions from electricity consumed during the production process (IEA Clean Coal Centre, 2012). Total sector emissions (sum of direct and indirect) were 16.6 million tonnes CO_2 in 2011, 18.4 million tonnes in 2012 and 22.8 million tonnes in 2013. EAF sites accounted for 6%, 6% and 4% of these emissions respectively (EEF, 2014). The split of emissions between direct and indirect emissions is shown in Table 5. It can be noted that whilst BF-BOF process emissions are mostly direct emissions (i.e. arising from the reduction of the iron ore in the BF using coke) those from the EAF production process are mostly indirect (i.e. not emitted by the plant, but by the electricity generators providing the electricity to power the process). On EAF sites[11], direct emissions mainly come from combustion (60%) whereas process emissions account for the remaining 40% (UK Steel, 2014).

	INTEGRATED SITES			EAF SITES		
Year	**2011**	**2012**	**2013**	**2011**	**2012**	**2013**
Direct CO_2 emissions	92%	93%	94%	33%	33%	NA

[11] Note that these numbers come from one single UK EAF site and therefore might not represent the sector's average.

Indirect CO_2 emissions	8%	7%	6%	67%	67%	NA

Table 5: Direct and indirect emissions (2011-2013) from UK steel production (EEF, 2014)

A more detailed split of emissions is shown in Figure 7, with direct emissions in blue and indirect emissions in purple (Carbon Trust, 2011). From this figure, it is clear that iron making accounts for the largest share of direct emissions (1.1-1.8 tonne CO_2/tonne hot rolled coil from BF), followed by sintering, steel making and coke making (0.4-0.7, 0.2-0.3, and 0.1 tonne CO_2/tonne hot-rolled coil from BF respectively). With regards to indirect emissions, the highest share comes from hot rolling followed by continuous casting (0.2-0.3 and less than 0.1 tonne CO_2/tonne hot-rolled coil from BF respectively).

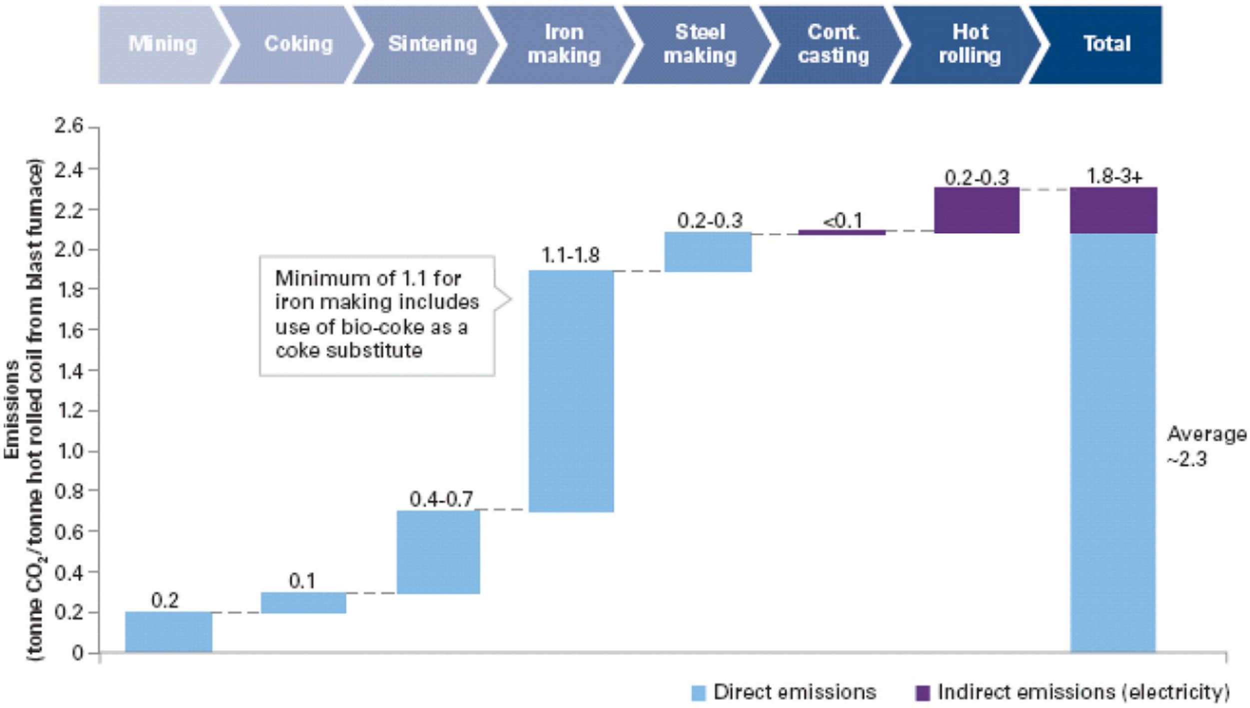

Figure 7: Direct and indirect emissions from the BF-BOF production of steel (Carbon Trust, 2011)

A shown in Figure 7 above, carbon intensity in the UK in 2011 averaged around 2.3 tonnes CO_2 per tonne of steel: integrated sites have an average carbon intensity of 2.2 tonnes CO_2 per tonne of crude steel whereas EAF sites have a lower average of 0.6 tonnes of CO_2 per tonne of steel (EEF, 2014). This value for average UK steelmaking was much lower than India and China (with carbon intensities in the range of 3.1-3.8 tonnes CO_2 in 2011) but somewhat higher than other countries such as Brazil (1.25 tonnes CO_2 – due to the use of hydro-power) and Mexico (1.6 tonnes CO_2 – due to a higher EAF capacity) (Centre for Low Carbon Futures, 2011).

3.3.3 Heat and Power Demand

Despite a long-term commitment from industry to reduce its energy consumption, the UK iron and steel sector still consumes large amounts of energy, over 70% of which is to provide heat, often at very high temperatures (over 1,000°C). The majority is obtained by burning fossil fuels such as gas, coal (transformed to coke) and oil. Because of this, industry is responsible for a quarter of UK carbon emissions. Iron and steel accounts for 9% of industry's energy use, the majority of which is used for high-temperature processes (DECC, 2013).

The following stages in the iron and steel production processes consume heat or power:

- Coke oven: pyrolysis of coking coal (heating to 1,000-1,200°C without oxygen) for 12-36 hours
- Sintering at high temperatures
- Iron making: production of reducing gas requires heating of air and burning of coke at 1,200°C for reacting coke and melting iron ore
- BOF: 99% pure oxygen to remove carbon from molten iron at high temperature
- EAF: electric current through electrodes for melting scrap at 1,600°C (EPA, 1995)

The practical minimum energy use (i.e. the sum of chemical energy, hot metal carbon content and energy in the hot metal) for a BF-BOF has been reported as being 10.4 GJ/tonne crude steel produced (IEA, 2007). The world best practice energy intensity for a BF-BOF was determined to be 14.8 GJ/tonne crude steel produced, whereas for EAF it was determined to be 2.6 GJ/tonne (Worrell et al., 2008). In the UK, 19.6 GJ/tonne crude steel was used in 2012: 2.5 GJ per tonne of crude steel was used by EAF sites, and the remaining 17.1 GJ per tonne of crude steel by BF-BOF sites (EEF, 2013). It can therefore be concluded that UK EAF sites are performing extremely well, whereas BF-BOF sites could still improve.

3.3.4 Carbon and Fuels Used

A significant proportion of CO_2 emissions from the integrated process route (BF-BOF) arises from the use of coke (and other fossil fuels) as a chemical reductant. Although natural gas is used as a reductant in some regions of the world in the direct reduction process, the price of natural gas makes this process prohibitively expensive in Europe.

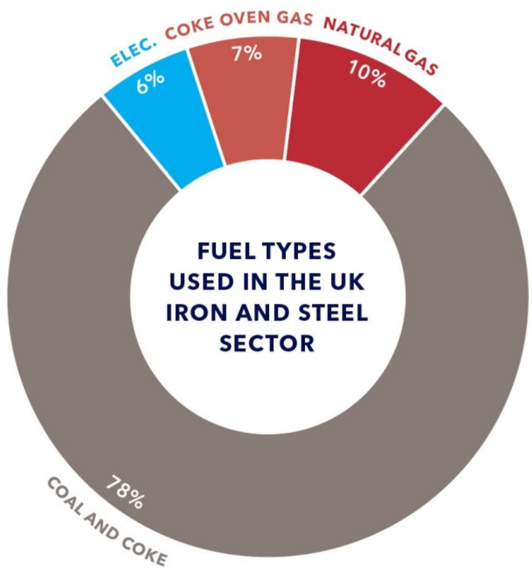

Figure 8: 2012 distribution of energy source use in the UK iron and steel industry (EEF, 2014)

In the UK, the total amount of energy sources used in 2012 in the iron and steel industry was 53,963 GWh, being mostly coal and coke (77.8%) as shown in Figure 8. At integrated (BF-BOF) sites, coal and coke are used both for their energy content and as a chemical reductant in the iron-making process. Purchased natural gas (9.7%) is used as energy source for steam production, reheating of secondary processes and EAF ancillary heating requirements. At integrated sites, gases arising from the coke ovens, BF and BOF are collected and used as energy sources throughout the sites (6.8%), including for electricity generation.

Propane and LPG are also used for smaller combustion processes and for cutting of material, but only in very small (negligible) amounts. The share of purchased electricity in the energy consumption of the sector is limited (5.5%), although about half of the energy on EAF sites is provided by the electricity grid. EAF sites use very little coal, and use electricity and natural gas instead.

3.3.5 Lifespan of Equipment and Key Timings

The bulk of UK iron and steel production is located in seven sites, i.e. three integrated sites and four main EAF sites.

Some of the BF at the integrated sites have been in operation for 60 to 70 years. In these cases, it is difficult to identify an investment cycle as the equipment is continuously upgraded and/or retrofitted rather than replaced. BF need to be relined regularly, new lining material have extended the time between relining to beyond 20 years (Jameson D. and Lungen H.-B., 2001). The largest three BF in the UK have recently been or are being relined (FT, 2014, Scunthorpe Telegraph 2014, BBC, 2012).

For the EAF sites, the main equipment age ranges from 4 to nearly 40 years. In these cases, an investment cycle in the order of 25 to 40 years can be assumed as an average. A large share of the existing capital stock or assets will need to undergo major refurbishment or replacement over the coming decades (Rootzén and Johnsson, 2013). The assumed average technical lifetime of key process equipment in the primary steel production is estimated at 50 years.

There are very few newly built plants in the UK. The majority of the plants have equipment from different time periods. As a consequence there are no publicly available key dates for when major equipment will be replaced. Often equipment has been refurbished or rebuilt, making it difficult to exactly determine its age.

For utilities, CHP (combined heat and power) and turbines have a typical life span of ten to 20 years (with a major refurbishment during this period). Vacuum pumps can easily reach 25 years' life whereas smaller utilities (compressed air, HVAC (heating, ventilation and air conditioning), lighting) have typical lifetimes of ten to 15 years before replacement or major upgrade. Electro-static precipitation filters in exhaust systems can last for several decades (EC, 2013).

To summarise, considering a typical investment cycle of 25 to 40 years for EAF process and utility equipment, there are one or at most two investment cycles before 2050. For primary steel production there is only one investment cycle before 2050.

3.4 Business Environment – Principal Question 2

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

Enablers and barriers were prioritised based on the evidence gathering process and workshop exercises. Table 6 and Table 7 below indicate how many times the enabler or barrier was mentioned across the different evidence gathering research methods. The categories were simply used as a means of identification for the workshops. Although the number of mentions provides some guidance as to the strength of sentiment towards a particular barrier or enabler, the discussions during workshops and interviews provided a greater understanding as to the detail and context behind each barrier and enabler.

3.4.1 Market Structure

The UK iron and steel industry is a highly mature and consolidated industry. Steel is globally traded and highly price sensitive. UK steel revenues in 2013 were £9.9 billion, with a profit of £672.8 million (Scotton, 2013). Tata Steel Europe Limited has 44.9% of the UK market share (with two integrated sites, one at Scunthorpe and one at Port Talbot, and one EAF site at Rotherham) and Celsa Steel UK Ltd. (with one EAF site at Cardiff) has 5.9% (Scotton, 2013). The remaining market share is comprised of SSI (with an integrated site at Teesside), Sheffield Forgemasters (with an EAF site at Sheffield) and Outokumpu (with an EAF site at Sheffield). The sector faces high barriers to entry and low technological changes. After several years of revenue contraction due to the recession, the gradual economic recovery of the automotive and construction sectors is holding a promise of resurgent global demand and increasing sales volumes (Scotton, 2013). Key drivers for future growth include: demand from motor vehicle manufacturing, total value of construction, government capital expenditure, world price of iron ore, and world price of coking coal (Scotton, 2013).

Production of steel can take many shapes, but generally speaking this can be divided into two categories:

- **Flat steel production**: slabs are rolled (hot or cold) to produce plates, coils, sheets, pipe products and coated steel products; used in automotive, heavy machinery, pipes and tubes, construction, packaging and appliances.
- **Long steel production**: blooms and billets are rolled into bars, wire rods, sections, rails, sheet piles, seamless tubes, slab and drawn wires; used in construction, mechanical engineering, energy and automotive.

The UK iron and steel sector's revenue is highly volatile and it is highly capital intensive. The future success of the industry is dependent upon its ability to access growing international markets, to take advantage of economies of scale in purchasing raw materials to keep costs down and in operating at full capacity, to reduce emissions, to obtain a reliable source of key inputs and to compete on price (Scotton, 2013).

As a result of the economic recession, mature market, and increasing global competition, the current business strategies in place are focused on business continuity, value-added projects, investing in growing markets (such as India), and increasing production efficiency. The consolidated market structure also enables R&D (research and development) and innovation to be a non-competitive area enabling good cooperation and cross-company learning. This was one of the key strengths of the sector mentioned at the evidence gathering workshop.

In 2012, apparent crude steel demand in the UK fell to 9.8 million tonnes from the 10.3 million tonnes seen in 2011, which is a decline of 32% on the pre-recession peak of 14.4 million tonnes seen in 2007 (UK Steel, 2012). The quarterly level of demand and import share during 2009 to 2012 can be seen in Figure 9. Lower levels of demand in the EU-27 and a strengthening GBP against the EUR have increased UK export share to wider global markets such as Asia (whereas USD markets have provided stronger demand).

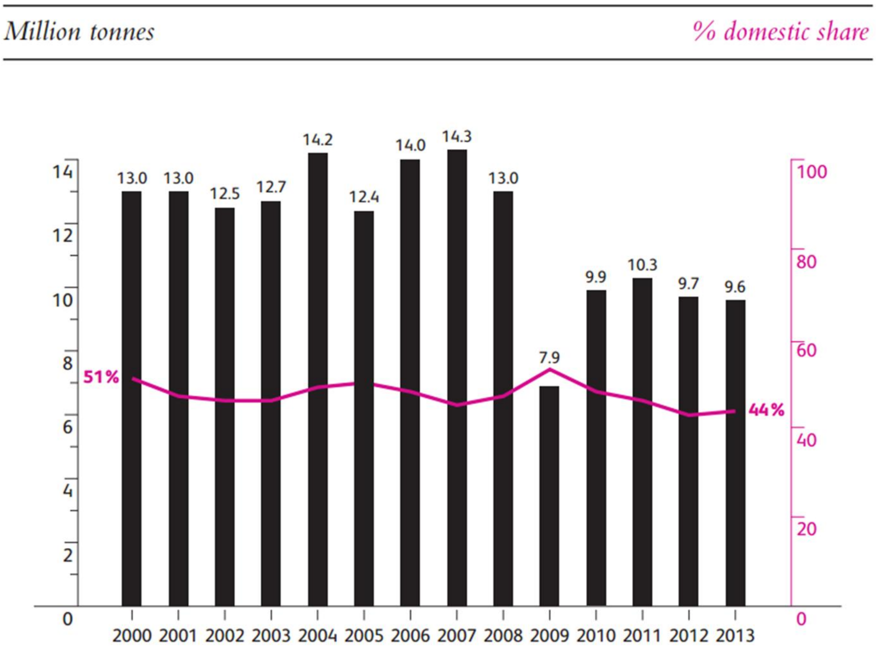

Figure 9: Crude steel demand in the UK and domestic share (UK Steel, 2012)

3.4.2 Business Strategies

Overall, the evidence from literature, interviews and workshops indicated that decarbonisation is not a strategic issue, mainly because of the lack of demand for low-carbon steel products from customers through purchasing requirements (EEDO, 2012). They are generally not looking for low-carbon products, rather customers are mostly cost driven. The current business strategies are therefore focused on business continuity, value-added projects, investing in growing markets (such as India), and increasing production efficiency, which can be summarised as **focusing on improving profitability and cost savings.**

A technical manager indicated: *"Decarbonisation is not a business goal and not the first priority amongst equals to the CEO at the moment. The iron and steel sector is struggling with profitability, getting into the black out of the red. Once this improves, there will be time to look at energy efficiency."* The same interviewee also stated: "*Carbon or energy efficiency competes with everything else in the business. It is not the driver of the business; it is one option for saving money*."

Interviewees with technical and commercial backgrounds also indicated that increasing raw material prices, including gas and electricity prices, can affect profit margins per tonne of steel, as steel manufacturers are unable to pass on the price increases to customers due to global competition causing steel to be highly price sensitive. Interviewees with technical and commercial backgrounds also indicated that like a decreasing global price for steel, increased energy taxes, levies and carbon prices that increase costs and **can reduce profits margins, which can make it more difficult for companies to invest in decarbonisation** in the UK, as it further reduces the cash available to invest in disruptive technologies.

A senior manager stated that they believe *"Decarbonisation can only be achieved if UK revenues increase so companies have funds to invest, which is led by where there is market growth. Moreover, new disruptive technologies need to become available in order to invest in them."*

The majority of the iron and steel manufacturers are trying to recover from the economic recession and therefore, although it is seen as an important issue, decarbonisation is not a strategic issue at an individual company level. There was one exception to this: one of the largest players, who see decarbonisation and sustainability as **creating reputational benefits**.

"Our company provides interim products to construction designers. Customers so far haven't requested low-carbon products but ask for responsible sourcing and traceability. Our company is trying to promote itself as greener steel provider."

Interviewees also indicated the desire for a collaborative way forward, with government and the sector, such as participating in joint demonstration projects coupled with a clear vision of the future. This would help to ensure that decarbonisation moves from a technical issue and incremental improvements to a key strategic priority for the sector. It was also stated that current thinking needs to go beyond direct impacts of iron and steel manufacturing and production, and that more collaboration is needed to develop decarbonisation strategies that take account of the whole value chain.

A senior manager stated: *"There are various low-carbon commercial opportunities across the value chain, for example wind turbines and the automotive sector which has a very active steel agenda. The opportunities vary by sector, for example for earth-moving equipment Caterpillar (JCB), the focus is on durability of the steel so that products last longer. The iron and steel sector should take advantage of these opportunities."*

Decarbonisation Strategies

There is some information available on decarbonisation strategies via company websites, and sustainability and annual reports. Three out of the five companies have sustainability reports and two have a specific corporate climate change strategy. Tata and Outokumpu have targets to reduce their CO_2 emissions per tonne of liquid steel by 20% by 2020 compared to 1990 levels according to their companies websites. These companies also discuss sustainability in their annual report. The inclusion of carbon-related information within the annual report is a positive indication that the issue is being taken seriously and integrated into business operations, as these publications are aimed at shareholders and investors.

Other examples of initiatives associated with decarbonisation strategies include an EAF steel company aiming to be a sustainable producer and having focused on recycling scrap as a mechanism for reducing its carbon emissions. In addition, a leading stainless steel producer has launched new sustainability key performance indicators in 2013 measuring its energy efficiency and CO_2 emissions against a baseline of 2007-2009 in its sustainability report.

Companies in the iron and steel sector have been looking at new ways to save energy over decades. However, payback time of ten years (or even longer) were perceived by technical experts to limit the technologies that can be implemented, and thus **energy saving has been seen as more of an incremental technical issue**.

Views from both interviews and workshops indicated a perception exists that the development and implementation of decarbonisation strategies in the UK is not a current priority due to the market conditions of the sector and the fact that **significant further decarbonisation needs breakthrough technologies**. All interviewees confirmed that decarbonisation is important, but there is not one technology that will pave the way for a decarbonised iron and steel sector.

A senior manager stated that *"The current business environment is not conducive to large-scale demonstration projects as there is limited capital available, and companies are currently focusing on business continuity and cost savings. As a result, decarbonisation is seen as a technical issue and not a strategic issue."*

Due to the small number of big players in the UK, **the field of innovation and R&D is generally a non-competitive area**. When asked at the evidence gathering workshop about the key strengths of the UK iron and steel sector, participants indicated that the UK is well placed in the innovation and R&D space through ULCOS (ultra-low CO_2 steelmaking) and because R&D is seen as a non-competitive area. The sector could further leverage this by tackling decarbonisation together but this will depend on availability of funding.

Decarbonisation has been discussed through EEF, and **the sector has invested in demonstration projects such as ULCOS**. The existing plan in the UK iron and steel sector is to leverage the research conducted as part of research programmes such as ULCOS. Representatives indicated that they were looking to identify how funding can be obtained for a CC demonstration project. It is currently considering how to move forward, but states that this must be a joint vision between the companies in the sector and government with all of their buy-in in order to succeed. This applies to other research programmes such as the material efficiency work in the WellMet2050 by Cambridge University, which explores opportunities to deliver the same quality of services for downstream industries with fewer material inputs (like light-weighting).

WellMet2050 has been superseded by the UK INDEMAND Centre, announced in November 2012 in the UK government's Energy Efficiency Strategy, and is one of six national research centres on end-use energy demand reduction. The UK INDEMAND Centre aims to enable delivery of significant reductions in the use of both energy and energy-intensive materials in the Industries that supply the UK's physical needs.

There are also global research activities beyond EU, such as the COURSE 50 (CO_2 ultimate reduction in steelmaking process by innovative technology for cool earth 50) research programme in Japan, POSCO (Pohang iron and steel company) programme in Korea, and Deep Decarbonisation Pathways Project in the US, that the Sector should consider how to gain better leverage from.

A senior manager stated that *"Although smaller improvements can and are being made, the sector is still considered to be at the stage that much larger investments are needed to realise the next scale of decarbonisation projects. The size of investments required is unlike what was needed before and different channels or ways of gathering that capital need to be investigated."*

3.4.3 Decision-Making Processes

Technical and senior managers were of the view that governance structures and consequently business decision-making processes vary depending on the company.

The view was expressed that typically smaller, more dynamic companies with closer proximity and relationships to key decision makers are able to leverage relationships when proposing the business case for investment for advanced technologies with payback periods longer than two years.

Conversely it was considered by the interviewees that companies that are very hierarchical in their decision-making structure, can significantly lengthen decision-making times, yet international links associated with such companies can also enable such companies to invest in decarbonisation projects despite their longer payback period of over two years. Although all decision-making processes vary by company, all companies interviewed used commercial and productivity criteria to inform their decision-making.

One interviewee, a senior manager, said: *"Our project managers identify new options and must come up with the business case for the leadership team to review. The leadership team, comprised of the Board and CEO (chief executive officer), assesses the project on a variety of criteria, including whether the investment will reduce costs through energy savings, improve environmental compliance or safety critical tasks, whether it will increase market share or enhance capacity or productivity, and whether the payback period is reasonable."*

A company's decision-making can also be focused on whether projects will improve compliance (environment, health and safety), but also whether the investment is aligned to its investment strategies, such as kit replacement, product development and operation, and cost savings. This focus is true even when the organisation has a sustainability and climate change strategy in place.

The governance structures of the companies interviewed can also impact their ability to invest in advanced technologies. For example, two of the companies whose UK operations are subsidiaries of larger international companies found that their influence over decarbonisation technologies was capped or limited to a certain level of investment. For larger investments, UK subsidiaries may find it challenging to get buy-in from the Group, and Group sign-off is required. Often, investment decisions for large international companies come from international headquarters, and therefore the technologies or investment strategies may not be aligned to the UK market, or the UK may not have much influence over the investment decisions being made.

In conclusion, decision-making processes in relation to decarbonisation and energy efficiency in the UK iron and steel sector follow a number of broad frameworks depending on company size and structure. Key decision-making parameters or factors such as the market dynamics, the regulatory environment and finance are key issues in energy-related decision-making, which is further discussed in the conclusions. Therefore this difference in decision-making between companies in the same sector may hold them back when looking to invest into decarbonisation due to lack of aligned governance in investments.

3.4.4 Financing Investments

The literature review found that companies are less likely to finance investments in decarbonisation if the payback period is longer than two years, whereas investments under one year are likely to be funded. For energy efficiency projects, the price of energy impacts the payback. This was reinforced by all interviews conducted, which identified that a payback of one year was needed and that the longer the payback period the more additional benefits a project must have in order to gain funding. In the case of major furnace replacement or kit replacement, energy efficiency and BAT are considered when choosing a replacement technology. The payback period in this case is much higher; this is accepted as it is a core part of the industry's operational model.

Several quotes from the interviews confirm the payback constraints:

"Investing in burners was a no brainer, with payback being three to six months."

"Any investment with payback time lower than one year is very likely to be done."

"The cost saving from reduced natural gas import and payback was about three years, which is on the high end to be accepted."

Another key barrier to financing, especially when it comes to disruptive technologies, is the availability of capital, both internal and external. Interviewees were open to a variety of capital arrangements, but struggle to obtain them. They indicated that decarbonisation projects often compete for internal capital with other projects proposed by different parts of the business. On the other hand, the research also showed that companies with an international presence were able to identify funding from outside the UK, which enabled them to fund projects with longer payback periods. But again they stated that, given the extensive competition for capital both internally and externally, it is not surprising that the investment criteria are stringent and that companies are taking a conservative and risk-averse approach to investment decisions.

For some companies, new investments are funded in order to replace existing equipment, or because the investment was part of a wider business strategy and therefore has been accounted for as part of a yearly budgeting cycle. Compliance with environmental, health and safety, and other regulatory requirements often drives investment decisions.

A senior manager stated: *"For projects we want to invest in, we look at financial criteria and other drivers including legislation and regulation. The most important is the financial justification. We only have a finite pot to finance investments. The projects with the best financial return will get ahead of the queue. Investments made purely to improve* CO_2 *emissions, without any impact on productivity or health and safety, will remain in the queue."*

The interview with EEF reinforced the findings from the interviews with individual companies. EEF highlighted that all UK iron and steel companies are capital constrained and might not able to fund technologies with longer payback periods. Through the interviews, all companies highlighted that their main source of capital for investing in energy efficiency and decarbonisation projects is from their own revenues. Thus, the current weak financial performance of the sector is limiting the decarbonisation projects companies can invest in, especially those with longer payback periods. An interview with a senior manager did identify that projects with longer payback periods can potentially be overcome through alternative financing. This could be a third-party taking on upfront capex costs through equity financing and the manager gave an example of a biomass waste fuelled heat plant.

3.4.5 Enablers and Barriers

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

Table 6 and Table 7 below indicate how many times the barrier or enabler was mentioned across the different evidence gathering research methods.

- There were more than 130 documents reviewed as part of the literature review. The number in the literature column below represents the prevalence in occurrence of the enabler or barrier; or in other words the number of sources that discuss it.
- There were seven telephone semi-structured interviews in total. The number in the interview column below represents the prevalence in occurrence of the enabler or barrier; or in other words the number of interviewees that discussed it.
- The workshop column shows the number of participants who considered the enablers and barriers as important during the evidence-gathering workshop group.
- The numbers on the left-hand side do not present a ranking but provide an easy point of reference to the order of analysis.

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

Top Enablers

#	Category	Enablers	Primary Source	Prevelance of occurance		
				Literature	Interviews	Workshop
1	Market	Access to growing markets	Workshop	3	2	12
2	Regulation	Improved policy framework	Literature	4	2	7
3	Market	Cost of carbon	Interviews	4	4	11
4	Operational	Location near to CCS infrastructure	Workshop	2	1	11
5	Market	Increased demand for materials used in renewable energy and energy efficiency	Literature	2	1	7
6	Financial	Link between environmental and safety issues in investment projects	Workshop	-	-	4

Table 6: Top Enablers

The first enabler – **access to growing markets** – was identified by literature (Scotton, 2013) and reflected during interviews and the workshop. Access to growing markets is perceived as the most important enabler for decarbonisation, as it bolsters revenues and increases capital availability, which was identified as a key barrier to investing in advanced decarbonisation technologies. Scotton found that the iron and steel market in the UK is on a decline, yet the first workshop and the IEA found that one of the key enablers to decarbonisation is the fact that iron and steel is a growing sector due to increasing global demand. This could suggest that there is a disconnection between the UK and the global market, and tapping into global growth could improve revenues and thus enable the sector to invest in decarbonisation technologies. It could also mean that since Scotton published the report there has been a change in global demand and that is increasing the growth of the UK iron and steel market.

"Key drivers for future growth include: demand from motor vehicle manufacturing, total value of construction, government capital expenditure, world price of iron ore, and world price of coking coal. This industry is in long-term decline, but will find some respite over the next five years. The future looks much brighter for the basic steel processing industry. As Britain continues on the path to economic recovery, greater investment in construction projects is expected to bolster demand for processed steel and bring sustained revenue growth to the industry. Import competition will also intensify into the future, alongside rising steel prices, which are expected to force inefficient operators out of the industry." (Scotton, 2013)

A manager responsible for the environment stated that: *"The best way to get investments in low carbon business is to allow business to thrive to have a future to invest in. All of our investments are linked to India as this is where we are experiencing growth."*

The second enabler – **improved policy framework** – supports industrial investment in innovation and deployment. Regulation drives energy efficiency investments through mandating compliance and was identified by literature (McKinsey, 2012; Ricardo AEA, 2013; and UNEP, 2013) and during interviews, and voted on at the workshop. Establishing a policy framework drives innovation, for example by developing European standards that promote sustainable production of steel construction products (PWC, 2014). Participants in the workshop supported the findings from the literature and interviews, but emphasised that a stable regulatory environment which does not create an uneven playing field, and that takes account of the energy-intensive industries' business environment, is important.

"Past climate change policies such as CCAs, CRCs, and solar FiTs have led to organisational change." (McKinsey, 2012)

“*CCAs and EU ETS (European Emissions Trading System) have already realised short-term carbon reductions.*” (DECC, 2013)

The third enabler –**cost of carbon** – was identified by literature (Carbon Trust, 2011; EEF, 2012; Okereke and McDaniel, 2012; Johnson, 2013) and reflected during both by interviews and workshops. The cost of carbon can be a driver for decarbonisation as it creates a financial incentive to avoid costs. A global carbon pricing model would level the playing field and incentivise decarbonisation if the price is high enough according to some of the decision makers interviewed. However, it is the view of the sector that in the absence of a global carbon price, or broadly comparable emissions abatement policy mechanisms in place in the major steel producing regions, a high carbon price is highly unlikely to bring forward the investment required for substantial emissions reductions and risks carbon leakage.

A manager responsible for the environment stated: *“The third largest component in the cost structure is the energy taxes, levies, etc.”*

A senior manager stated: *“In terms of energy and carbon control it is really a financial consideration for me.*

“Absorbing the cost of carbon under the EU ETS carbon legislation or passing it onto consumers represents a significant challenge to the iron and steel industry. Ultra low-steel making will provide the sector with the opportunity to significantly reduce emissions from steel making. However this will not be in line with the timeframe of proposed emissions reductions in the current EU ETS. The sector will require significant investment to realise these technologies and the predicted cost of Phase 3 of EU ETS will limit the sector's ability to invest in the project.” (EEF, 2012)

“The iron and steel sector will increasingly be exposed to policies that seek to impose a cost of carbon on production emissions, through the development of new pricing mechanisms over time. As a result, producers of steel should continue to invest in the research, development and demonstration of technologies that will decarbonise production over the long term, including top gas recycling, carbon capture and storage, bio-coke substitution, and alternative processes such as electrolysis.” (Carbon Trust, 2011)

“*The iron and steel industry may be particularly vulnerable to competitiveness impacts because a carbon price of £20/tonne could amount to a 15% increase in production costs for a typical integrated steel mill, which is significant for an industry with relatively tight margins and high trade intensity.”* (Okereke and McDaniel, 2012)

The fourth enabler – **location near to CCS infrastructure** – was identified in the literature review (Centre for Low Carbon Innovation, 2011) and discussed at the workshops. Sites located near CCS infrastructure will have a competitive advantage and will be able to realise cost and energy savings compared to CCS enabled sites not located near infrastructure. Participants in the workshop thought that sites located near the North Sea have a high potential for offshore storage and, if infrastructure were to be developed, significant emissions reductions could be achieved. This would require government support.

“Some industrial regions may benefit from a concentration of production (e.g. Aire valley), as plants located outside identified regional CCS clusters may be prevented from accessing CCS transportation and storage networks due to high pipeline connection costs.” (Centre for Low Carbon Innovation, 2011)

One manager responsible for the environment stated: *“We are lucky that most of our sites (two out of three big sites) are on the North Sea so we can connect to CCS if it were to happen.”*

The fifth enabler – **increased demand for materials used in renewable energy and energy efficiency** – was identified as an enabler by the literature (BCG and VDEh, 2013; EEF and Tata Steel, 2011) and supported by one interview and discussions at the workshop. If demand for steel increased, especially for renewable energy or other energy efficiency technologies such as light-weighted cars, the sector would see increased revenues which it could then use to invest in decarbonisation. Increased demand for these products would also improve carbon emissions along the value chain. During the workshop, participants considered that higher valued products could also support increased revenues. They also stated that the emissions savings across the value chain should be considered when making the best decisions on how to reduce emissions in the UK. This enabler links to 'access to growing markets' above.

"Light-weighting of cars has the highest abatement opportunity, but technical barriers to doing so include design codes which place constraints on the design and performance of the product. In the design stage, there may be conflicting constraints such as performance trade-offs. Manufacturing and installation costs of light-weight cars are higher, the handling of the product in the distribution stage of the supply chain can constrain the product's design, and light-weighting may limit the possible reuse of the product." (EEF and Tata Steel, 2011)

A senior manager stated: *"Currently there is lots of focus on the end of the supply chain. Companies and people using renewables receive lots of positive attention for their decarbonisation efforts, yet what is often ignored is the supply chain that enables these technologies to happen. It is depressing that steel companies are hampered for being polluters but are helping make reductions. A whole value chain approach is needed, and a serious approach to scope 3*[12] *emissions hot spots is needed."*

The sixth enabler – **link between environmental and safety issues in investment projects** – was identified during the second workshop. Investments in advanced technologies have a higher likelihood of being signed off if they help the companies to improve their market share, capacity, HSE (health, safety and environment) performance, productivity or save costs or meet new regulations.

A manager responsible for environment highlighted that: *"Energy efficiency projects will not be undertaken unless it is a side benefit to a critical safety task. Especially if it is a big spend. Capex decisions are normally focused on the short term. If a project would pay back in several years, but it is not a critical safety capex, the capex will not be made. There are several exceptions to this, when commitments to expenditures were already made before 2006 or 2007, before the financial crisis broke out."*

[12] Greenhouse gas emissions are categorised into three groups or scopes by the Greenhouse Gas Protocol. Scopes 1 and 2 cover direct emissions sources from fuel combustion, company vehicles, fugitive emissions and purchased electricity, heat and steam. Scope 3 covers all indirect emissions due to the activities of a company or organisation, such as from purchased goods and services, travel, transportation and distribution, etc.

Top Barriers

#	Category	Barriers	Primary Source	Prevelance of occurence		
				Literature	Interviews	Workshop
1	Market	Global competition from lower-cost producers	Workshop	3	2	19
2	Financial and decision-making	Shareholders demand quick payback	Interviews	2	7	12
3	Financial and decision-making	Availability of capital or competition for funds	Workshop	2	3	15
4	Market and economy	Increasing electricity and gas prices	Literature	8	4	12
5	Market and economy	Slow rate of capital stock turnover	Workshop	2	2	8
6	Value chain	Steel customers primarily make decisions on costs, not on carbon emissions	Interviews	1	4	-
7	Legislation	Regulatory uncertainty	Workshop	2	2	10
8	Financial	Increasing cost of carbon and uneven playing field	Literature	7	3	8

Table 7: Top Barriers

The first barrier – **global competition from lower-cost producers** – was identified by literature (EEF, 2012; EC, 2013; and Scotton, 2013) and reflected during interviews and workshops. A higher electricity price was highlighted in the literature review as a key barrier specifically for EAF. The interviews identified that the cost of operating in the UK is higher due to higher electricity costs. Higher electricity prices were considered to potentially increase costs, reduce competitiveness against companies that operate in countries with lower electricity prices, and compound the barrier of availability of cash to make investments. Interviewees were also of the opinion that increasing raw material prices (including gas and electricity) are affecting profit margins, as companies are unable to pass on the price increases to their customers, due to global competition causing steel to be highly price sensitive. Also, for BF-BOF, newer builds overseas were believed to conventionally have larger furnace sizes, which have higher operating efficiencies and enable producers to enjoy greater economies of scale. It is anticipated that plants in the UK that are operating below their capacity will have their efficiency negatively affected.

"Import competition is intense, particularly at the lower-value added end of the product range. Revenue volatility is very high, due to both fluctuations in the price of steel inputs and shifts in demand. Industry exports are expected to contribute 60.3% of industry revenue in 2013-2014. This shows an extremely high level of export dependence for industry players, with about two-thirds of revenue generated from shipping products overseas." (Scotton, 2013)

"*The UK manufactures a wide range of specialised, high-quality steel products. However, the large bulk of our output, as with other developed nations, is of qualities available from non-EU competitors. Steel is a globally produced and traded product and the global market is highly price sensitive. The principal sources of import competition are Russia, Ukraine, China, Turkey, Republic of Korea, Serbia, Switzerland, India, Brazil* *and Belarus, none of which has internalised costs of carbon. It would therefore be impossible to pass on the costs of carbon to our EU customers, who could very simply switch to imported sources."* (EEF, 2012)

The second barrier – **shareholders demand quick payback** – was identified by literature (EEF and Tata Steel, 2011; McKinsey, 2012) and reflected during interviews and workshops. The literature review found that companies are less likely to finance investments in decarbonisation if payback periods are higher than two years. This was reinforced by all the interviews conducted, identifying that the longer the payback period, the more additional benefits a project must have in order to gain funding. Technologies with payback periods of less than one year are more likely to be invested in. Shareholders were commonly considered to desire quick payback periods, whereas advanced technologies often require longer payback times and will therefore be subject to more stringent investment criteria including impacts on production, critical safety improvements, compliance, availability of capital and key strategic priorities. Investment decisions for decarbonisation go through an extensive application process and governance hurdles such as approval by management, the Board and CEO.

A senior manager stated: *"For an investment with a three- or four-year payback, the project sponsor will have to come up with additional reasons to improve the payback period. There must be a strong business case."*

"*In the commercial and industrial sectors, stakeholders demand a rapid payback period of ca. two years, while many energy efficiency investments have a longer payback period."* (McKinsey, 2012)

The third barrier – **availability of capital or competition for funds** – was identified by literature (EEF and Tata Steel, 2011; Centre for Low Carbon Innovation, 2011) and reflected during interviews and workshops. Medium- and long-term decarbonisation technologies are anticipated to incur significant capital investment, and those costs are highly uncertain at present. Many markets are growing faster than the UK, signifying increased internal competition within multinational companies for funds to invest. Companies are often struggling to obtain capital arrangements, and decarbonisation projects often compete with other projects proposed by different parts of the business. Companies may not always have enough cash flow and revenues to meet banks' lending criteria. Two interviewees mentioned that there seem to be few external funds or schemes to apply for, that the funds are minimal in comparison to the investments put forward by the companies themselves, or that the schemes are not stable enough. Others highlighted that they are applying to the Green Investment Bank (GIB) and other finance sources such as Horizon 2020 to obtain funds. One interviewee mentioned that these research-funding mechanisms and other scheme application processes are too bureaucratic and complex, suggesting an action for government to simplify its application processes. Interviews also mentioned that, given the extensive competition for capital both internally and externally, investment criteria are stringent and that companies are taking a conservative and risk-averse approach towards investment decisions.

A technical manager indicated: *"Main issue is the availability of capital, not the length of the payback. The amount of money you can invest and have is limited by the capital you have to invest."*

"A large proportion of UK companies operating in the energy-intensive sector are subsidiaries of global organisations. They compete internally for capital investment. Higher costs make it more difficult to justify internal group investment in the UK." (Centre for Low Carbon Innovation, 2011)

The fourth barrier – **increasing electricity and gas prices** – was identified by literature (Brunke and Blesl, 2014; Kennedy and Kmjetowicz, 2013; Eurofer, 2013; EC, 2013; Capros et al., 2013) and reflected during interviews and the workshop. A higher electricity price was highlighted in literature as a key barrier, specifically for EAF as higher costs limit the amount of funds available to invest in advanced decarbonisation technologies. Current electricity prices for industrial consumers in the UK are high relative to those in the rest of the EU and internationally, largely reflecting higher base prices (wholesale plus network costs) with higher low-carbon price adding £12/MWh (Kennedy and Kmjetowicz, 2013). This number approaches £20/MWh by

2015 (ICF International, 2012). US shale gas and increasing pressure to export scrap, together with increasing gas and electricity prices, will threaten EAF competitiveness (Eurofer, 2013). Pressure to decarbonise the UK and the electricity grid might counteract the current pressure to export scrap. Participants at the workshop agreed that higher electricity prices in the UK compared to other EU countries is creating an uneven playing field. However, through a sensitivity analysis, Brunke and Blesl (2014) found that energy-related production costs of the BF-BOF route will increase on average by 6-13% between 2013 and 2035. Increasing electricity costs can be an enabler for EAF sites to invest in reducing energy consumption through innovation to compensate for the high electricity prices although the impact on competiveness would be the overarching factor. It is also recognised that the main opportunities for EAF to reduce energy consumption may have already been implemented.

A senior manager stated: *"Electricity prices are going up, which is hurting the iron and steel industry."*

A senior manager said: *"Electricity is the second-highest component in the cost structure, and is therefore of paramount importance."*

A manager responsible for the environment stated: *"There is no single market for energy prices. UK energy prices are higher than in Holland, and those in Holland are higher than in other EU countries. You could argue this could help companies in terms of energy efficiency schemes, but you are actually taking money away from the companies by taking away profitability."*

A manager responsible for the environment said: *"We have a large dilemma with energy. We want to decentralize low-carbon energy, but we also need cheaper energy. That problem needs to be solved."*

A technical manager stated: *"UK electricity prices (including CO_2 allowances) are more expensive than in Germany or France. Cost of operating in the UK therefore hinders investment to some extent."*

"A number of representatives identified the high and rising costs of energy and energy taxes in the UK, as well as rising commodity prices, as a barrier to investment." (Centre for Low Carbon Innovation, 2011)

A recent publication of Agora Energiewende (2014), however, illustrates that the comparison of electricity wholesale prices between sectors and countries is a difficult task. A recent communication from the European Commission on energy prices and costs in Europe shows that UK electricity prices for industry are very similar to the average EU-28 prices. (EC, 2014).

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

There is evidence to show that when it comes to the largest and most energy-intensive industrial energy consumers, the UK has a relatively higher electricity price. Analysis conducted on behalf of BIS in 2012 demonstrated the extent to which energy intensive industry in the UK was projected to be exposed to significantly higher climate change policy costs in electricity bills then elsewhere in the EU and further afield (ICF International, 2012).

The fifth barrier – **slow rate of capital stock turnover** – was identified by the workshop participants as a key barrier, as it impacts when new advanced technologies can be deployed, given the long life cycles of blast and EAF. Investment cycles vary for different equipment but can be as long as 50 years, limiting the opportunities for investing in large-scale advanced technologies. Interviews and literature (Rootzén and Johnsson, 2013) support this issue.

"A large share of the existing capital stock or assets will need to undergo major refurbishment or replacement over the coming decades. The assumed average technical lifetime of key process equipment in the primary steel production is set to 50 years." (Rootzén and Johnsson, 2013)

A technical manager said: *"Whether we start working more in the UK would be based on the cycle. We have got to be bringing in something during a blast furnace shutdown."*

The sixth barrier – **steel customers primarily make decisions on costs, not on carbon emissions** – was identified by literature (Tata Steel, 2014) and reflected during both by interviews and workshops. Interviewees indicated that decarbonisation is more likely to become a strategic issue if more customers demanded low-carbon steel products through purchasing requirements. All interviews indicated that customers are currently not requesting this type of information, which may differ from more consumer-facing sectors.

The seventh barrier – **regulatory uncertainty** – was identified by literature (Ernst and Young, 2013; McKinsey, 2012) and reflected during both by interviews and workshops. The complex and changing policy landscape at EU and UK level is very challenging for companies: not all companies are even aware of the existing energy efficiency incentives. Inconsistencies in and changing of policy creates uncertainty and leads to companies delaying investment decisions, as they are unsure whether future investments will be sound if policies are changed again. Companies penalised by previous changes in policy may now be more likely to hesitate to make investments, fearing that the policy environment will change again, rendering the investment uneconomic.

A technical manager stated: *"If we look at CCS, what we are trying to do is develop the project. But we need to deal with government or regulatory and technological uncertainty, and have to identify ingenious ways of funding the project. Regulatory environment and uncertainty is a key barrier. Risks and benefits will constantly change. The end dates of schemes aren't really clear. CCS, CCL (Climate Change Levy), compensation schemes for energy costs, etc.: there are no guarantees of the life of the scheme*."

The eighth barrier – **increasing cost of carbon and uneven playing field** – was identified by literature (Wooders, 2012; TUC, 2012; Ernst and Young, 2013; PWC, 2014; EEF 2012; Centre for Low Carbon Innovation, 2011; Johnson, 2013) and supported by the interviews and workshop. Interviewees stressed that as energy costs and regulatory compliance costs are already high, increasing UK or EU carbon prices would add an additional operating cost limiting the amount of funds available to invest in advanced decarbonisation technologies. Moreover, the literature review and interviews indicated that electricity prices and operating costs can be higher in the UK than in other countries, placing UK iron and steel manufacturers at a competitive disadvantage. Some participants at the workshop stated their opinion that having a high cost of carbon in the UK/EU has a negative impact on competiveness as it leads to production going outside of the UK to less energy efficient manufacturers.

"Competitiveness and leakage concerns must be taken into account in decision-making for decarbonising steel." (Wooders, 2012)

"Energy-intensive industry is currently under enormous pressure as a result of both the general economic climate and UK and European environmental and energy policies. There is significant evidence that, unless immediate steps are taken, these policies will have a corrosive effect on the viability of individual businesses and entire industry sectors within the UK. As witness to these concerns, the closure of the UK's last

remaining aluminium smelter in the north-east and the announced closure of a steel plant in north Kent are just two current examples of industries under intense pressure."* (TUC, 2012)

"Energy costs are still the primary driver of abatement efforts. Regulation has encouraged many companies to put in place carbon management strategies. Improved carbon disclosure has helped to increase awareness and transparency of climate change issue. Cap-and-trade programmes have had little positive financial impact on corporates, but this will change. Climate change represents an important opportunity for business, as well as a risk." (Ernst and Young, 2012)

"Absorbing the cost of carbon under the EU ETS carbon legislation or passing it onto consumers represents a significant challenge to the iron and steel industry." (EEF, 2012)

A senior manager indicated: *"We have been hit by a number of issues. We can't fire on a new boiler plant due to EU ETS limits. We are doubling our emissions, because of the policy. The gas coke oven of our new plant doesn't meet EU ETS levels, but this doubles our emissions. This is the UK implementation of the EU ETS policy. EU ETS is a significant cost to us."*

3.5 Technologies to Reduce Carbon Emissions

The options distilled from the literature review, interviews, evidence gathering workshop, discussions with trade associations and input from academia are presented in appendix C (the data for these options are also listed). Figure 10 shows a comprehensive schematic of the iron and steel production processes, illustrating different decarbonisation options in the production process chain. CC is not shown in this figure.

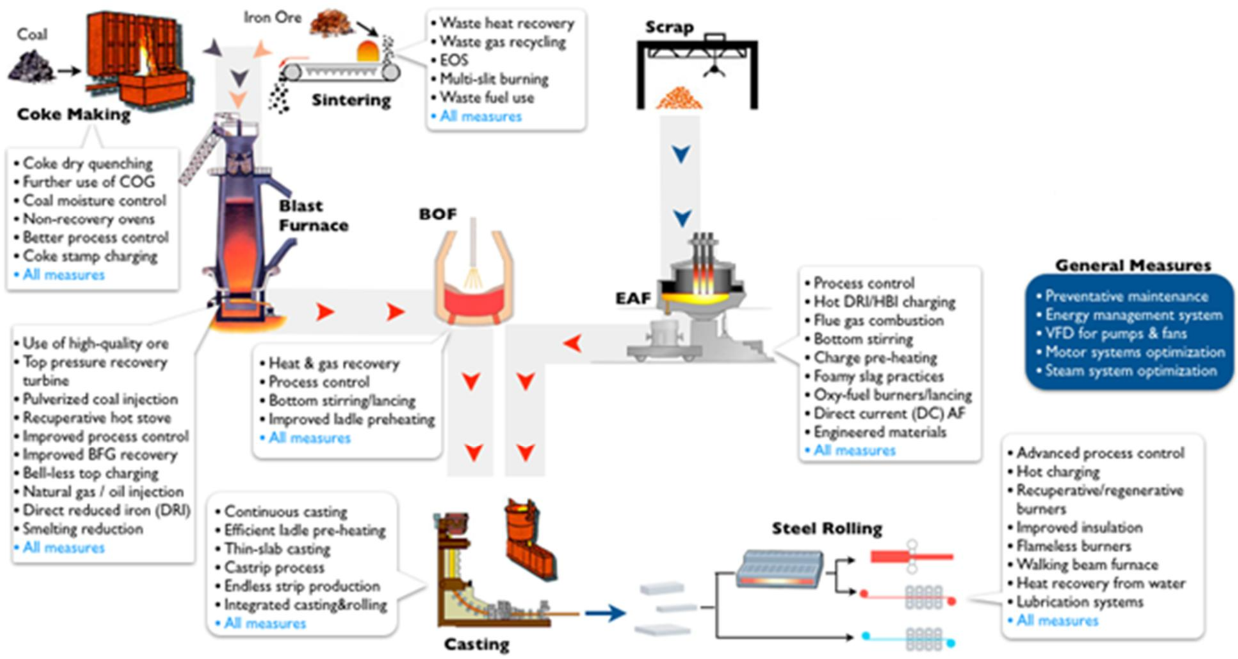

Figure 10: Schematic of iron and steel production processes (IIP, 2014)

Options were grouped into short-, medium- or long-term perspective, but were also categorised into two types: incremental and disruptive. The disruptive options fall into the medium-/medium-long-term group of options and the incremental options in the short- or short-medium-term categories. The disruptive options were regrouped from a technology-specific categorisation to a more generic grouping during the workshop (see appendix C). This is because participants felt unable to identify specific technologies that are expected to play a significant role in different pathways. The regrouping was subsequently discussed in the sector team and adopted for the remainder of the project.

Incremental options are characterised by smaller incremental CO_2 savings to different parts of the production process. It should be noted that not all of the following options are available or practical for certain grades of steel requiring specific treatment:

- **Generic options**: improved automation and process control, heat recovery and re-use (both conventional and innovative options), installing VSDs (variable speed drives) on electrical motors, improved planning, optimisation of compressed air and steam or power production systems, use of premium efficiency electrical motors, reduced yield losses, biomass-based steam generation, energy management, lighting optimisation, right-sizing of equipment, substitution for low-carbon fuels, and reduction of distribution losses.
- **Coke making**: coke dry quenching, coal moisture control, fuel substitution, further use of coke oven gas, coal stamp charging, automation and process control system, heat recovery coke ovens, and use of petroleum coke instead of coke.
- **Sintering**: selective waste gas recycling (EPOSINT, environmentally process optimisation sintering), improved ignition oven efficiency with multi-slit burners or curtain flame ignition system, waste fuel use, emissions optimised sintering (EOS), waste-heat recovery, wood char in sinter making, pelletised BF dust, automation and process control, improved charging system, leakage reduction, and increased strand width.
- **BF**: automation and process control, use of high-quality ore, top pressure recovery turbine, pulverised coal injection (PCI), improved BF gas recovery, bell-less top (BLT) charging, natural gas or oil injection, fuel substitution, increased BF top pressure, improved hot stoves process control, injection of coke oven gas, plastic waste injection, charging of carbon composite agglomerates (CCB), slag heat recovery, hot stove heat recuperation, increased hot blast temperature, substitution of coal by biomass in PCI, and stove flue gas recycling.
- **BOF**: BOF heat and gas recovery, BOF bottom stirring, improved ladle preheating, aluminium-bronze alloy for BOF walls and hoods, improved process monitoring and control, and recycling of BOF steelmaking slag.
- **EAF**: bottom stirring or stirring gas injection, charge or scrap preheating, foamy slag practices, oxy-fuel burners or lancing, improved process control, flue gas monitoring and control, waste-heat recovery, airtight EAF process, co-melt, CONTIARC arc furnace, twin-shell DC arc furnace, engineered refractories, eccentric bottom tapping, ultra-high power transformers, DC arc furnace, ECOARC and scrap densification or shredding.
- **Casting**: continuous casting, efficient ladle preheating, near-net-shape casting, endless strip production, direct rolling, process re-engineering, heat recovery from cooling water, efficient tundish heating, un-heated tundish, continuous temperature monitoring and control, on-line laser ultrasonic measurement system, MAG-Gate for continuous caster, accelerated cooling, sequencing of casts for speciality sequences, and heat recovery from hot slabs other than direct rolling.
- **Secondary processes**: hot charging, regenerative or recuperative burners, improved insulation, flameless burners or dilute oxygen combustion, walking beam furnace, heat recovery from cooling water, improved planning and throughput optimisation, process control in hot strip mill, proper reheating temperature, oxygen level control and VSDs on combustion fans, pressure control for furnace, avoid furnace overloading, premium efficiency motors for rolling mill drives, installing lubrication system, cold rolling optimisation, pulse firing in reheating furnace and switch to dry vacuum pumps.

Disruptive options, in contrast, are breakthrough technologies such as rebuild or retrofit of integrated sites with advanced technologies, including:

- **HIsarna**: a technology based on bath-smelting, combining coal preheating and partial pyrolysis in a reactor, a melting cone for ore melting and a smelter vessel for final ore reduction and iron production. It requires significantly less coal usage, thereby reducing the amount of CO_2 emissions. The three separate technologies of this technology have been proven independently at small scale. Next step is to commission a HIsarna pilot plant (ULCOS, 2015).
- **Corex**: a direct smelting reduction process that allows production of hot metal directly from iron ore and non-coking coal. Iron ore is charged into a reduction shaft where it is reduced to DRI (direct reduced iron) by a reduction gas moving in counter flow. In the melter gasifier, the final reduction and melting take place in addition to all other metallurgical reactions (Siemens, 2015). Several Corex plants have already been built.
- **Finex**: an optimised fine-ore reduction process for the reduction of iron ore fines. The smelting-reduction process is based on the direct use of non-coking coal and fine ore. The fine ore is preheated and reduced to fine DRI in a multi-stage fluidised bed reactor, progressively reducing the fine ore to fine DRI. This fine DRI is then compacted and charged as hot compacted iron into the melter gasifier. This charged iron is subsequently reduced to metallic iron and melted (Siemens, 2015). Several Finex plants have already been built.
- **Carbon capture**: a technique for capturing carbon dioxide emitted from large point sources and compressing it. Carbon capture and storage (CCS) also includes transporting it to a suitable geological storage site where it is injected into a stable geological formation, generally more than one kilometre below the surface. Rather than treating the carbon dioxide as waste (as is the case with CCS), carbon capture and utilisation (CCU) attempts to convert it into commercially saleable products such as bio-oils, chemicals, fertilisers and fuels. This technology is not yet commercialised on a large scale (CO_2 Chem, 2015) and requires more investigation to demonstrate whether it is commercially viable. CCU is not considered as an option in this report.

As you will see in section 4 there has been a further regrouping into two major disruptive options:

- Retrofit solutions (with or without CC)
  - This includes option Top Gas Recycling and on-site power plant CC in the case with CC
- Advanced technologies and rebuild
  - This include options HIsarna, Corex and Finex and process CC in the case with CC

3.5.1 Biomass Carbon Intensity

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

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

Given the wide variation in pre-combustion emissions, a carbon intensity (based on pre-combustion emissions) was derived from a low scenario from the DECC-commissioned Bioenergy Emissions and Counterfactual Model report (published 2014) for modelling purposes. An emission value of 20 kg CO_{2e}/MWh_{th} has been used for solid biomass use, and this has been modified to 25 kg CO_{2e}/MWh_{th} if the pathways includes pyrolysis, and 30 kg CO_{2e}/MWh_{th} if the pathways includes production of biogas.

3.5.2 Cost of Options

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

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

4. PATHWAYS

4.1 Key Points

The pathways development and analysis shows that the maximum decarbonisation potential of the iron and steel sector in the current trends scenario is a reduction to 9.2 Mt of CO_2 emitted in 2050 in the Max Tech pathway, which corresponds to a reduction in emissions of 60% compared with emissions in 2012 (EEF, 2012). Significant reductions of 67% and 53% could be achieved under challenging world and collaborative growth scenarios respectively. The same technologies are important in the different scenarios and could represent a 'least regret' approach for the sector. Some of these technologies are still under development such as HIsarna and CC and would require a significant investment in demonstration facilities. One important challenge in the iron and steel sector is the long lifetime of equipment: the sector needs to carefully plan its major retrofitting or rebuild to coincide with when the technology is ready. The reductions have been achieved through a range of options, the most significant being:

- Advanced technologies and rebuild of existing integrated iron and steel (BF-BOF) plants, for example using HIsarna, Corex or Finex techniques
- Advanced technologies and rebuild with CC, such as HIsarna with integrated CC processes
- Retrofit solutions to existing BF-BOF plants, using top gas recycling (TGR)
- Retrofit solutions with CC, installing TGR systems with integrated CC
- Improved site and sector integration
- Upgrading onsite steam and power plants, to improve fuel combustion efficiency

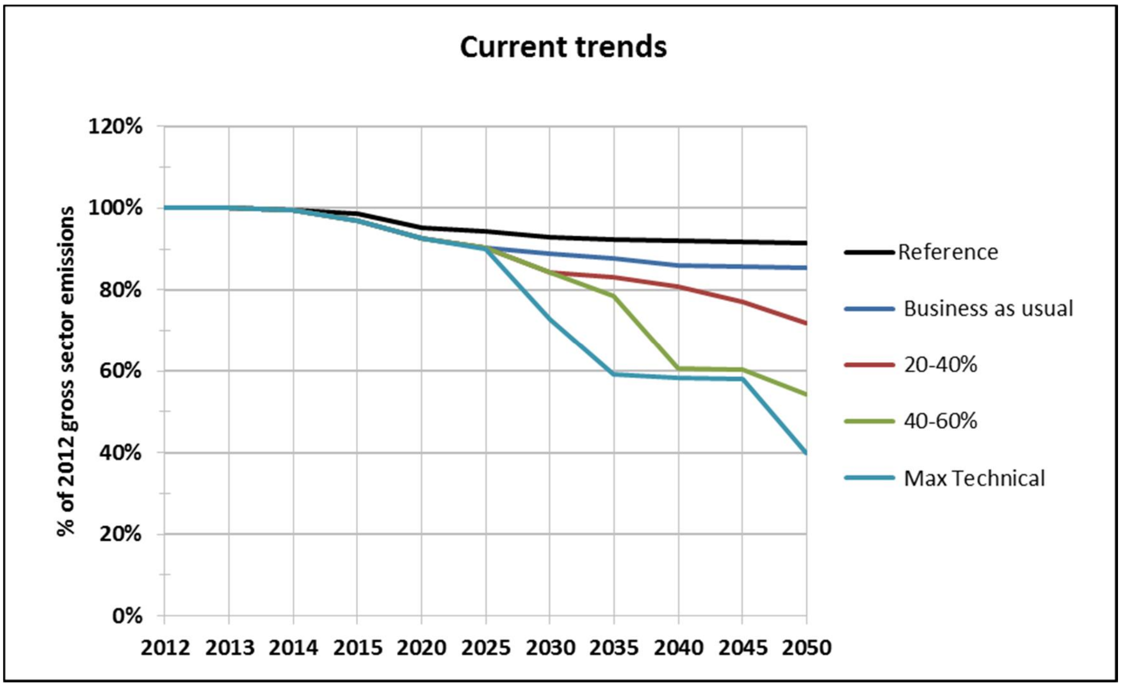

Figure 11: Performance of pathways for the current trends scenario

Figure 11 shows the wide range of decarbonisation and energy efficiency pathways that are possible for the current trends scenario:

- BAU represents where existing trends in energy efficiency and decarbonisation continue. Incremental options provide savings earlier in the pathway, and major options including stove flue gas recycling and steam or power plant upgrades are implemented by 2050.
- 20-40% CO_2 reduction pathway is similar to BAU but with increased deployment of stove flue or top gas recycling in most BF-BOF sites from 2030 to 2050. In addition, the plant rebuild option using advanced steel production technology is applied late in the pathway, giving further emissions savings.
- 40-60% CO_2 reduction pathway adds to these measures through deployment of plant retrofit with CC from 2035, and deployed to 75% of integrated BF-BOF sites by 2050.
- Max Tech pathway consists of the maximum deployment of the CC disruptive options, in which half of existing BF-BOF sites have been rebuilt using advanced technologies and integrated CC, and the other half of existing sites have been retrofitted.

The sensitivity analyses identified the following main results:

- The Max Tech pathway emissions reductions are reliant on CC technologies, and in the absence of CC, even if adding biomass, emissions reduction of 41% will be achieved, compared to 60% with CC.
- Adding material efficiency could increase the emissions reductions as it achieves a reduction of 64% compared to the 60% that the Max Tech pathway achieves.
- Alternatively, using biomass alongside CC technologies achieves a 63% emissions reduction potential compared to the 60% that the Max Tech pathway achieves.
- Another alternative includes increasing the percentage of steelmaking by EAF, which could increase the emissions reduction potential for the sector to 67% compared to the 60% that the Max Tech pathway achieves.

4.2 Pathways and Scenarios – Introduction and Guide

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

A pathway consists of decarbonisation options deployed over time from 2015 to 2050, as well as a reference emissions trend. The analysis covers three 'scenarios', with pathways developed under a central trend ('current trends' scenario) and alternative future outlooks ('challenging world' and 'collaborative growth' scenarios).

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

The three scenarios were developed covering a range of parameters. They characterise possible versions of the future by describing assumptions relating to international consensus; international economic context; resource availability and prices; international agreements on climate change; general technical innovation; attitude of end consumers to sustainability and energy efficiency; collaboration between sectors and organisations; and demographics (world outlook). These scenarios were used during the workshop to help decide on deployment rate for the different options.

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

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

The methodology is summarised in Figure 12.

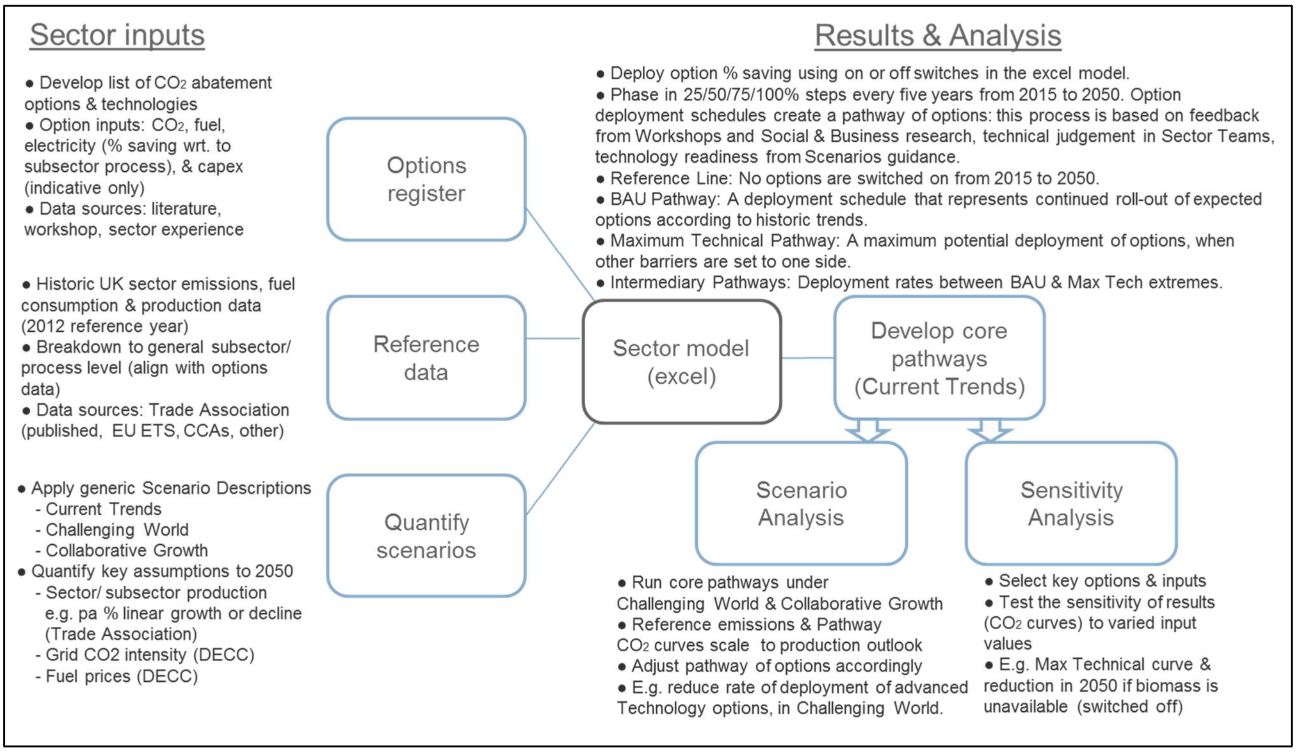

Figure 12: Summary of analysis methodology

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

Pathway	Current Trends Scenario	Challenging World Scenario	Collaborative Growth Scenario

Reference Emissions Trend	*Scenario assumptions only linked to production outlook and grid decarbonisation No options deployed in the model*		
BAU	Builds on the reference line by deploying options from 2015 to 2050 in the model, to construct a BAU pathway. Run model under current trends.	Builds on BAU pathway current trends by adjusting option selections and deployment schedule, to reflect the scenario assumptions and technology constraints. Run model under challenging world.	Adjust BAU pathway current trends, i.e. option selections and deployment schedule, to reflect scenario assumptions and technology constraints. Run model under collaborative growth.
20-40%[13]	Builds on BAU for example by: deploying more advanced options, extending further across sector, deploying options earlier. Run under current trends.	Builds on 20-40% pathway current trends in the same way. Run under challenging world.	Adjust 20-40% pathway current trends in the same way. Run under collaborative growth.
40-60%	Builds on 20-40% in the same way. Run under current trends.	Builds on 20-40% pathway current trends in the same way. Run under challenging world.	Adjust 20-40% pathway current trends in the same way. Run under collaborative growth.
60-80%	Builds on 40-60% in the same way. Run model under current trends.	Builds on 40-60% pathway current trends in the same way. Run under challenging world	Adjust 40-60% pathway current trends in the same way. Run under collaborative growth.
Max Tech	Configure a schedule of options from 2015 to 2050 that broadly represents a maximum rate and spread across the sector. Run model under current trends.	Adjust Max Tech pathway current trends in the same way. Run under challenging world.	Adjust Max Tech pathway current trends in the same way. Run under collaborative growth.

Table 8: Pathways and scenarios matrix

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

4.3 Baseline Evolution – Principal Question 3

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

The UK iron and steel sector has faced volatile conditions over the past five years. The industry heavily relies on demand from the construction and automotive sectors, and this demand contracted during the economic downturn in 2008-2009. Steel prices subsequently plunged in 2009 as demand dried up in the

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

wake of the financial crisis. However, recovery came just as quickly as the decline. The revenue growth was restored by rebounding automotive markets and government policies stimulating construction. The iron and steel sector is recovering, and in the coming five years an annual growth of 3% is expected (IBIS World, 2014).

Confidence in the UK economy continued to strengthen throughout 2013 with GDP (gross domestic product) growth amounting to 1.8%. GDP growth for 2014 is forecast at 2.7%, and this high level of optimism is supported in two of the UK's main steel-consuming sectors. Structural fabricators are enjoying their healthiest forward order load for five years, anticipating a demand growth of 6% in 2014. In the automotive sector, the 3% increase in vehicle output in 2013 will be dwarfed by the 33% increase forecast over the next four years. Combined with the positive UK steel demand figure of the fourth quarter of 2014, this gives some hope that steel demand may finally have turned the corner (EEF, 2013).

Despite the recent positive trends for the sector, it has been decided that for an outlook to 2050 - considering the fluctuations of the iron and steel market over time - a more modest outlook compared to recent growth rates would be used for this project.

The evolution of the sector was varied under the three scenarios, using different assumptions of sector growth or decline (in terms of total tonnes of UK steel production):

- Current trends – steel production assumed flat (0% growth) from 2014 to 2050
- Challenging world – steel production assumed to fall (1.5% per annum decline)
- Collaborative growth – steel production assumed to rise (1.5% per annum growth)

The split between BF-BOF and EAF steel production is assumed constant over the period to 2050, at 83% BF-BOF and 17% EAF in all scenarios. The effect on total emissions of shifting production from BF-BOF to EAF plant is tested in the pathways sensitivity analysis, noting constraints related to the availability of scrap metal for EAF.

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

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

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

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

The list of Enablers and Barriers has informed the list of technical options that are being deployed in the different pathways. They also informed the deployment of the different technical options both with regards to time and degree of deployment. For example, the enabler 'location near to CCS infrastructure', led to deployment that is linked to the location of the current iron and steel plants.

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

- Current trends: 100g CO_2 per kWh by 2030 and 26g CO_2 per kWh in 2050
- Challenging world: 200g CO_2 per kWh by 2030 and 150g CO_2 per kWh by 2050

- Collaborative growth: 50g CO_2 per kWh by 2030 and 25g CO_2 per kWh by 2050

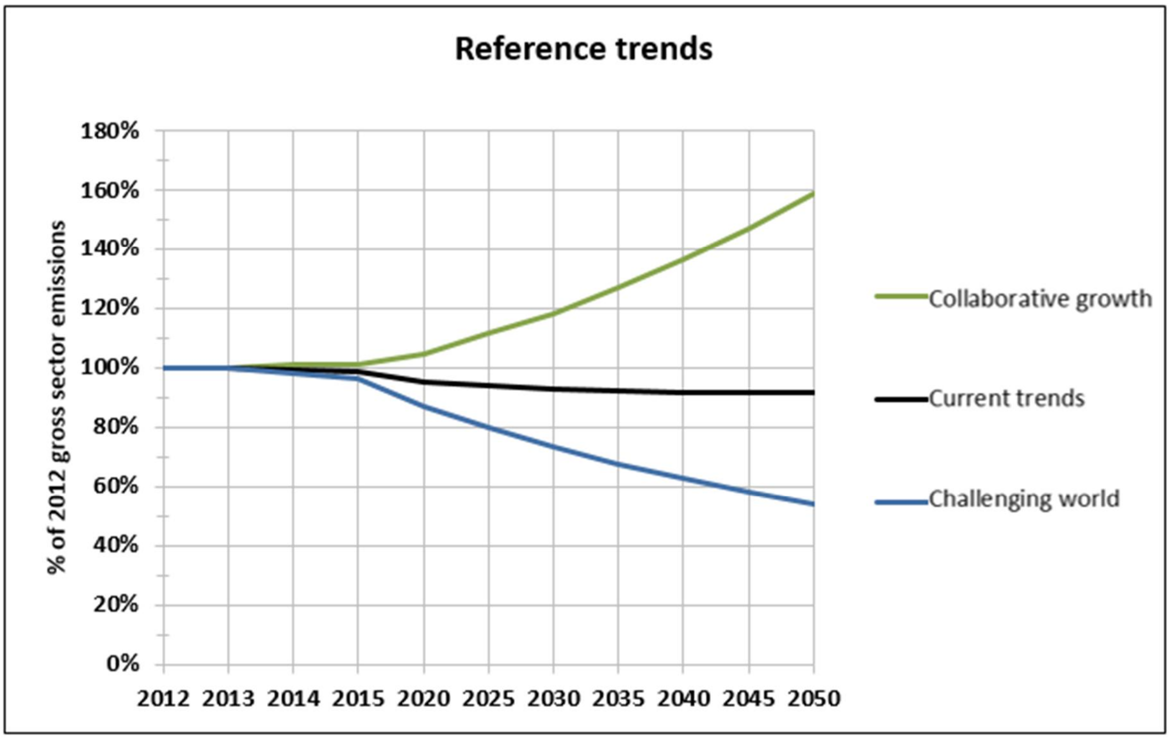

Figure 13: Reference trends for the different scenarios

For all of the pathways, to have the total CO_2 reduction, growth or decline of the sector, indirect (emissions from using electricity from the electricity grid) and direct emissions need to be accounted for. The indirect emissions and growth or decline of the sector are illustrated by the reference trends. In Figure 13, the reference trends for the different scenarios are shown. The shape of the line is linked both to growth or decline of the sector and the different levels of decarbonisation of the electricity grid.

4.4.1 Business as Usual Pathway

Pathway Summary

The guiding principle for the BAU pathway was to outline a set of decarbonisation and energy saving options that would be expected if current rates of efficiency improvement in the UK iron and steel industry continued, and no significant intervention or outside support was provided to decarbonise the sector by 2050. Options were chosen that required no policy intervention, compared to today, and only minor changes within the sector.

Deployment for the Current Trends Scenario

Figure 14 shows the option deployment for the BAU pathway for the current trends scenario. The first column lists the decarbonisation options on the left, each with its relevant subsector (process) to which it applies in the second column:

- Total: the option is applied across the total sector emissions
- Secondary: the option is applied to the secondary processes related emissions only (including rolling, milling, casting, final product processing)
- EAF: the option is applied to EAF-related emissions only

- Integrated: the option is applied to BOF-BF related emissions only
- Sintering: the option is applied to sintering-related emissions only
- Coking: the option is applied to coking-related emissions only

The next two columns are the estimated adoption (ADOPT.) rate in 2012 and the applicability rate (APP.) assumption for the option. The applicability rate indicates to what level this option is applicable to the sector, or its relevant subsector. To the right of the applicability rate column is the actual deployment of the option over time to 2050. The CO_2 reductions are estimated based on the direct CO_2 reductions assumed for the option for its relevant process, the adoption rate, applicability rate, and deployment.

OPTION	ADOPT.	APP.	DEPLOYMENT								
			2014	2015	2020	2025	2030	2035	2040	2045	2050
Short Term											
01 Heat Recovery & Re-use - Conventional Options	50%	88%	0%	25%	50%	75%	75%	75%	75%	75%	75%
02 Improved Automation & Process Control	20%	63%	0%	25%	50%	75%	75%	75%	100%	100%	100%
03 Hot Charging	3%	80%	0%	25%	50%	75%	100%	100%	100%	100%	100%
04 Fuel Substitution - coking plant	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
05 Improved Planning & Throughput Optimisation - sec processes	12%	100%	0%	25%	50%	75%	75%	75%	100%	100%	100%
06 Installing VSDs on Electrical Motors (Pumps & Fans)	50%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
07 Pulverised Coal Injection (PCI)	85%	100%	0%	25%	25%	25%	25%	25%	25%	25%	25%
08 Reducing yield losses	40%	100%	0%	25%	50%	75%	75%	100%	100%	100%	100%
09 Scrap Densification / Shredding	35%	70%	0%	25%	50%	100%	100%	100%	100%	100%	100%
10 Compressed Air System Optimization	34%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
11 Re-heating Furnace Optimization	19%	100%	0%	25%	50%	75%	75%	75%	100%	100%	100%
Short-Medium Term											
12 Near Net Shape Casting	10%	20%	0%	0%	0%	25%	25%	25%	50%	50%	75%
13 Use of premium efficiency electrical motors	13%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
14 Waste Heat Recovery - sintering	7%	100%	0%	25%	50%	75%	75%	75%	100%	100%	100%
15 BOF Heat & Gas Recovery	29%	100%	0%	0%	25%	50%	50%	75%	100%	100%	100%
16 Endless Strip Production (ESP)	0%	20%	0%	25%	25%	50%	75%	75%	50%	50%	25%
17 Heat Recovery from Cooling Water	0%	100%	0%	0%	25%	50%	75%	100%	100%	100%	100%
18 Steam / Power Production System Upgrades	32%	86%	0%	25%	25%	50%	50%	50%	50%	50%	50%
19 UHP Transformers	33%	75%	0%	25%	75%	100%	100%	100%	100%	100%	100%
20 Regenerative / recuperative burners - sec processes	54%	100%	0%	25%	50%	50%	75%	75%	100%	100%	100%
Medium Term											
21 Heat Recovery & Re-use - Innovative Options	0%	88%	0%	0%	0%	0%	25%	25%	25%	25%	25%
22 Improved Process Control - EAF	48%	100%	0%	0%	0%	0%	25%	50%	50%	75%	100%
23 Retrofit Solution without CCS	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24 Stove Flue Gas Recycling (without CCS)	0%	100%	0%	0%	0%	0%	0%	0%	25%	25%	25%
25 Stove Flue Gas Recycling (with CCS)	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
26 Increased EAF production share	Sensitivity test		0%	0%	0%	0%	0%	0%	0%	0%	0%
Medium-Long Term											
27 Coke Dry Quenching (CDQ)	0%	50%	0%	0%	0%	0%	0%	0%	25%	25%	50%
28 Retrofit Solution with CCS	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
29 Advanced Technologies without CCS & Rebuild	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30 Improved site / sector integration	10%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
31 Advanced Technologies with CCS & Rebuild	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
32 Advanced Electrolysis Techniques	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 14: Option deployment for the BAU pathway

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

- **Steam and power production system upgrades**: The option is deployed to 50% of potential by 2025, and accounts for 26% of the total emissions reduction from deployment of options in 2050.
- **Stove flue gas recycling at integrated BF-BOF sites:** The option is deployed later in the pathway to 25% of the sector by 2040, accounting for 26% of the total emissions reduction from deployment of options in 2050.

- **Reducing yield losses or avoiding off-spec products**: The option is deployed to 100% of the total sector by 2035, and accounts for 25% of the total emissions reduction from deployment of options in 2050.
- **Other options** which contribute appreciable savings to the pathway include: improved automation and process control, heat recovery and re-use, near-net-shape casting, pulverised coal injection, and coke dry quenching.

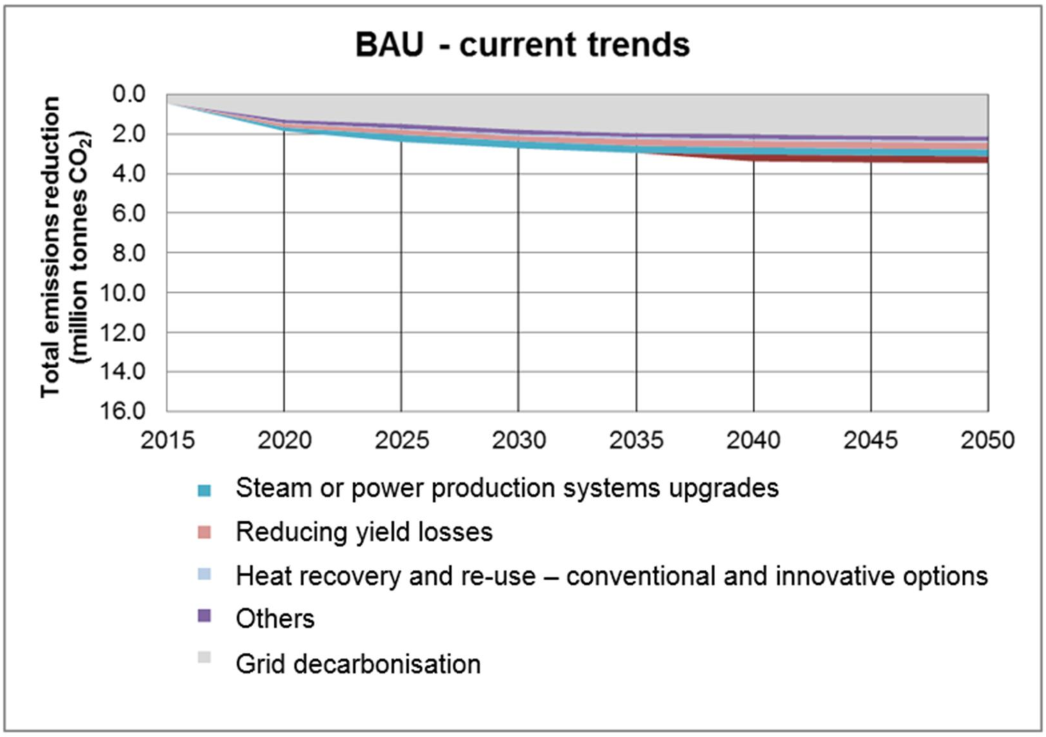

Figure 15: Contribution of principal options to the absolute emissions savings throughout study period, for the BAU pathway, current trends scenario

For the current trends scenario, the options deployed in the BAU pathway give an overall reduction of 15% in 2050, compared to 2012. This includes the emissions reduction linked to the deployment of options and decarbonisation of the grid.

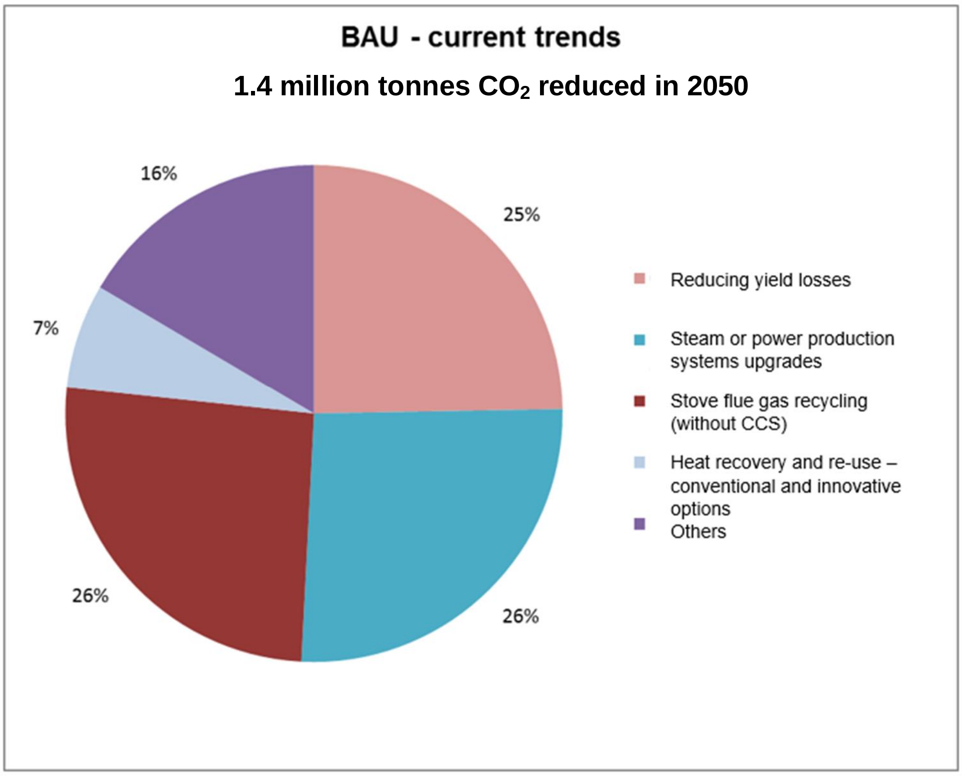

Figure 16: Breakdown of 2050 emissions savings, for the BAU pathway, current trends scenario

The CO_2 reduction contributions in 2050 revealed that most of the carbon reductions in BAU came from a few key options[14]: stove flue gas recycling without CC, steam and power plant upgrades, and reducing yield losses (Figure 16).

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

Option Deployment for other Scenarios

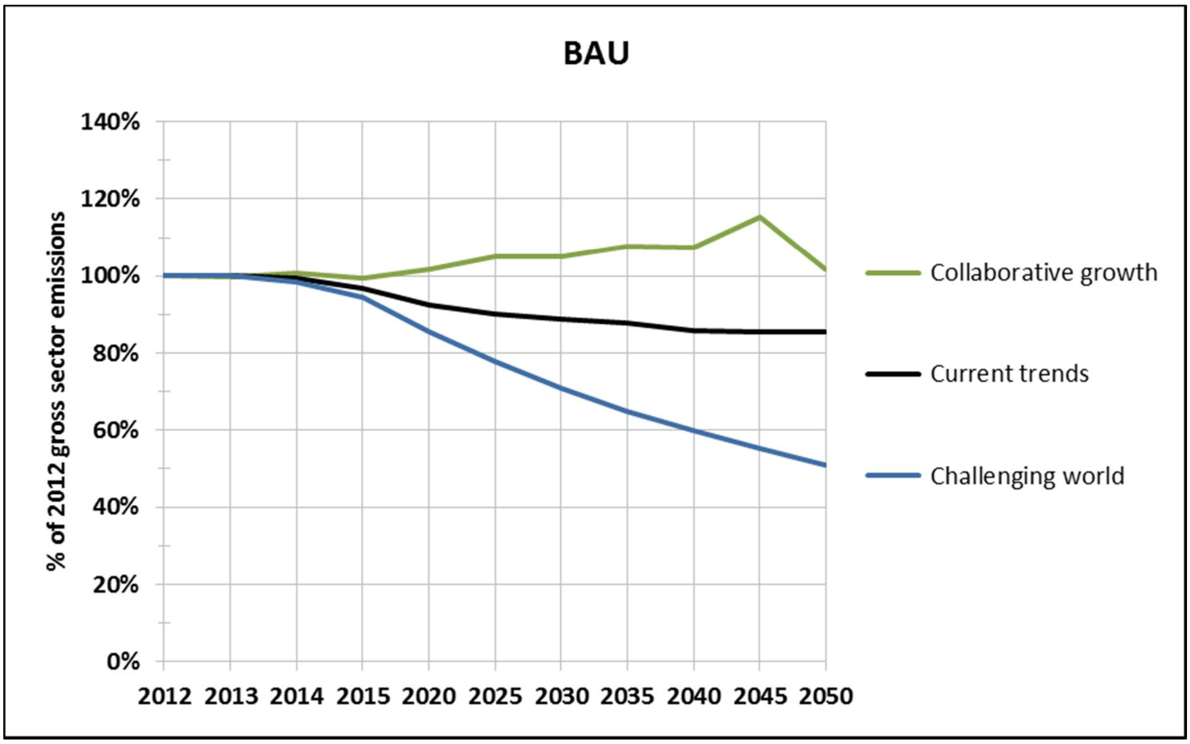


Figure 17: BAU pathways for the different scenarios

Figure 17 shows the BAU pathways for the different scenarios. As can be seen, the current trends scenario delivers an overall CO_2 reduction of 15%, the challenging world scenario delivers an overall CO_2 reduction of 49%, and the emissions for the collaborative growth scenario remain the same as in 2012.

The BAU pathway under challenging world only consists of the short- and short-medium-term options deployed at a slower rate from 2015 to 2050. None of the medium-term and disruptive options is applied at all: specifically, stove flue gas recycling, heat recovery and re-use (innovative) option, and coke dry quenching.

The BAU pathway under collaborative growth contains a range of disruptive options deployed in both the medium and long term which counteract the rising reference emissions, due to sector production growth. Stove flue gas recycling and BF-BOF retrofits (without CC) are deployed from around 2030. The advanced technology rebuild option (without CC) is applied from 2040 to 25% of BF-BOF sites, and then switching up to 50% by 2050. Retrofit CC is also applied to 25% in 2050.

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

4.4.2 20-40% CO_2 Reduction Pathway

Pathway Summary

The 20-40% CO_2 reduction pathway delivers a higher saving of 28% by 2050 compared to 2012, and shows the effect of increased deployment of retrofit solutions and advanced technology (without CC). Incremental, short- to medium-term options were deployed at the same rate as BAU, but with extended deployment of two major options: retrofits to existing BF-BOF plant (TGR, without CC) together with steam and power plant upgrades. In addition, the advanced technology rebuild option (without CC) is applied to 25% by 2050.

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

Deployment for the Current Trends Scenario

Figure 18 shows the Option Deployment for the BAU pathway under the current trends scenario.

OPTION	ADOPT.	APP.	DEPLOYMENT								
			2014	2015	2020	2025	2030	2035	2040	2045	2050
Short Term											
01 Heat Recovery & Re-use - Conventional Options	50%	88%	0%	25%	50%	75%	75%	75%	50%	50%	50%
02 Improved Automation & Process Control	20%	63%	0%	25%	50%	75%	100%	100%	100%	100%	100%
03 Hot Charging	3%	80%	0%	25%	50%	75%	100%	100%	100%	100%	100%
04 Fuel Substitution - coking plant	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
05 Improved Planning & Throughput Optimisation - sec processes	12%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
06 Installing VSDs on Electrical Motors (Pumps & Fans)	50%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
07 Pulverised Coal Injection (PCI)	85%	100%	0%	25%	25%	25%	25%	25%	25%	25%	25%
08 Reducing yield losses	40%	100%	0%	25%	50%	75%	75%	100%	100%	100%	100%
09 Scrap Densification / Shredding	35%	70%	0%	25%	50%	100%	100%	100%	100%	100%	100%
10 Compressed Air System Optimization	34%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
11 Re-heating Furnace Optimization	19%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
Short-Medium Term											
12 Near Net Shape Casting	10%	20%	0%	0%	0%	25%	25%	50%	50%	75%	75%
13 Use of premium efficiency electrical motors	13%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
14 Waste Heat Recovery - sintering	7%	100%	0%	25%	50%	75%	100%	100%	100%	100%	75%
15 BOF Heat & Gas Recovery	29%	100%	0%	0%	25%	50%	75%	100%	100%	100%	75%
16 Endless Strip Production (ESP)	0%	20%	0%	25%	25%	50%	75%	50%	50%	25%	25%
17 Heat Recovery from Cooling Water	0%	100%	0%	0%	25%	50%	75%	100%	100%	100%	100%
18 Steam / Power Production System Upgrades	32%	86%	0%	25%	25%	50%	75%	75%	100%	100%	100%
19 UHP Transformers	33%	75%	0%	25%	75%	100%	100%	100%	100%	100%	100%
20 Regenerative / recuperative burners - sec processes	54%	100%	0%	25%	25%	50%	50%	50%	50%	75%	100%
Medium Term											
21 Heat Recovery & Re-use - Innovative Options	0%	88%	0%	0%	0%	0%	25%	25%	50%	50%	50%
22 Improved Process Control - EAF	48%	100%	0%	0%	0%	0%	25%	25%	50%	75%	100%
23 Retrofit Solution without CCS	0%	100%	0%	0%	0%	0%	25%	25%	25%	50%	50%
24 Stove Flue Gas Recycling (without CCS)	0%	100%	0%	0%	0%	0%	0%	0%	25%	25%	25%
25 Stove Flue Gas Recycling (with CCS)	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
26 Increased EAF production share	Sensitivity test		0%	0%	0%	0%	0%	0%	0%	0%	0%
Medium-Long Term											
27 Coke Dry Quenching (CDQ)	0%	50%	0%	0%	0%	0%	0%	0%	25%	25%	50%
28 Retrofit Solution with CCS	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
29 Advanced Technologies without CCS & Rebuild	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	25%
30 Improved site / sector integration	10%	50%	0%	0%	0%	0%	0%	0%	0%	0%	25%
31 Advanced Technologies with CCS & Rebuild	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
32 Advanced Electrolysis Techniques	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 18: Option deployment for the 20-40% CO_2 reduction pathway

In this pathway, the principal options that contribute to emissions savings in 2050 are:

- **Retrofit solutions and stove flue gas recycling (without CC):** These options together are deployed to 75% of the BF-BOF sector by 2045. The options together account for 43% of the total emissions reduction from deployment of options in 2050.
- **Advanced technologies and rebuild (without CC):** This option is deployed to 25% of BF-BOF sites in 2050. The option accounts for 22% of total emissions reduction from deployment of options in 2050.
- **Steam and power production system upgrades:** This option is deployed to 100% by 2040. The option accounts for 14% of the total emissions reduction from deployment of options in 2050.

- **Improved site and sector integration:** This option is deployed to 25% by 2050. It accounts for 6% of total emissions reduction from deployment of options in 2050.
- **Shorter term options:** This option consists of a range of conventional options as well as innovative technologies also deployed under BAU pathway. Many of these options are taken away (‘undeployed’) by 2050, as their deployment rate is reduced at the end of the pathway. This ensures option savings are not double counted when disruptive rebuild options are deployed.

Figure 19 shows the absolute emissions reduction from the principal options along the pathway.

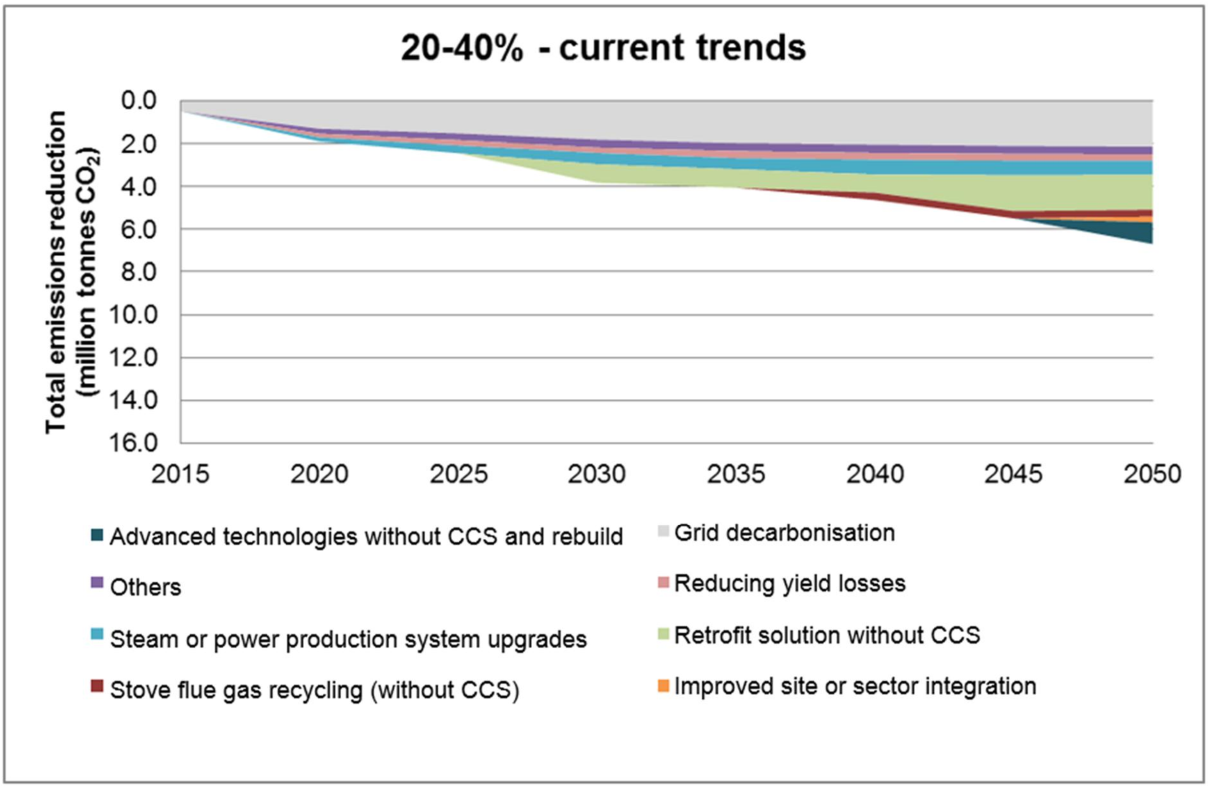


Figure 19: Contribution of principal options to the absolute emissions savings throughout the study period for the 20-40% CO_2 reduction pathway, current trends scenario

For the current trends scenario, the options deployed in the 20-40% reduction pathway give an overall reduction of 28% in 2050, compared to 2012. This includes the emissions reduction linked to the deployment of options and decarbonisation of the grid.

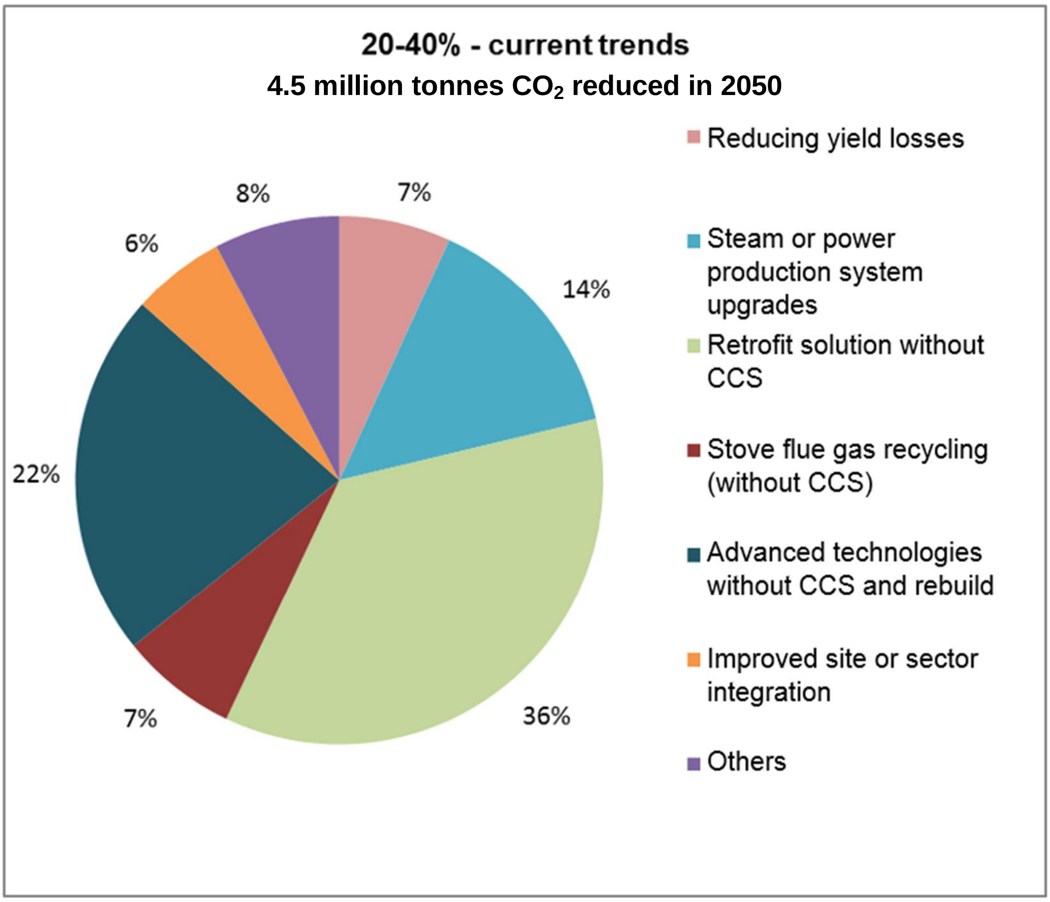


Figure 20: Breakdown of 2050 emissions savings, for the 20-40% CO_2 reduction pathway, current trends scenario

The CO_2 reduction contributions in 2050 are shown to mainly come from: retrofit solutions without CC, advanced technologies without CC, steam and power plant upgrades across the sector, stove flue gas recycling, and reducing yield losses (Figure 20).

Option Deployment for other Scenarios

The BAU pathway achieves over 40% reduction for the challenging world scenario so no additional 20-40% CO_2 reduction pathway was developed for that scenario.

The 20-40% CO_2 reduction pathway under collaborative growth builds on the deployment under current trends with an earlier deployment of retrofit solutions and off-gas recycling (without CC) from 2020-2025, retrofit with CC from 2030 ramping up to 50% in 2040, and advanced technology rebuild with CC integrated deployed by 2050.

4.4.3 40-60% CO_2 Reduction Pathway

Pathway Summary

The 40-60% CO_2 reduction pathway reaches a 46% CO_2 reduction compared to 2012 for the sector. The increased savings build on the 20-40% CO_2 reduction pathway by introducing CC options.

Deployment for the Current Trends Scenario

Figure 21 shows the option deployment for the 40-60% CO_2 reduction pathway for the current trends scenario.

OPTION	ADOPT.	APP.	DEPLOYMENT								
Short Term			2014	2015	2020	2025	2030	2035	2040	2045	2050
01 Heat Recovery & Re-use - Conventional Options	50%	88%	0%	25%	50%	75%	75%	75%	50%	50%	50%
02 Improved Automation & Process Control	20%	63%	0%	25%	50%	75%	100%	100%	100%	100%	100%
03 Hot Charging	3%	80%	0%	25%	50%	75%	100%	100%	100%	100%	100%
04 Fuel Substitution - coking plant	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
05 Improved Planning & Throughput Optimisation - sec processes	12%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
06 Installing VSDs on Electrical Motors (Pumps & Fans)	50%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
07 Pulverised Coal Injection (PCI)	85%	100%	0%	25%	25%	25%	25%	25%	25%	25%	25%
08 Reducing yield losses	40%	100%	0%	25%	50%	75%	75%	100%	100%	100%	100%
09 Scrap Densification / Shredding	35%	70%	0%	25%	50%	100%	100%	100%	100%	100%	100%
10 Compressed Air System Optimization	34%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
11 Re-heating Furnace Optimization	19%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
Short-Medium Term											
12 Near Net Shape Casting	10%	20%	0%	0%	0%	25%	25%	50%	50%	75%	75%
13 Use of premium efficiency electrical motors	13%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
14 Waste Heat Recovery - sintering	7%	100%	0%	25%	50%	75%	100%	100%	75%	75%	75%
15 BOF Heat & Gas Recovery	29%	100%	0%	0%	25%	50%	100%	100%	75%	75%	75%
16 Endless Strip Production (ESP)	0%	20%	0%	25%	25%	50%	75%	50%	50%	25%	25%
17 Heat Recovery from Cooling Water	0%	100%	0%	0%	25%	50%	75%	100%	100%	100%	100%
18 Steam / Power Production System Upgrades	32%	86%	0%	25%	25%	50%	75%	75%	100%	100%	100%
19 UHP Transformers	33%	75%	0%	25%	75%	100%	100%	100%	100%	100%	100%
20 Regenerative / recuperative burners - sec processes	54%	100%	0%	25%	25%	50%	50%	75%	75%	100%	100%
Medium Term											
21 Heat Recovery & Re-use - Innovative Options	0%	88%	0%	0%	0%	0%	25%	25%	50%	50%	50%
22 Improved Process Control - EAF	48%	100%	0%	0%	0%	0%	25%	25%	50%	75%	100%
23 Retrofit Solution without CCS	0%	100%	0%	0%	0%	0%	25%	25%	50%	50%	25%
24 Stove Flue Gas Recycling (without CCS)	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
25 Stove Flue Gas Recycling (with CCS)	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	25%
26 Increased EAF production share	Sensitivity test		0%	0%	0%	0%	0%	0%	0%	0%	0%
Medium-Long Term											
27 Coke Dry Quenching (CDQ)	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28 Retrofit Solution with CCS	0%	100%	0%	0%	0%	0%	0%	0%	25%	25%	50%
29 Advanced Technologies without CCS & Rebuild	0%	100%	0%	0%	0%	0%	0%	0%	25%	25%	25%
30 Improved site / sector integration	10%	50%	0%	0%	0%	0%	0%	0%	25%	25%	25%
31 Advanced Technologies with CCS & Rebuild	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
32 Advanced Electrolysis Techniques	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 21: Option deployment for the 40-60% CO_2 reduction pathway

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

- **Retrofit solutions with CC:** This option is deployed at 25% in 2040 and to 50% by 2050. It accounts for 52% of total emissions reduction from deployment of options in 2050.
- **Stove flue gas recycling with CC:** This option accounts for 12% of total emissions reduction from deployment of options in 2050.
- **Advanced technologies without CC and rebuild:** This option is deployed to 25% from 2040. The option accounts for 11% of total emissions reduction from deployment of options in 2050.
- **Retrofit solutions without CC:** This is a separate option deployed earlier in the pathway, from 2030. The option is mutually exclusive with the retrofit with CC option, so it is assumed the options apply to separate sites at any one point along the timeline. This is represented when the retrofit solutions without CC option is 'undeployed', that is turned down from 50% to 25% deployment in 2050, and the retrofit solutions with CC option is correspondingly deployed, that is deployed to 50% by 2050.

The sites using the retrofit without CC option account for 9% of total emissions reduction from deployment of options in 2050.

- **Improved site and sector integration:** This option is deployed to 25% from 2040. The option accounts for 3% of total emissions reduction from deployment of options in 2050.
- **Steam and power plant upgrade.** This option is deployed to 100% of the sector by 2040 and accounts for 7% of total emissions reduction from deployment of options in 2050.
- **Shorter-term options.** The range of short- and medium-term, incremental options are also deployed, some of which are later 'undeployed'. This ensures option savings are not double counted when disruptive options are deployed. The deployment of these options is similar to the BAU and 20-40% CO_2 reduction pathways.

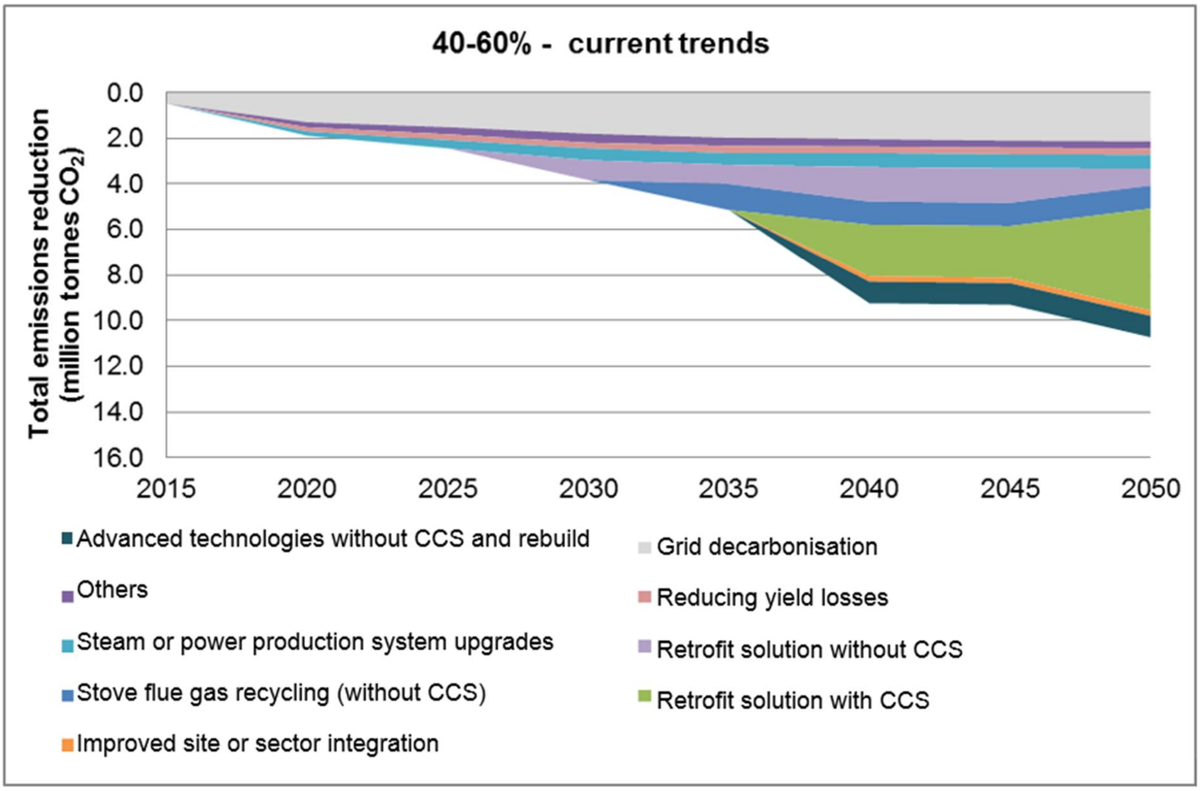


Figure 22: Contribution of principal options to the absolute emissions savings throughout study period, for the 40-60% CO_2 reduction pathway, current trends scenario

For the current trends scenario, this pathway gives an overall reduction of 46% in 2050, compared to 2012. This includes the emissions reduction linked to the deployment of options and decarbonisation of the grid.

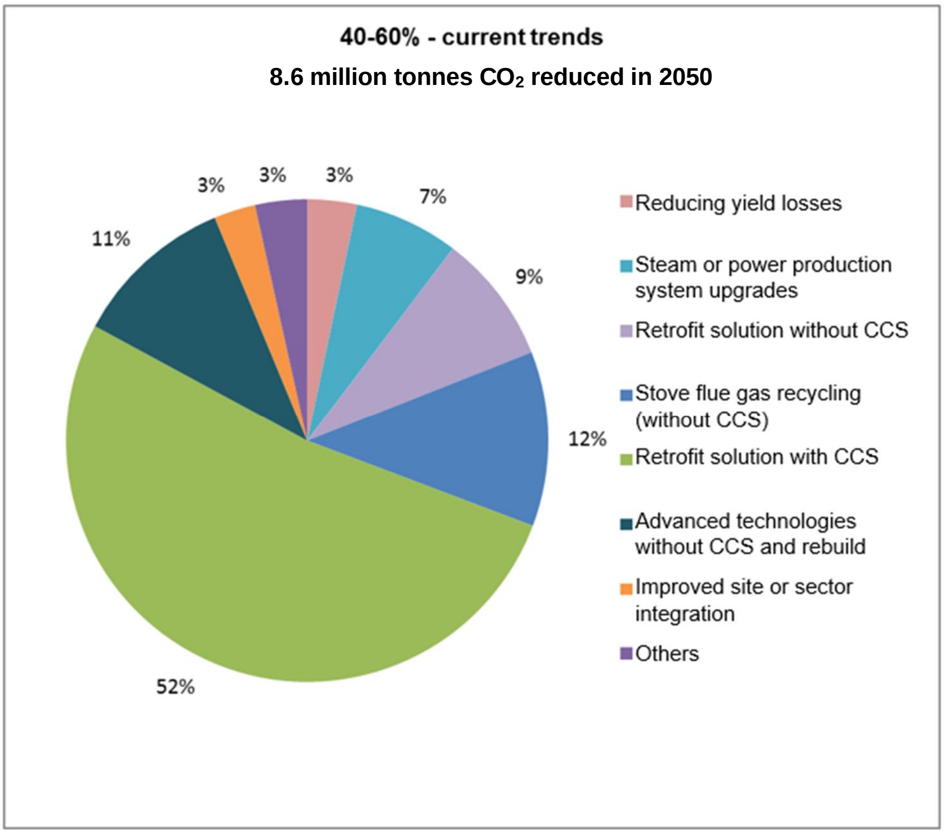


Figure 23: Breakdown of 2050 emissions savings, for the 40-60% CO_2 reduction pathway, current trends scenario

Most of the CO_2 reduction contributions in 2050 come from: retrofit solutions with CC, advanced technologies without CC, stove flue gas recycling with CC, retrofit solutions without CC and steam and power system upgrades (Figure 23).

Option Deployment for other Scenarios

The BAU pathway achieves over 40% reduction for the challenging world scenario so no additional 40-60% CO_2 reduction pathway was developed for that scenario.

The 40-60% CO_2 reduction pathway under collaborative growth builds on its deployment of options under current trends through early and wider adoption of CC. CC is started to be deployed by 2030, ramping up to 100% by 2050 (made up by 75% advanced rebuild with CC and 25% retrofit with CC to remaining sites).

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

4.4.4 Maximum Technical Pathway

Pathway Summary

The Max Tech pathway for the current trends scenario results in a 60% CO_2 reduction for the sector compared to 2012.

The option deployments include a complete expansion of CC across the sector from 2040. Half of the sector is retrofitted with CC and the other half is rebuilt using advanced technologies with CC.

Deployment for the Current Trends Scenario

Figure 24 shows the option deployment for the Max Tech pathway for the current trends scenario.

OPTION	ADOPT.	APP.	DEPLOYMENT 2014	2015	2020	2025	2030	2035	2040	2045	2050
Short Term											
01 Heat Recovery & Re-use - Conventional Options	50%	88%	0%	25%	50%	75%	75%	75%	50%	50%	50%
02 Improved Automation & Process Control	20%	63%	0%	25%	50%	75%	100%	100%	100%	100%	100%
03 Hot Charging	3%	80%	0%	25%	50%	75%	100%	100%	100%	100%	100%
04 Fuel Substitution - coking plant	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
05 Improved Planning & Throughput Optimisation - sec processes	12%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
06 Installing VSDs on Electrical Motors (Pumps & Fans)	50%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
07 Pulverised Coal Injection (PCI)	85%	100%	0%	25%	25%	25%	25%	25%	25%	25%	25%
08 Reducing yield losses	40%	100%	0%	25%	50%	75%	75%	100%	100%	100%	100%
09 Scrap Densification / Shredding	35%	70%	0%	25%	50%	100%	100%	100%	100%	100%	100%
10 Compressed Air System Optimization	34%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
11 Re-heating Furnace Optimization	19%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
Short-Medium Term											
12 Near Net Shape Casting	10%	20%	0%	0%	0%	25%	25%	50%	50%	75%	75%
13 Use of premium efficiency electrical motors	13%	100%	0%	25%	50%	75%	100%	100%	100%	100%	100%
14 Waste Heat Recovery - sintering	7%	100%	0%	25%	50%	75%	100%	75%	75%	75%	50%
15 BOF Heat & Gas Recovery	29%	100%	0%	0%	25%	50%	100%	75%	75%	75%	50%
16 Endless Strip Production (ESP)	0%	20%	0%	25%	25%	50%	75%	50%	50%	25%	25%
17 Heat Recovery from Cooling Water	0%	100%	0%	0%	25%	50%	75%	100%	100%	100%	100%
18 Steam / Power Production System Upgrades	32%	86%	0%	25%	25%	50%	75%	75%	100%	100%	100%
19 UHP Transformers	33%	75%	0%	25%	75%	100%	100%	100%	100%	100%	100%
20 Regenerative / recuperative burners - sec processes	54%	100%	0%	25%	25%	50%	50%	75%	75%	100%	100%
Medium Term											
21 Heat Recovery & Re-use - Innovative Options	0%	88%	0%	0%	0%	25%	25%	25%	50%	50%	50%
22 Improved Process Control - EAF	48%	100%	0%	0%	0%	25%	25%	50%	75%	100%	100%
23 Retrofit Solution without CCS	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
24 Stove Flue Gas Recycling (without CCS)	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
25 Stove Flue Gas Recycling (with CCS)	0%	100%	0%	0%	0%	0%	25%	25%	25%	25%	25%
26 Increased EAF production share	Sensitivity test		0%	0%	0%	0%	0%	0%	0%	0%	0%
Medium-Long Term											
27 Coke Dry Quenching (CDQ)	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
28 Retrofit Solution with CCS	0%	100%	0%	0%	0%	0%	25%	25%	25%	25%	50%
29 Advanced Technologies without CCS & Rebuild	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
30 Improved site / sector integration	10%	50%	0%	0%	0%	0%	0%	25%	25%	25%	50%
31 Advanced Technologies with CCS & Rebuild	0%	100%	0%	0%	0%	0%	0%	25%	25%	25%	50%
32 Advanced Electrolysis Techniques	0%		0%	0%	0%	0%	0%	0%	0%	0%	0%

Figure 24: Option deployment for the Max Tech pathway

In this pathway, the principal options that contribute to the emissions savings in 2050 are (Figure 25):

- **Advanced technologies with CC and rebuild:** This option is deployed to 25% in 2040, and increased to 50% by 2050 and accounts for 49% of the total emissions reduction from deployment of options in 2050.
- **Retrofit solutions with CC:** This option is applied to the other 50% of the sector by 2050. The option accounts for 31% of total emissions reduction from deployment of options in 2050.
- **Stove flue gas recycling with CC:** This option is deployed together with the retrofit solution, accounting for 8% of total emissions from deployment of options in 2050.
- **Steam and power production system upgrades** are deployed to 100% by 2040 and account for 5% of total emissions reduction from deployment of options in 2050.
- **Improved site and sector integration:** This option is deployed to 25% in 2040 and increased to 50% by 2050 accounting for 4% of the total emissions reduction from deployment of options in 2050.

- **Other short- and medium-term options** are deployed from 2015 as in the other pathways, but are then 'undeployed' from 2040 when the disruptive rebuild and retrofit options are deployed. This ensures that savings are not double counted. The deployment of these options is similar to the BAU, 20-40% and 40-60% CO_2 reduction pathways.

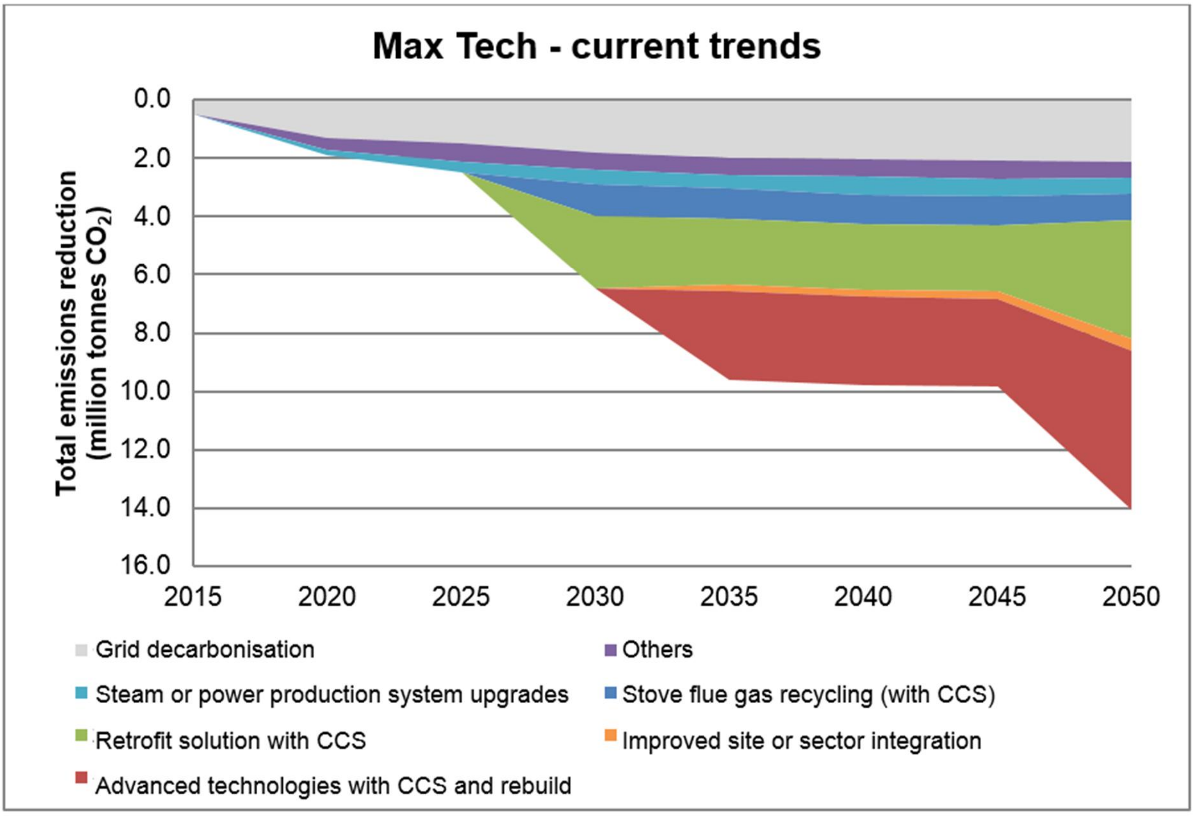


Figure 25: Contribution of principal options to the absolute savings throughout the study period, for the Max Tech pathway, current trends scenario

For the current trends scenario, this pathway gives an overall reduction of 63% in 2050, compared to 2012. This includes the emissions reduction linked to the deployment of options and decarbonisation of the grid.

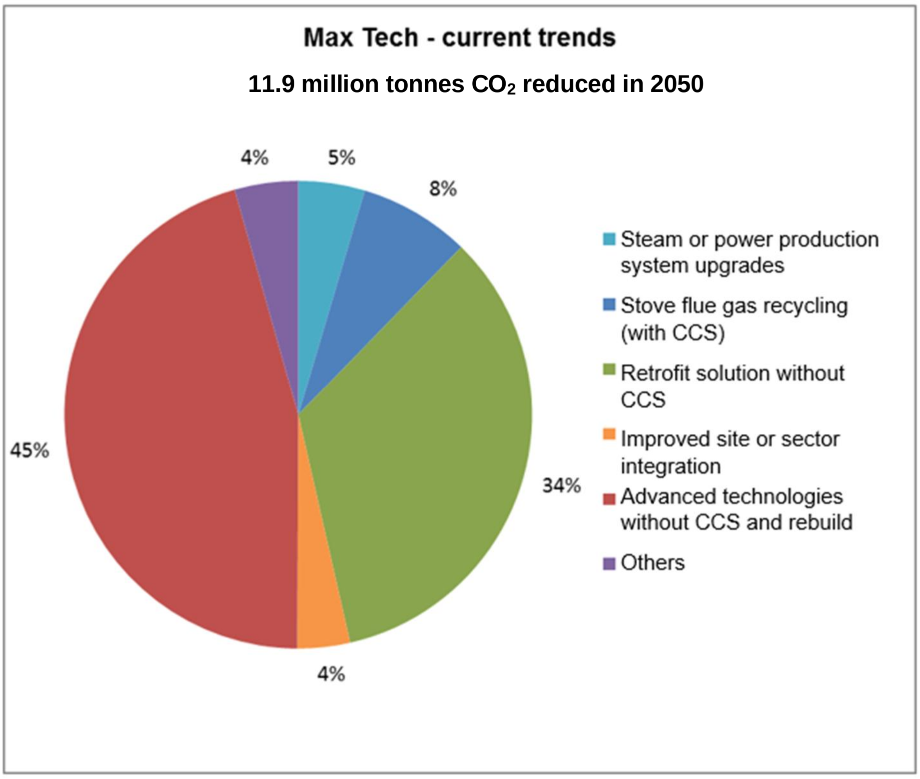


Figure 26: Breakdown of 2050 emissions savings, for the Max Tech pathway, current trends scenario

Most of the CO_2 reduction contributions in 2050 come from: advanced technologies with CC and rebuild, retrofit solutions with CC, and stove flue gas recycling with CC (Figure 26).

Option Deployment for other Scenarios

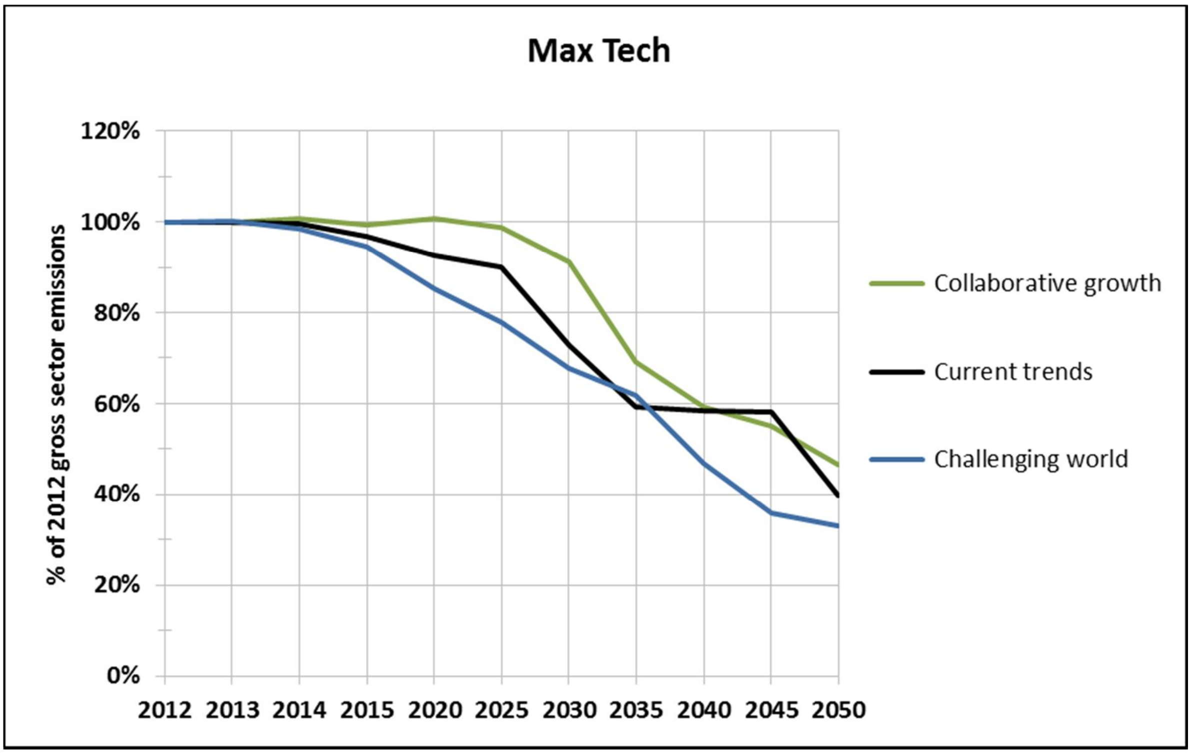


Figure 27: Max Tech pathway for the different scenarios

Figure 27 shows the Max Tech pathways for the different scenarios. As can be seen, the current trends scenario delivers a CO_2 reduction of 60%, the challenging world scenario delivers a CO_2 reduction of 67% and the collaborative growth scenario delivers CO_2 reduction of 53%.

For the challenging world scenario, retrofit with CC and advanced rebuild with CC options were deployed at a slower rate compared to the current trends scenario, only deployed to 25% by 2050.

In the collaborative growth scenario, advanced technologies with CC or rebuild of integrated production sites were deployed at a faster rate compared to the current trends scenario reaching a full 100% deployment by 2050. Retrofit CC is also deployed earlier in the pathway starting in 2030.

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

4.5 Sensitivity analysis

A number of sensitivities tests were performed on the model to examine the impact of various parameters and option constraints on emissions savings. For iron and steel it is particularly important to evaluate the consequences and alternatives to CC, as it is an important part of the higher decarbonising pathways. It is uncertain to what level the different sites can or will deploy CC and also if or when there will be a CC infrastructure in the UK. The following sensitivities were identified for the iron and steel sector:

- Shift in production from BF-BOF to EAF
- Improvement in material efficiency in the sector
- No CC available
- No CC available and full availability of bio-charcoal for PCI

- Full CC available and full availability of bio-charcoal for PCI

The results of the five sensitivities for the Max Tech pathway for the current trends scenario are shown in Figure 28.

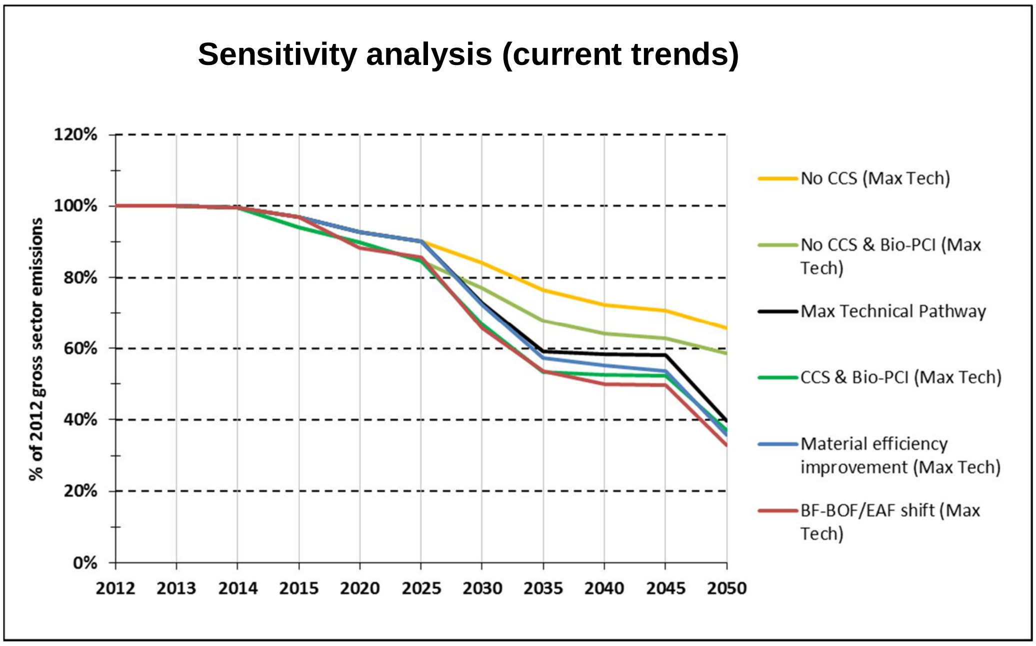
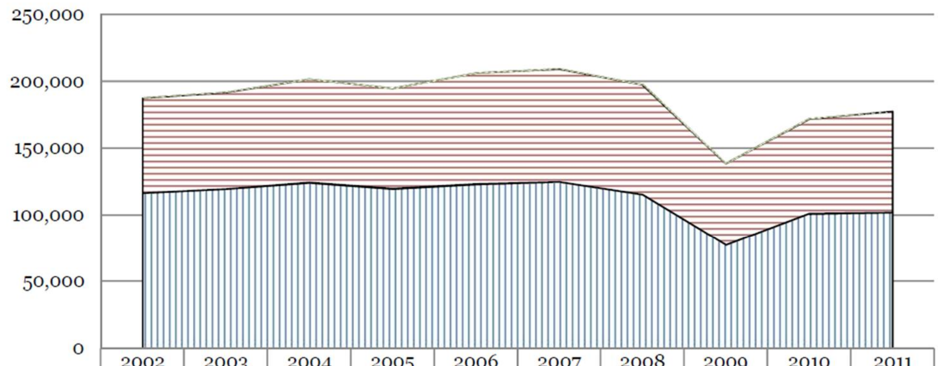


Figure 28: Sensitivity analysis BF-BOF/EAF split, current trends scenario

Electrolysis is an option and alternative to CC but it has not been part of this work as it is not yet sufficiently developed, but may become available in the future.

4.5.1 BF-BOF/EAF split

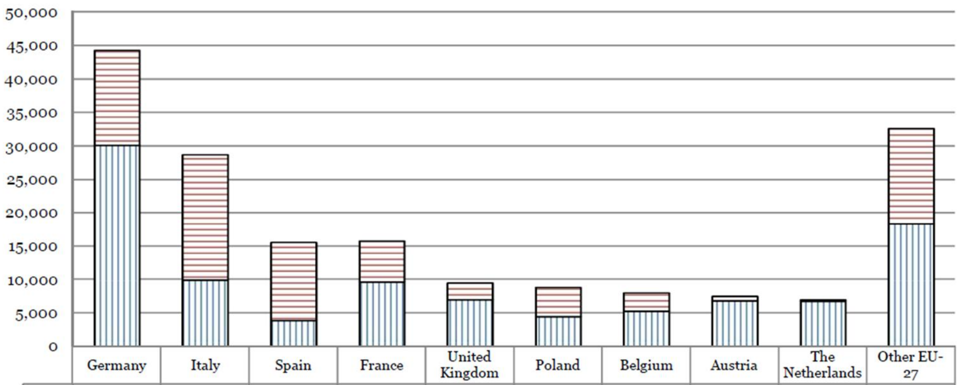
The evolution of steel production in Europe by different production routes is shown in Figure 29. As can be seen, the overall share of EAF has remained quite stable with a small increase of EAF over time. It is likely that this is due to the economic crisis that has closed more of the BF-BOF production facilities in 2009 rather than an increase in EAF production. Nevertheless, in 2002, about 62% of total production was carried out in BF-BOF, 38% in EAF. In 2012, EAF accounted for about 43% of steel produced and BF-BOF for 57%.



	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
OHF	525	518	660	686	688	696	635	692	655	0
EAF	71,054	72,194	77,257	74,987	82,957	84,626	82,223	61,156	71,014	75,683
BOF	116,665	119,800	124,411	119,830	123,277	124,857	115,338	77,518	101,118	101,991

Figure 29: EU production (in thousand tonnes) of crude steel by steelmaking technology (OHF = open hearth furnace) 2002-2011 (Egenhofer et al., 2013)

On average, there is a higher share of total steel production manufactured by EAF in Europe than in the UK. In 2012, 78% of the production is by BF-BOF and 22% from EAF for the UK. The comparison between selected EU Member States can be seen in Figure 30.



	Germany	Italy	Spain	France	United Kingdom	Poland	Belgium	Austria	The Netherlands	Other EU-27
EAF	14,204	18,843	11,660	6,128	2,532	4,378	2,773	689	172	14,304
BOF	30,079	9,892	3,844	9,652	6,946	4,446	5,253	6,785	6,765	18,329

Figure 30: Production of crude steel (in thousand tonnes) by steelmaking technology in selected EU member states in 2011

To see the impact of changing production from BF-BOF to EAF in the decarbonisation and energy efficiency pathways, the EAF was increased by 5 percentage points every ten years starting in 2020 and the BF-BOF was reduced correspondingly. In 2012, EAF contributed to 22% of UK steel production, in 2013 this share had decreased to 17%. This share was kept constant in the sensitivity analysis until 2020, and then increased to 22% again for the next ten years. In 2030, the EAF share was increased again to 27% and kept constant until 2040. Finally, the EAF share was increased again for the last ten-year period up to 32%, and reaching 37% in 2050. This led to a 63/37% split (BF-BOF/EAF) in 2050 that approaches the European average of 2012 (57/43%). Figure 31 shows the results of this sensitivity analysis on the different pathways for the current trends scenario.

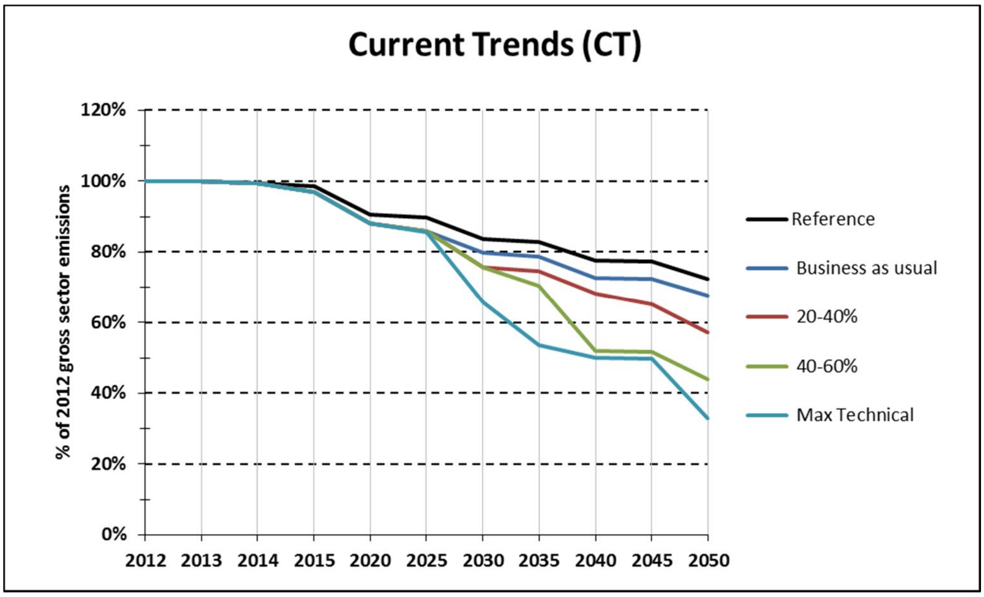


Figure 31: Sensitivity analysis BF-BOF/EAF split, current trends scenario

By shifting to EAF production, the electricity use increases and the direct emissions from BF-BOF decrease. As the grid is decarbonised, this shift from BF-BOF to EAF leads to an overall reduction of emissions.

In general, option deployment is not adjusted for this sensitivity analysis. However, the option savings related to the BF-BOF subsector are reduced, due to the reduced production of BF-BOF steel. This means that the need for CC and installations of other disruptive options is decreased as well. The net result of increasing the percentage of steelmaking by EAF is a Max Tech pathway delivering a 67% reduction in emissions compared to 2012, compared to the 60% that the Max Tech pathway achieves. Similar improvements can be seen across the different pathways.

Adjusting the BF-BOF/EAF split is potentially a significant option to reduce carbon emissions, but it indicates a switch to electricity (with perceived higher relative costs and competitiveness issues), reliance on grid decarbonisation, reliance on scrap availability and affordability plus an increase in demand from the electricity grid potentially requiring investment elsewhere.

4.5.2 Material Efficiency

Steel production includes two key components: iron ore and recycled (scrap) steel. In order to identify all opportunities to reduce carbon emissions from steel, it is essential to take a full life cycle approach (see Figure 32), not only considering the emissions associated with the manufacture of steel products, but also the reduction in energy consumption from the use of new-generation steels in lighter and stronger products (Worldsteel, 2014).

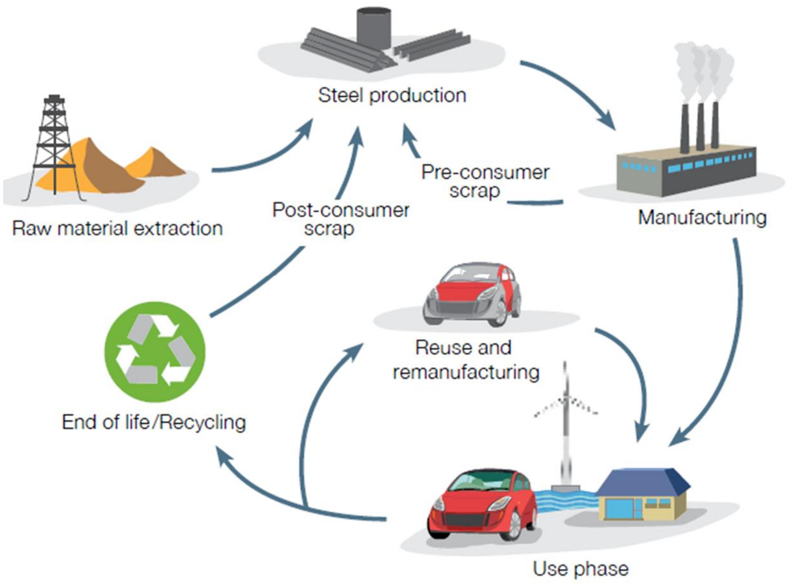


Figure 32: Steel life cycle (Worldsteel, 2014)

Material efficiency is described as the ratio of material service delivered over the new material that is being produced, aiming to deliver the same quality or level of steel services with less new steel input. There are six different strategies to increase material efficiency (Allwood, 2013): increasing light-weight design, reducing yield losses (by improving yield ratios along the supply chain), diverting manufacturing scrap to avoid the high energy use involved in melting for recycling, re-use metal components without recycling, longer-life products (by delaying end-of-life by using building and products longer), and using products more intensively.

An increased rate of scrap recycling was already modelled in the previous sensitivity on the BF-BOF/EAF split. According to Worldsteel (2014), 94-98% of raw materials used to make crude steel are converted to products and by-products, sending only very little waste to incineration or landfill. In this section, material efficiency is therefore focused on re-use without re-melting and product innovation for light-weight design.

Re-use of steel products involves the re-use with little or no re-processing, and offers greater environmental advantages than recycling. As an example, re-using a steel beam in its existing form is better than re-melting it and rolling a new beam, because the energy for re-melting is saved. Some products are more amenable to re-use than others, and therefore designers should be encouraged to think about this re-use in the design of new products (Milford, 2010).

One example of material efficiency is moving to higher-value steel products and more efficient steel use, resulting in delivering the functions of steel (such as stability and strength) with less weight. Since CO_2 emissions from steel production are largely proportional to its weight, this would reduce total emissions (Allwood et al., 2011). Developments differ significantly across the main applications of steel. In the automotive sector, innovative high-strength steel and forming techniques have achieved about 30-40% savings in body weight since 2005 (Zuidema, 2012) and it is estimated that a further 17-25% of the weight of the body in white could be reduced in the future (Worldsteel, 2008). In the construction sector, no such progress has been made (Giesekam et al., 2014), despite studies showing that efficient steel use in building is possible by using tailored shapes, supporting multiple loads with fewer structures, aligning loads to avoid bending, or avoiding over-specifications of loads (Allwood et al., 2012). A recent study by Moynihan and Allwood (2014), assessing 23 case studies of steel framed buildings in the UK, found that 36% of a building's beam mass could be removed without any loss of safety.

To evaluate the impact of material efficiency, we have added a sensitivity analysis to our model, reducing the amount of new steel produced. This could have a big impact on the sector emissions but it would have many other consequences for the economy as well, which need to be considered: these consequences are no technically challenging strategies, but would change the way steel is produced and used in the UK with its associated macro-level impacts such as employment and sector-level output In this work we have only tested material efficiency from an emissions perspective.

We have reduced the overall output of the sector by 0.5% annually to represent material efficiency starting from 2030. This would mean that material efficiency represents 10% of the sector's output by 2050. This reduces the emissions from each one of the pathways. The option deployments are kept constant to the current trends scenario. The net result from the improved materials efficiency for the Max Tech pathway is a 64% reduction by 2050 from the 2012 level compared to the 60% that the Max Tech pathway achieves. Similar improvements can be seen across the different pathways. The pathway results for this sensitivity under the current trends scenario are shown in appendix D.

4.5.3 No Carbon Capture

To evaluate the impact of the iron and steel sector reliance on CC, a third sensitivity analysis was performed. This third case is a Max Tech pathway with no CC options deployed, that is, no deployment of retrofit and advanced rebuild with CC. Retrofit solutions and advanced rebuild options without CC are extended, each deployed to 50% by 2050. All other options are kept as in the regular Max Tech pathway. This deployment leads to a 34% reduction compared to 2012. This is a significant reduction in emissions reduction performance compared to the 60% that the regular Max Tech pathway achieves, which demonstrates the high reliance on CC for decarbonisation. The pathway results for this sensitivity under the current trends scenario are shown in appendix D.

4.5.4 Biomass and no Carbon Capture

This sensitivity analysis intends to evaluate the potential CO_2 reduction by using biomass instead of coal in the BF. This sensitivity also removes the deployment of CC to evaluate the sector's decarbonisation potential without CC. To use biomass for steel making, biofuels could be introduced in the BF, which can be done through three different routes: (i) solid biofuels as partial replacement for top coke, (ii) blending of biomass during coke making to produce bio-coke, and (iii) use of biofuels as partial or complete replacement for pulverised coal through injection (PCI). Raw biomass cannot be used directly in any of the routes, given its high-moisture and volatile content, and its low energy density. Biomass needs to be upgraded before use, which can be done e.g. by pelletisation, pyrolysis, torrefaction, steam explosion, hydrothermal carbonisation or anaerobic digestion. Currently, only pelletisation and pyrolysis are commercialised (Wang et al., 2013).

To include a sensitivity analysis in our model of the use of biomass in steel production, we have considered bio-PCI: injecting pulverised charcoal from biomass to replace coal. A very recent model (Feliciano-Bruzual, 2014) used actual BF operational parameters from nine different highly fuel-efficient plants (see Figure 33) to calculate the CO_2 reduction potential of using bio-PCI, considering a complete substitution of coal. This model shows CO_2 reductions accounting from 0.28 to 0.59 tonnes of CO_2 per tonne hot metal, resulting in 18-40% saving potential, when bio-PCI is used instead of fossil coal and natural gas.

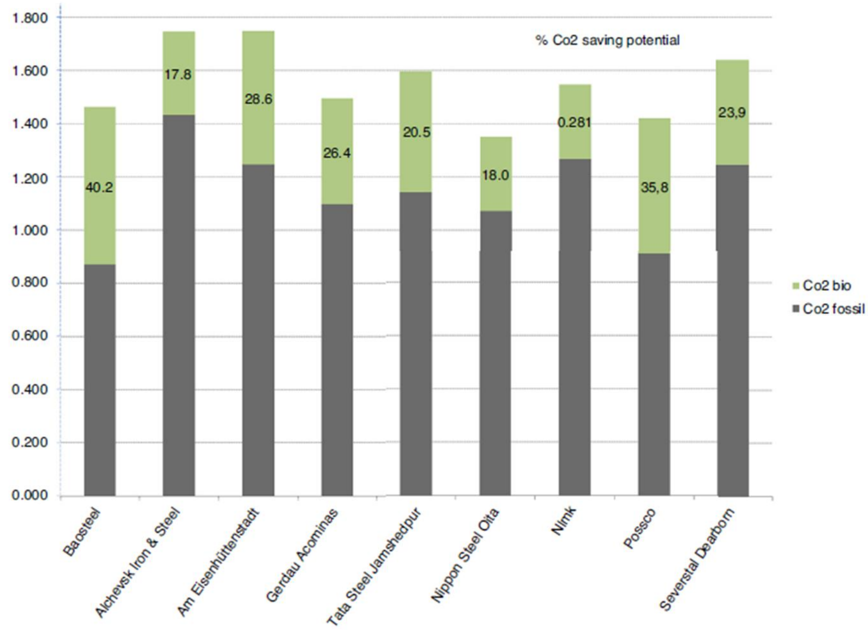


Figure 33: CO_2 reduction potential using bio-PCI (Feliciano-Bruzual, 2014)

The sensitivity analysis to include biomass used the average of the CO_2 reductions mentioned above, i.e. a 29% reduction potential. This is consistent with a recent UK study where the CO_2 reduction potential was identified as 28% from the BF by replacing coal-PCI by bio-PCI (DECC, 2014). However, given that this value assumes biomass to be carbon neutral (i.e. carbon intensity of 0.0 kg CO_2e/kWh), the CO_2 reduction is slightly adjusted in light of an agreed approach for the present study – which assumes an emission factor of bio-char to 0.025 kg CO_2e/kWh. The 29% value is therefore adjusted down by factor of 0.088 (i.e. the ratio of biomass to coal carbon intensity), giving an input CO_2 reduction of 25.5% for the bio-PCI option.

In this sensitivity, the bio-PCI option is deployed from 25% in 2015 to 100% by 2035 and onwards by replacing coal in the Pulverised Coal Injection option. As bio-coal has a higher volatility than metallurgical coal, it seems like bio-PCI is compatible with complete rebuild options such as HIsarna (Meijer et al., 2011; and Kiuru and Hyytiäinen, 2013). This deployment leads to a 41% reduction compared to 2012. This represents a reduced performance compared to the regular Max Tech, as it has no CC; it does, however, increase the performance compared to the Max Tech pathway with no CC that only achieves a 34% reduction compared to 2012.

4.5.5 Biomass and Carbon Capture

The fifth sensitivity case tested here is full availability of CC with the addition of bio-PCI. The option deployment follows the same deployment as the regular Max Tech with the addition of bio-PCI. The bio-PCI is deployed from 25% in 2015 to 100% by 2035 and onwards. This deployment leads to a 63% reduction compared to 2012 compared to the 60% that the regular Max Tech pathway achieves. The pathway results for this sensitivity under the current trends scenario are shown in appendix D.

In the option interaction calculation, the ‘no interaction’ case adds approximately 20% to the carbon reduction in 2050 in the Max Tech pathway.

4.6 Pathway Costs

4.6.1 Introduction

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

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

4.6.2 Calculation of Pathway Costs

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

1. Capital costs of deployment for each decarbonisation and energy efficiency option are calculated based on the order of magnitude capital costs to deploy that option at one site (or installation or unit of equipment). This is then deployed to the applicable number of sites (or installations or units of equipment) for the (sub)sector in the pathway as defined by the model.
2. Capital costs reflect the additional cost of delivering the carbon dioxide and/or energy reduction options compared to continuing production without deploying the options. For a number of major

investment options, including replacement of life-expired assets with BAT (for a list of options in this category see appendix C), only a proportion of the cost is assumed to be attributed to carbon dioxide emission or energy reduction, as a significant factor for the investment in this case would be to replace retiring production capacity and to recognise that options may be implemented for reasons other than decarbonisation or energy efficiency. In the absence of detailed information this proportion (attributed to the capital cost calculation in this analysis) is assumed to be 50%. For all other technology options the entire capital cost (i.e. 100%) is attributed to energy or carbon reduction. Capital costs are applied at the year of each deployment step (as modelled in the carbon reduction pathways), and adjusted in cases where the asset life defined in the option register would extend beyond 2050 to reflect their residual value on a linear depreciation basis.

3. The annual capital expenditure of each pathway is calculated from the capital cost and deployment of each of the options selected. Capital costs are presented in present day value (i.e. 2015) and assumed to remain constant throughout the period. The discount rate for costs has been chosen to be 3.5% to value the costs from a social perspective and in accordance with standard HM Treasury methodology for this type of assessment. In other words, all proposed capital expenditure on the various pathways are adjusted for the time value of money, so costs (which occur at different points in time) are expressed on a common basis in terms of their 'net present value' using the discount rate of 3.5%. The effect of this standard methodology is to reduce the apparent cost of large investments that are deployed in the pathways later in the study period.

The following specific assumptions apply:

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

4.6.3 Limitations

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

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

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

- The values are a starting point to help assess relative benefits of different technologies over the long term.
- The cost analysis results should not be used in isolation to compare decarbonisation technologies or decide on priorities for their development: additional techno-economic analysis should be carried out on individual options or groups of options.
- The cost analysis is part of a process of research and exploration and is being shared in a transparent way to support the development of broader strategy. The results are effectively provisional order of magnitude estimates which need to be developed further on the basis of thorough research before they can be used to inform decisions.

4.6.4 Cost Analysis Results

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

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

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

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

Pathway	Total Discounted Capital Cost 2014-2050 (million £)[15]	Cumulative CO_2 Abated 2014-2050 (million tonnes CO_2)[16]	Projected Impact on Fuel or Energy use and Fuel or Energy cost
BAU	300	26	This pathway includes deployment of options such as stove flue gas recycling, steam or power upgrades and reduced yield losses. In the study period 2014-2050, this pathway would result in a reduction in energy and fuel used. The projected value of this saving will depend on the fuel cost forecast adopted.
20-40%	400	32	This pathway includes deployment of options such as retrofit solution and installation of advanced technologies. In the study period

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

			2014-2050, this pathway would result in a potential reduction in energy and fuel used. The projected value of this saving will depend on the fuel cost forecast adopted.
40-60%	500	87	The carbon reduction in this pathway is dominated by carbon capture. This is projected to result in an overall increase in energy use and therefore increased energy costs are projected. The scale of the increased cost would depend on the fuel cost forecast adopted.
Max Tech	600	122	The carbon reduction in this pathway is dominated by carbon capture. This would result in an overall increase in energy use and therefore increased energy costs are projected. The scale of the increased cost would depend on the fuel cost forecast adopted.

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

4.7 Implications of Enablers and Barriers

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

- Shorter-term options
- Heat recovery with advanced technologies
- Retrofit and rebuild solutions without CC
- CC

From the evidence gathered during the project (from literature, interviews and workshops) there are a number of Enablers and Barriers associated with these options. These are discussed below.

4.7.1 Shorter-term options

This option is a grouping of several incremental technology options such as improved automation and process control, improved planning and throughput optimisation, installing VSDs on electrical motors, compressed air system optimisation. These options have the biggest impact on the BAU and 20-40% CO_2 reduction pathways.

Although implementing all of these shorter-term options together would contribute to significant carbon emissions savings, there are specific barriers which need to be overcome such as the shareholders demanding quick paybacks (less than two years) and availability of capital. Also, the sink costs in some technologies and their long lifespan could be another hurdle for these shorter-term options.

Enablers	Link between environmental and safety issues in investment projects Increasing regulation Cost of carbon
Barriers	Shareholders demand quick payback Availability of capital or competition for funds Slow rate of capital stock turnover

4.7.2 Heat Recovery with Advanced Technologies

This option is a future technology option that impacts all the pathways, and is therefore an important technology. It is assumed that it will start to be deployed in 2030, but it is still in the demonstration phase and has not yet been adopted by any steel manufacturer in the UK. Organic rankine cycles (ORC), or Kalina cycles, have not yet been deployed due to several barriers including long payback time (between six and ten years) and high capex requirements. To overcome these barriers, government could support knowledge sharing, demonstration projects, and funding from existing governmental schemes could be earmarked to support demonstration projects. For BOF heat and gas recovery and waste-heat recovery, the amount recovered will be linked to the technologies' location and interactions with other options.

Enablers	Increasing regulation Cost of carbon and its application to all steel producers
Barriers	Shareholders demand quick payback Availability of capital or competition for funds Slow rate of capital stock turnover

4.7.3 Retrofit and rebuild solutions without CC

This option is to retrofit the furnaces without CC including TGR, and is being deployed in the BAU and 20-40% CO_2 reduction pathways. Rebuild solutions such as HIsarna, Finex and Corex are only being deployed in the Max Tech pathway. The key barrier to retrofitting or doing a complete rebuild is the large cost associated with it; this is linked with both the barrier for shareholders demanding quick payback but also the availability of capital. As some of the technologies need further research and would replace equipment with a very long lifespan there is an additional barrier of slow rate of capital stock turnover that would apply to these retrofit solutions.

Many different routes for low-carbon steel manufacturing were explored through the ULCOS project, but a planned retrofit (ArcelorMittal plant in Florange in France) has fallen through as funding has not been secured. Sharing costs across a consortium of industry, research institutions, and government bodies may help mitigate the RD&D barrier, as would sector or trade association execution of feasibility studies. New and innovative financing options would be needed to make the necessary investments.

Enablers	Increasing regulation Cost of carbon and its application to all steel producers
Barriers	Shareholders demand quick payback Availability of capital or competition for funds

4.7.4 Carbon Capture

For CC, key barriers include the significant investments required. The technology is still seen as unproven or uncertain and is limited to specific geographies (which can also be an enabler). Capex requirements are very high, and there is limited business appetite to invest in large capex projects given the lack of capital available. Payback periods can be very long or even non-existing, as low carbon prices might not cover additional energy requirements. Cost of carbon can in this case be both a barrier and an enabler. Despite these challenges, companies located close to the North Sea coast are well placed from a geographical perspective to implement CC, and the UK is well placed to leverage the research from ULCOS for a demonstration plant. Improving the commercial attractiveness for investments in the transport infrastructure required to support CC can also help mitigate these barriers.

Enablers	Increasing regulation

	Cost of carbon and its application to all steel producers Location near to CCS infrastructure
Barriers	Shareholders demand quick payback Availability of capital or competition for funds Regulatory uncertainty Increasing cost of carbon and uneven playing field

5. CONCLUSIONS – PRINCIPAL QUESTION 6

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

The section is structured as follows:

- Eight 'strategic conclusions' or themes have been developed by analysing the main enablers and barriers. Example next steps or potential actions are also included for each strategic conclusion.
- Six key technology groups are discussed, many of which link to the themes above. As described in section 4, a small group of technologies make a significant contribution to decarbonisation in 2050, especially for Max Tech savings[17]. Example next steps are included to assist with developing, funding and implementing the technologies.

It is intended that government and industry use the roadmap to develop and implement an action programme in support of the overall aim of decarbonisation while maintaining competitiveness in the sector.

5.1 Key Points

During the development of potential pathways to decarbonisation, the barriers to their implementation and enablers to promote them were summarised in section 4.6. Having cross-referenced the enablers and barriers through three different research methods, we have summarised the main points in key strategic conclusions (or themes) and key technology groups.

Strategic Conclusions

Strategy, Leadership and Organisation

The scale of change and investment required to meet the carbon reduction challenge require a strategy to be developed and pursued through leadership and organisation. This links to all other conclusions below, including research, development and demonstration (RD&D), energy supply and business case barriers.

Business Case Barriers

One of the most important barriers to decarbonisation and energy efficiency, based on the literature, interviews and workshops, is lack of funding for investments as the return of investment is not attractive enough or there is a lack of capital available.

Future energy costs, energy supply security, market structure and competition

The UK energy supply system will influence company decisions to invest in the sector. In the absence of a global price on carbon, it is important that these competitiveness risks to UK industry are assessed and managed when designing approaches to reduce emissions.

[17] These technology groups apply to the iron and steel sector and also the other seven sector roadmaps.

Industrial Energy Policy Context

Given the highly competitive market for steel, and international ownership of many UK sites, along with the significant investment challenge facing the sector to reduce emissions, the policy context needs to carefully balance industrial regulation and investment support. Many in the sector have emphasised that a long-term energy and climate change policy framework alongside policy support for industrial competitiveness is key to investor confidence.

Life-Cycle Accounting

Improvements in standardised carbon accounting methodologies enable measurement, valuation and comparison of steel products, and facilitate the iron and steel sector to differentiate their products produced using low carbon options. Work to develop standardised methodologies will benefit from involving academia, industry and government, as well as the value chain.

Value Chain Collaboration

Steel customers primarily make purchasing decisions based on cost for service delivery, rather than on carbon emissions. Many of the technology combinations illustrated by the pathways analysis are likely to incur additional production costs for the steel manufacturers. In addition there is potential for steel services to be delivered with enhanced material efficiency. A viable business model could be developed to achieve these pathways through value chain collaboration.

Research, Development and Demonstration

In order to realise significant decarbonisation in the sector, deployment of medium to longer term technology is needed. Some of the decarbonisation options identified in this work require further technology innovation and development before commercial scale demonstration can be considered.

People and Skills

This strategic conclusion supports a number of themes, for example, people need the right skills to develop the investment business case for new projects, to deploy options and also to research and develop new technologies. The iron and steel sector’s carbon reduction will be dependent on a skilled and knowledgeable workforce in the UK.

Key Technology Groups

Electricity Grid Decarbonisation

As shown in this work, the decarbonisation of electricity supply has an important contribution to make to overall sector decarbonisation. Various projections for electricity decarbonisation are incorporated here and these would need to be achieved to deliver significant levels of emission reduction.

Electrification of Heat

Electrification of heat can deliver emissions reductions in the iron and steel sector through an increased proportion of steel production via the EAF route. The potential for emissions reductions by increasing the share of EAF produced steel, has been assessed through a sensitivity analysis. The extent to which this option can be utilised is also highly dependent on the costs and availability of scrap as well as the demand for the types of steel produced by EAFs. The level of decarbonisation from these options is also dependent on the level to which the grid is decarbonised.

Fuel and Feedstock Availability (Including Biomass)

Biomass provides a possible opportunity for the iron and steel industry to decarbonise, as illustrated in the biomass sensitivity analysis, resulting in a potentially significant decarbonisation. However, at present, the use of biomass as a significant decarbonisation option is considered to be a low priority, given uncertainty about cost, availability of biomass and the need for further technical demonstration in the UK.

Energy Efficiency and Heat Recovery

As identified in this work, shorter term options are only partly implemented to date. Accelerated deployment of energy efficiency options can bring operational benefits including life cycle cost savings, however their investment continues to compete with other investment opportunities as companies are capital constrained.

Clustering

Improved site and sector integration could deliver significant emissions reductions in the iron and steel sector. Many of these technical options could be enabled by further industrial clustering around existing iron and steel sites.

Carbon Capture

As the pathways and sensitivity analyses show, CC technologies are expected to play a key role in a decarbonised iron and steel sector. There are a range of specific technologies which could deliver the emissions reductions, the best technology will need to be identified through research, development and demonstration.

5.2 Strategic Conclusions

5.2.1 Strategy, leadership and organisation

The scale of change and investment required to meet the carbon reduction challenge require a strategy to be developed and pursued through leadership and organisation. This links to all other conclusions below, including research, development and demonstration (RD&D), energy supply and business case barriers.

Strategy provides long-term aims and a plan of action of how to achieve the aims. The constructive collaborative approach seen between government, industry and academia during this project could be continued to develop an overall strategic approach for delivering emissions reductions in this sector. Government, industry and academics could continue to work together to take forward delivery of actions agreed as a result of this work. The strategic approach could also emphasise the links with the economic value of iron and steel production for the UK including its use in delivering products for the low carbon transition. Continued engagement between these parties will enable them to take the roadmap forward with shorter-term action plans, for example, in five-year intervals.

The UK iron and steel sector could also all benefit from developing longer term strategies for emissions reductions which are integrated with their investment strategies to time major carbon reduction investment, consistent with the pathways developed, with their overall investment approach. A strategic approach to developing alternative investment models, research, development and demonstration could also lead to increased decarbonisation of the sector.

Leadership is required to drive delivery. At an international level, the UK can use its evidence base on the potential for emissions reduction in the iron and steel sector to lead the case for decarbonisation. There could be a role for members of the UK iron and steel sector to lead the international iron and steel sector decarbonisation effort, and benefit from market advantage that this could bring. With the UK iron and steel sector, there is a potential opportunity for individual companies to demonstrate leadership through life cycle accounting on their products and publication of long term strategies for emissions reduction.

5.2.2 Business Case Barriers

The business case for significant investment in carbon reduction is not yet clear for the iron and steel sector. The R&D, demonstration and commercial deployment of major technologies requires significant capital expenditure as well as potentially incurring additional operating costs.

One of the most important barriers to decarbonisation and energy efficiency, based on the literature, interviews and workshops, is lack of funding for investments as the return of investment is not attractive enough or there is a lack of capital available (see barriers number 2 and 3 in Table 7 in section 3.4.5). While this is not the only barrier to implementation of decarbonisation and energy efficiency projects (others include risk of implementing new technology, lack of skills, lack of management time), it is an important issue. The EU Emissions Trading System (EU ETS) has created a market that aims to incentivise energy efficiency and carbon reduction. The current programme of developing reforms to the EU ETS intends to support emitters to meet the carbon reduction challenge. Where market failures persist, the UK government could consider further support to the sector to encourage and enable it to meet policy objectives, for example through support for specific technologies. Support for research, development and demonstration of technologies is covered below (see 5.2.7).

The long term trajectory of higher CO_2 costs presents a clear challenge for the European and particularly UK iron and steel sector until there is a global climate change agreement and a multilateral commitment to CO_2 pricing.

5.2.3 Future energy costs, energy supply security, market structure and competition

The sector's investment in decarbonisation and energy efficiency should not adversely affect the position with respect to overall cost-competitiveness of the UK sector compared to competing businesses operating in other regions of Europe, and the world. This strategic conclusion links to a number of external factors that influence the business environment in which the sector operates. These include energy security and energy cost comparison to other regions (both reality and perception), as these factors are important when investment decisions are made (see section 3.4.3). There is a role for government in recognising the importance of and the link between energy security to investment decisions made by companies in the UK iron and steel sector. The UK energy supply system will influence company decisions to invest in the sector (especially those investments that rely on secure competitive energy supply).

It could prove difficult to develop a credible and long term business case for significant investment in decarbonisation if it could not be demonstrated that this could lead to some competitive advantage over steel producers that have not taken action to reduce emissions. The UK's commitment to meet the challenge of climate change will best be achieved within a global agreement to limit carbon emissions. In the absence of a global price on carbon, it is important that these competitiveness risks to UK industry are assessed and managed when designing approaches to reduce emissions.

5.2.4 Industrial energy policy context

Given the highly competitive market for steel, and international ownership of many UK sites, along with the significant investment challenge facing the sector to reduce emissions, the policy context needs to carefully balance industrial regulation and investment support. Many in the sector have emphasised that a long-term energy and climate change policy framework alongside policy support for industrial competitiveness is key to investor confidence, as identified in the findings section of this report (see section 3.4.4 and 3.4.5).

Regulatory uncertainty has been identified to be a barrier (see barrier 7 in Table 7 section 3.4.5). Many in the sector have emphasised that investments associated with the more ambitious pathways will require long-term commitment to policy support, particularly when the business case for investment is marginal.

It is important to recognise the wider regulatory landscape in which the steel sector operates. Where possible, efforts should be made to assess the regulatory burden placed on the sector as a whole.

5.2.5 Life-cycle accounting

Improvements in standardised carbon accounting methodologies enable measurement, valuation and comparison of steel products, and facilitate the iron and steel sector to differentiate their products produced using low carbon options. Work to develop standardised methodologies will benefit from involving academia, industry and government, as well as the value chain.

Agreed life-cycle accounting methodologies could enable some of the actions under value chain collaboration (see 5.2.6). On the basis of agreed methodologies, there may be a market for user-friendly tools for evaluating life-cycle carbon impacts of steel for different markets (e.g. construction, automotive).

5.2.6 Value chain collaboration

As identified in 3.4.2 and 3.4.5, steel customers primarily make purchasing decisions based on cost for service delivery, rather than on carbon emissions. Many of the technology combinations illustrated by the pathways analysis are likely to incur additional production costs for the steel manufacturers. Further, there is potential, illustrated by the pathways sensitivity analysis in 4.5.2, for steel services to be delivered with enhanced material efficiency (through for example light-weighting end-use components, or reuse of products). A viable business model could be developed to achieve these pathways through value chain collaboration.

Initially, steel companies might benefit from raising awareness within their value chain of the potential to manufacture steel with lower carbon emissions.

Extending the current EU requirement for energy labelling of consumer white goods to manufactured goods, combined with joint PR to increase awareness of the label, could change the market perspective of low carbon steel. Further, an enhanced Government procurement approach could then take into account these eco-labels, procuring lower carbon steel to lead the market (while still meeting EU procurement legislation). This would help mitigate barrier 6 in Table 7 section 3.4.5.

5.2.7 Research, Development and Demonstration

In order to realise the 40-60% or Max Tech pathways, deployment of medium to longer term technology is needed. Several of the medium to long term decarbonisation technologies identified in section 3.5- such as retrofit and rebuilding employing advanced technologies - require further technology innovation and demonstration before commercial scale deployment can be considered. Also, the material efficiency opportunities require a range of further research and demonstration activities to realise the carbon reduction benefits. The pathway information can now be used to inform technology innovation strategies for government and companies. The specific priority technologies, once identified, will require a level of innovation investment to reach commercial readiness that exceeds most company or country innovation budgets.

Innovation in technologies as they approach commercial scale requires very significant investments. Given the scale of investment required, alternative approaches to funding technology innovation are required to realise the 40-60% or max tech pathways. Early stage innovation can benefit from the UK's active academic research capability, in collaboration with international research bodies, and industry. Technology innovation and RD&D for medium-long term technologies seem to be an area where steel makers can collaborate, the ULCOS programme is evidence of that and has until recently provided a focus for cross-company and cross-border collaboration within the European steel industry. European funding sources, and joint funding models may provide the best opportunity for accelerating progress on innovation. The forthcoming NER400 programme may provide a central opportunity in this area.

The innovation needs for the sector should be jointly monitored through industry, academia and government, based on this project's pathway results and other sources in order to inform prioritisation by the companies, research councils and Innovate UK. Innovation leadership in this area will benefit the UK economy through global market opportunities for the technologies developed.

5.2.8 People and Skills

This strategic conclusion supports a number of themes, for example, people need the right skills to develop the investment business case for new projects, to deploy options and also to research and develop new technologies. The iron and steel sector's carbon reduction will be dependent on a skilled and knowledgeable workforce in the UK.

The technologies that will deliver the majority of the decarbonisation require further development, such as the different rebuild and retrofit options. These new technologies will require continued investment in skills and knowledge within companies, and better knowledge sharing between companies and sectors.

5.3 Key Technology Groups

5.3.1 Electricity grid decarbonisation

As shown in the pathway modelling (section 4), the decarbonisation of electricity supply has an important contribution to make to overall sector decarbonisation (especially for sites with electricity import requirements such as EAF sites). The government's reforms of the electricity market are already driving electricity grid decarbonisation, and this report uses assumptions of a future electricity decarbonisation trajectory that is consistent with government methodology and modelling. These trajectories would need to be achieved to deliver the levels of emission reduction in the pathways. Decarbonisation of electricity supply is not within the control of the sector.

5.3.2 Electrification of Heat

Electrification of heat can deliver emissions reductions in the iron and steel sector through an increased proportion of steel production via the EAF route, or through electrolysis techniques. The potential for emissions reductions by increasing the share of EAF produced steel, has been assessed through a sensitivity analysis (see section 4.5.1). The potential for emissions reductions through electrolysis has not been quantitatively assessed in this study, as the technology was not considered to be sufficiently developed. The level of decarbonisation from these options is dependent on the level to which the grid is decarbonised (see also grid decarbonisation above).

There could be limitations to the proportion of steel produced by EAFs in the UK; the price and availability of scrap steel are the most immediately obvious of these limitations but consideration must also be given to the quality and types of steel produced by recycling. Whilst improvements can be made, particularly through the use of higher quality scrap, there remain some speciality steels, for example those for use in lightweight automotive bodies, that cannot be produced through the EAF route.

5.3.3 Fuel and feedstock availability (including biomass)

Biomass provides a possible opportunity for the Iron and Steel Industry to reduce emissions as illustrated in the biomass sensitivity analysis (see section 4.5.4 and 4.5.5). Deployment of biomass to substitute pulverised coal could deliver significant carbon reduction. However, at present, the use of biomass as a significant decarbonisation option is considered to be a low priority. This is largely as a result of the sector's perception of biomass availability, price uncertainty. Use of biomass is likely to incur additional operational costs, and additional policy support could enable investment in this area. The use of pulverised charcoal as a substitute for pulverised coal injection remains an unproven technology, and technical demonstration would be needed in the UK to better understand performance, costs and wider impacts as well as assessment of biomass availability.

5.3.4 Energy Efficiency and Heat Recovery

As identified in the findings and pathways analysis, shorter term options are only partly implemented to date. Accelerated deployment of energy efficiency options can bring operational benefits including life cycle cost savings, however their investment continues to compete with other investment opportunities as companies are capital constrained. Companies could drive deployment of short term options by taking a strategic approach, setting internal objectives regarding deployment, and systematically overcoming the specific barriers within their influence.

Specific technologies include: heat recovery (conventional options), improved automation and process control, hot charging, improved planning and throughput optimisation, pulverised coal injection, reduce yield losses, compressed air system optimisation, re-heating furnace optimisation, waste heat recovery in sintering, BOF heat and gas recovery, steam and power production system upgrades, regenerative and recuperative burners, and stove flue gas recycling. For example, for the 20-40% CO_2 Reduction Pathway, these technologies represent 38% of the CO_2 reductions identified.

Where the technologies offer a payback within the companies' financial requirements, the investment may be enabled through better development of the internal business case, creating the link where possible between the other benefits the investment may bring (safety, environmental).

Where the short term technologies do not offer a payback within the companies' financial requirements, alternative off balance sheet finance may enable investments to be made, or additional policy support may be developed to incentivise investment.

Medium-term technologies may be less well known within sector companies, or require demonstration in order to improve confidence in the technical performance. Information sharing about these technologies is useful to improve understanding and improve confidence for investment.

5.3.5 Clustering

As the pathways analysis shows, improved site and sector integration, along with carbon capture and biomass could deliver significant emissions reductions in the iron and steel sector. Many of these technical options could be enabled by further industrial clustering around iron and steel sites. Clustering allows infrastructure investment to benefit from economies of scale in serving multiple sites. It also allows the development of labour market expertise and skills in a cluster area, alongside research and innovation facilities. Clustering also allows waste or by-products from one process to be used beneficially by another process, to enable energy efficiency or carbon reductions. Waste heat recovery can bring further energy efficiency benefits through reuse of low grade heat by other heat users outside of this sector.

To deliver these benefits would require other industrial processes to be co-located with UK steel sites. It is recognised that relocating a steel plant is unlikely due to the scale of operations and size of sites, but this could still be considered in future developments. Further research is needed to identify specific opportunities from clustering, as well as particular policy support requirements.

5.3.6 Carbon Capture

As the pathways and sensitivity analyses show, carbon capture technologies are expected to play a key role in a decarbonised iron and steel sector.

Within the disruptive technology group used in the pathways, there are a range of carbon capture technologies. These technologies are currently at varying levels of development, but globally there are few, if any, examples of commercial-scale carbon capture from iron and steel processes. Initially, retrofit carbon capture is most likely to be deployed on an integrated site power station as a first-of-a-kind full scale demonstration. However, capturing further emissions from integrated sites will require accelerated innovation, to allow deployment in the timescale envisaged in the 40-60% and Max Tech pathways. The pathways, alongside other research in this area will enable the development of an innovation strategy by the sector and government to identify the technology innovation needs. There are a range of specific technologies which could deliver the emissions reductions, the best technology will need to be identified through research, development and demonstration as discussed in the RD&D section above. Carbon Capture innovation will be best supported through joint investment programmes, involving international collaboration.

Deploying carbon capture technologies at commercial scale is expected to incur significant capital and operational expenditure. There is currently no business case for companies to make this investment. An investment mechanism could enable companies to cover the additional costs of capture plant, transport and storage, whilst maintaining their competitiveness. Many in the sector have emphasised that policy support in this area would need to provide long-term certainty to enable the sector to plan their investment.

Geographical constraints to carbon capture from integrated sites have not been addressed in this work but do require further research.

5.4 Closing Statement

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

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7. GLOSSARY

Adoption

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

Applicability

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

Barrier to Decarbonisation or Energy Efficiency

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

Business as Usual (BAU)

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

Decarbonisation

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

Carbon Reduction Band or Bin

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

Carbon Reduction Curve or Profile

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

Competition Law

The UK has three main tasks:

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

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

Deployment

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

Enabler for Decarbonisation or Energy Efficiency

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

Grid CO_2 Emission Factor

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

Maximum Technical Pathway (Max Tech)

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

Option

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

Option Register

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

Pathway

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

Projection of Production Changes

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

Reference Trend

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

Scenario

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

Scenario Assumptions

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

Sensitivity case

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

8. ACKNOWLEDGMENTS

The authors would like to thank all those who contributed to this project. This included trade associations and their members, academic institutions and government officials within the sector team and also all those who contributed to the project through attending workshops, engaging in interviews and providing data, review and comment to early drafts of the outputs.

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