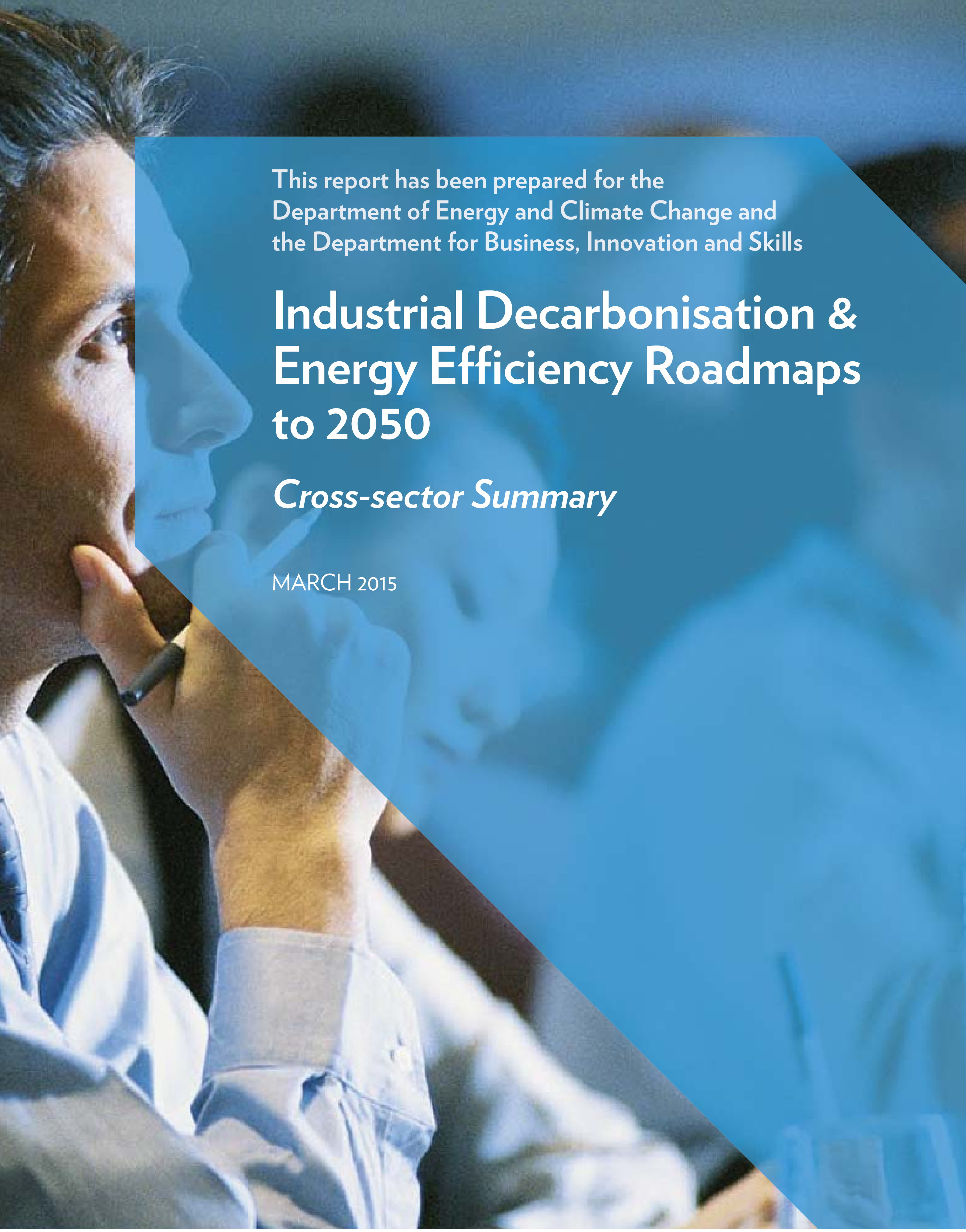

This report has been prepared for the Department of Energy and Climate Change and the Department for Business, Innovation and Skills

Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050

Cross-sector Summary

MARCH 2015

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1. INTRODUCTION

This report forms a cross-sector summary of eight Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050, each focused on an individual industry sector. Together these reports present the potential for and challenges of realising carbon dioxide emissions reductions across these sectors, while maintaining their competitiveness.

The government's 2011 Carbon Plan suggested that decarbonising the UK economy could mean a reduction in overall industry emissions of up to 70% by 2050, relative to 2009 emissions. Currently, two thirds of industrial emissions come from eight energy-intensive sectors: cement, ceramics, chemicals, food and drink, glass, iron and steel, oil refining, and pulp and paper. Between them, these sectors employ around 2% of the UK's workforce, and contribute an annual £50 billion to the economy, approximately 4% of the UK's gross value added (GVA). Across industry, these sectors use the greatest amount of energy and produce the most carbon dioxide emissions.

A consortium of Parsons Brinckerhoff and DNV GL was appointed by the Department of Energy and Climate Change (DECC) and the Department for Business, Innovation and Skills (BIS) to produce a decarbonisation and energy efficiency roadmap for each sector. This sector-specific approach is designed to reflect the individual nature of the challenges and opportunities for each sector, while drawing out commonalities. The purpose of each roadmap is to establish a shared evidence base to inform future policy, including an improved understanding of the emissions abatement potential of individual industrial sectors, and to identify strategic conclusions and next steps to help deliver cost-effective decarbonisation for UK energy-intensive industries in the medium to long term (over the period from 2020 to 2050).

This cross-sector report combines analysis from the eight sector roadmaps to identify strategic conclusions that apply to multiple sectors and technology groups that are common to several sectors and that appear to have the most potential to reduce carbon dioxide emissions. Emerging cross-sector analysis was presented at a stakeholder workshop in February 2015, and this report takes account of feedback during the workshop.

The combined results in **section 2** of this report show that continued deployment of energy efficiency technologies, combined with electricity grid decarbonisation could deliver 32% emissions reduction by 2050. This could be increased to a 73% emissions reduction by deploying our assessment of what is technically possible for these sectors, the combined 'maximum technology' pathway, which sets aside all economic and commercial considerations. These assessments are set against assumptions of how industrial emissions will change as a result of changing production levels.

Section 3 explores the potential of six key technology groups, four of which deliver the bulk of emissions reduction in the assessment of maximum potential across the eight sectors – carbon capture, biomass as fuel and feedstock, electricity grid decarbonisation, and energy efficiency and heat recovery – and two that make a substantial contribution in at least two sectors and have potential to be used more widely (electrification of heat and industrial clustering).

Building on the analysis and wider evidence, including on business decision-making, **section 4** suggests that there is substantial scope for collaboration between industry, government and others to take steps in the short term that could enable industry sectors to make deeper emissions reductions over the longer term while staying competitive. It draws strategic conclusions organised under eight themes: 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 deployment (RD&D); and people and skills.

1.1. Overall Methodology

Development of each roadmap consisted of three main phases:

1. Gathering of evidence relating to technical options and business-related enablers and barriers for decarbonisation. Evidence was collected via a literature review, analysis of publicly available data, interviews, workshops and surveys of sectors with a large number of firms. Validation of evidence and early development of the possible options for decarbonisation and energy efficiency took place during the first of two workshops.
2. Development of decarbonisation and energy efficiency 'pathways' to 2050 to identify and investigate an illustrative technology mix for a range of emissions reduction levels, using a simple operator-led model. Draft results were validated at a second workshop.
3. Interpretation and analysis of the technical and business-related evidence to draw conclusions and identify potential next steps. These example actions, informed by the evidence and analysis, aim to assist with overcoming barriers to delivery of technologies within the decarbonisation and energy efficiency pathways, while helping sector firms maintain competitiveness.

Figure 1: Roadmap methodology

Stakeholder engagement has been a central part of the project. For each roadmap, a sector team was established, including project staff from Parsons Brinckerhoff and DNV GL (sector lead, social and business, modelling and stakeholder specialists), the industry sector trade association, DECC and BIS and academics. The sector team informed the detailed methodology, provided inputs and reviewed draft and final outputs.

We have worked closely with sector trade associations to identify and engage appropriate people from each industry, supply chain services, academia and other institutions (e.g. financial services). 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.

These different sources of evidence together with the outputs are shown in Figure 2.

Figure 2: Evidence gathering process

The data we collected from the different sources was referenced and triangulated to improve our certainty in the analytical inputs, and improve robustness of the overall research output. We analysed the data collected to develop a consolidated list of barriers and enablers for decarbonisation, and a register of technical options. The register includes estimates of adoption rate, applicability, technology readiness level (TRL), carbon reduction potential, fuel impacts and capital costs. These parameters were used as input parameters to the pathway development described below.

1.2. Pathways Development

The pathways analysis is an illustration of how sectors could decarbonise from the base year (2012) to 2050. Together, the set of pathways developed in the study help give a view of the range of technology mixes that the sector could deploy over coming decades. Each pathway consists of different technology options that are implemented over time to different extents. Up to five pathways were developed for each sector, three of which were created to explore possible ways to deliver CO_2 emissions to prescribed decarbonisation bands by 2050, 20-40%, 40-60% and 60-80% reduction relative to the base year. Two further pathways were also created, assessing (i) what would happen if no additional interventions were taken to accelerate decarbonisation (business as usual, BAU) or (ii) maximum technical potential for decarbonisation in the sector (Max Tech).

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. The Max Tech pathway deploys a range of technologies generally at least at a pilot stage of development, subject to reasonable constraints. It is designed to investigate what might be technically possible when other barriers are set to one side. Other disruptive technology options, which could make a substantial difference but are not mature enough for inclusion in the pathways, are covered in the commentary.

Pathways were developed with stakeholders in an iterative manual process and not through a mathematical optimisation process. They were tested under three scenarios, each of which includes a set of conditions that could directly or indirectly affect the ability of sectors to decarbonise. These include future electricity grid decarbonisation, sector growth, energy costs and cost of carbon. In broad terms, the 'current trends' scenario assumes low stable growth; 'challenging world' assumes industry decline and 'de-prioritisation' of climate action; and 'collaborative growth' assumes a more positive economic environment and global collaboration on decarbonisation. The pathways analysis in this cross-sector report uses the results from the current trends scenario.

The focus of this study is carbon dioxide, rather than other greenhouse gas emissions, because the former make up the vast majority of emissions from these sectors. Only emissions from production or manufacturing sites are in scope (from combustion of fuels, 'process' emissions[1] and indirect emissions from imported electricity). Consumed and embedded emissions are outside the scope of this project; energy demand reduction from material efficiency is mainly outside the scope of the quantitative analysis but is covered in the conclusions given the opportunities it presents. The pathways are assessed in terms of a snapshot of emissions at 2050, rather than in terms of cumulative emissions over the period to 2050.

[1] 'Process' emissions result from the chemical changes in raw materials during heating or chemical reaction.

2. COMBINED RESULTS

2.1. Decarbonisation and Energy Efficiency Pathways

This section presents the combined results of eight separate sets of sector analysis of decarbonisation and energy efficiency potential to 2050. The sector pathways analysis is presented in detail in the sector roadmap reports. The analysis suggests that it is technically possible to make substantial emissions reductions in all eight industrial sectors with recognised technologies deployed in a reasonably foreseeable way. This is projected in the context of assumed production growth in most sectors as well as government assumptions for decarbonisation of the electricity grid. There is significant variation in decarbonisation potential and technical options selected between sectors driven by a range of factors, including the different process characteristics that are used in the sectors and proximity of sites to potential CCS infrastructure.

Based on more limited analysis, the analysis suggests how material efficiency improvements could play a role in reducing emissions in some sectors, and that a fuller assessment of these opportunities could identify further potential. It also identifies a range of less mature technologies that would benefit from innovation support, some of which could make a substantial impact in these sectors, including in reducing emissions. Finally, this section gives an initial estimate of the overall capital costs of the technology options included in the pathways. In this analysis, the options from all sectors have been categorised as follows: see Table 1.

Technology option group	Description Including examples from sectors
Carbon capture	Includes post combustion, oxy-combustion (cement sector only) and capture on process emissions from steam methane reforming hydrogen and ammonia processes (chemicals and refining sectors) and top gas recycling (iron and steel).
Electricity grid decarbonisation	All sectors: progressive decarbonisation of 2012 electricity use as defined in the DECC-supplied scenarios
Biomass	All sectors: includes (either or both) biomass fuel and biomass feedstock
Energy efficiency and heat recovery	All sectors: a range of improvements including energy management, utilities, heat recovery, improved process control, improved equipment and insulation (e.g. motors, pumps, compressors, fans), improved furnace design, compressed air to electric drives, maintenance.
Electrification of heat	Low temperature applications in pulp and paper and food and drink and high temperature applications in glass (electric melting), ceramics (electric kilns) and iron and steel (increased use of electric arc furnaces)
Material efficiency[2]	Food waste and packaging reduction, reducing yield losses, scrap densification/shredding and reuse of steel (steel), lighter bricks (ceramic), reduce product weight (ceramic), increased cullet use through recycling (glass)
Clustering	Applied quantitatively in the chemicals and pulp and paper sectors – but possibilities in other sectors too
Fuel switching	Includes pulverised coal injection (iron and steel) use of waste-derived fuels, hydrogen and oxygen enrichment technology and on site renewable generation of electricity. Excludes electrification and biomass
Other	Examples include substitution of materials and alternative cements, olefin catalytic cracking (chemicals), batch pelletisation and reformulation (glass), pre-calcining of clay (ceramic)

Table 1: Option categorisation used for analysis of combined pathways results

[2] Not a full material efficiency evaluation: options included here are limited and only apply to production site processes.

Table 2 summarises the decarbonisation potential by 2050 (relative to 2012, the base year) of each pathway in the current trends scenario for each sector. In some cases, Max Tech is presented as a single pathway; in others more than one alternative pathways are presented that could be used to deliver the substantial emissions reductions illustrated by Max Tech.

Sector	Pathway	Base year (2012) emissions (million tonnes CO_2)	Relative emissions reduction in 2050 (relative to 2012)	Absolute emissions reduction in 2050[3] (million tonnes CO_2)	Technology groups (in descending order of relative contribution)
Cement	BAU	7.5	12%	0.9	Others; Energy Efficiency
	Max Tech - with or without carbon capture		33-62%	2.5-4.7	(CCS); Biomass; Others; Energy Efficiency; Fuel Switching
Ceramics	BAU	1.3	27%	0.3	Energy Efficiency; Others; Material Efficiency; Fuel Switching; Biomass
	Max Tech		60%	0.8	Electrification of Heat; CCS; Energy Efficiency; Biomass; Others; Material Efficiency; Fuel Switching
Chemicals	BAU	18.4	31%	5.8	Biomass; Energy Efficiency; CCS; Fuel Switching; Clustering; Others
	Max Tech – with and without biomass		79-88%	14.6-16.1	CCS; (Biomass); Others; Energy Efficiency; Clustering; Fuel Switching
Food and Drink	BAU	9.5	40%	3.8	Energy Efficiency; Biomass; Electrification of Heat; Material Efficiency; CCS; Others; Fuel Switching
	Max Tech - with and without electrification of heat		66-75%	6.2-7.2	(Electrification of Heat); Energy Efficiency; Biomass; Others; Material Efficiency; CCS; Fuel Switching
Glass	BAU	2.2	36%	0.8	Energy Efficiency; Material Efficiency; Others; Fuel Switching
	Max Tech – with or without carbon capture		90-92%	2.0-2.0	(CCS); Electrification of Heat; Fuel Switching; Material Efficiency; Energy Efficiency; Others
Iron and Steel	BAU	23.1[4]	15%	3.4	Energy Efficiency; Material Efficiency; Fuel Switching
	Max Tech		60%	13.9	CCS; Energy Efficiency; Clustering; Material Efficiency; Fuel Switching
Oil Refining	BAU	16.3	44%	7.2	Energy Efficiency; Fuel Switching
	Max Tech		64%	10.4	Energy Efficiency; CCS; Fuel Switching
Pulp and Paper	BAU	3.3	32%	1.0	Energy Efficiency; Electrification of Heat
	Max Tech – clustering and electrification		98%	3.2	Energy Efficiency; Clustering; Electrification of Heat
	Max Tech - biomass		98%	3.2	Biomass; Energy Efficiency; Electrification of Heat

Table 2: Decarbonisation potential for the eight sectors

Figures 3 and 4 below illustrate the pathways on bar charts in which the base year refers to emissions in 2012, while the pathways refer to emissions in 2050.

[3] Based on the assumptions and judgements inherent in developing the pathways to 2050 described in the sector roadmaps
[4] For the iron and steel sector, the base year used is 2013. This was chosen due to the large production increase from the re-commissioning of SSI Teesside steelworks in 2012.

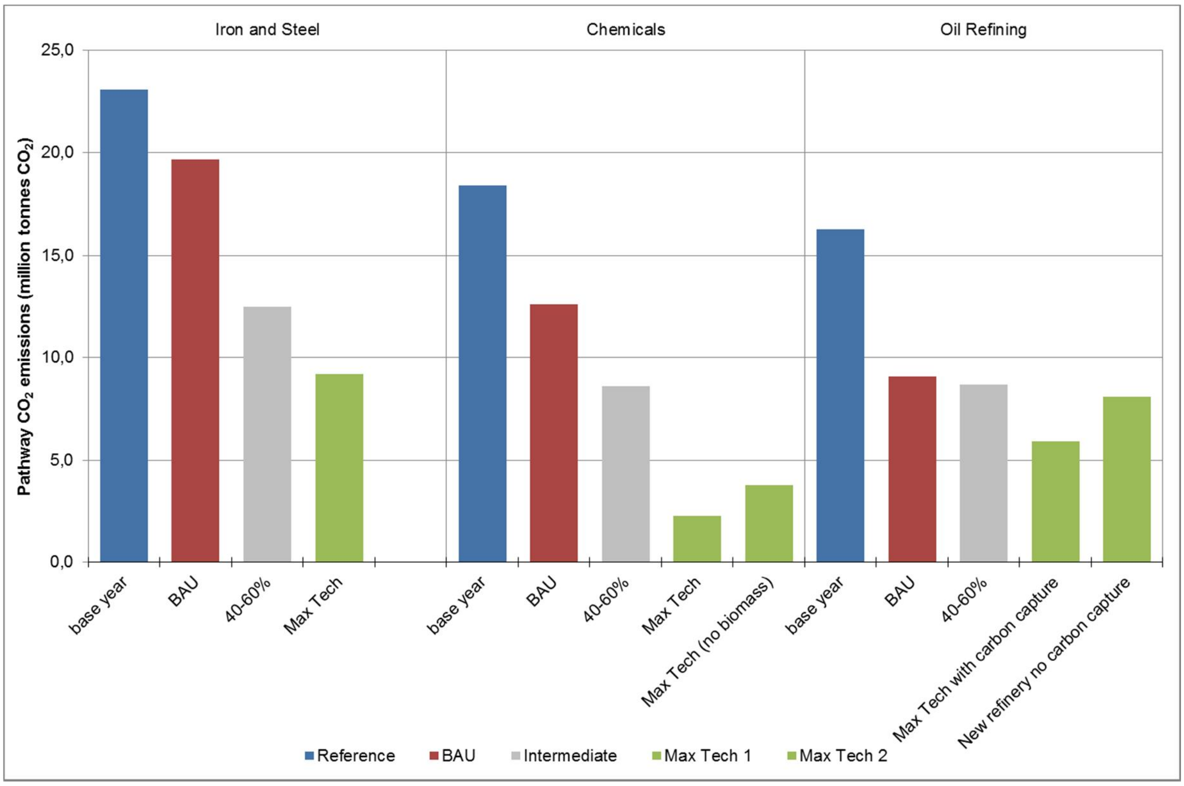

Figure 3: Summary of pathways in iron and steel, chemicals and oil refining sectors

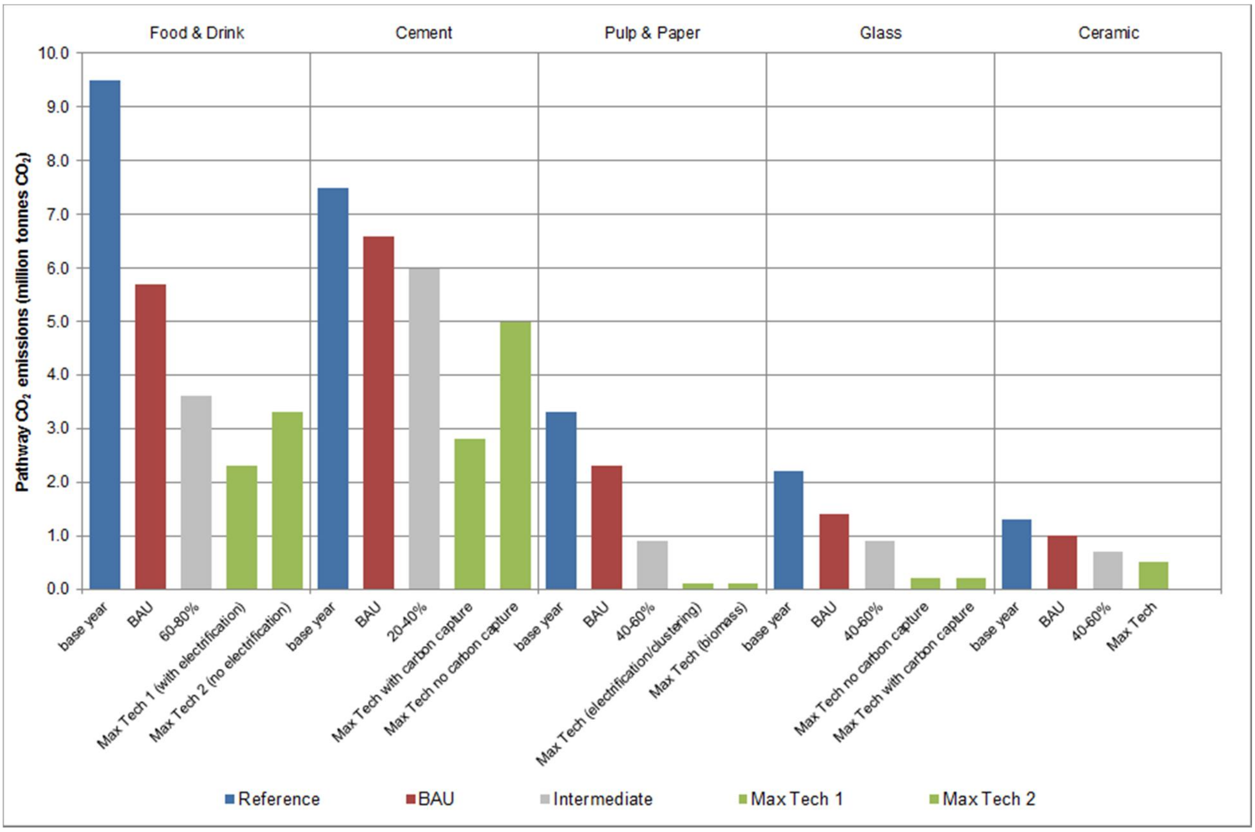

Figure 4: Summary of pathways in food and drink, cement, pulp and paper, glass and ceramic sectors

The following graphs present the pathway results showing the numerical outputs for all sectors added together in order to give a sense of scale for options that appear in multiple sectors' roadmaps. Figure 5 presents the combined reference trend for the three scenarios – starting at the base year of 2012 when the total emissions from the sectors was estimated at approximately 81 million tonnes of CO_2.

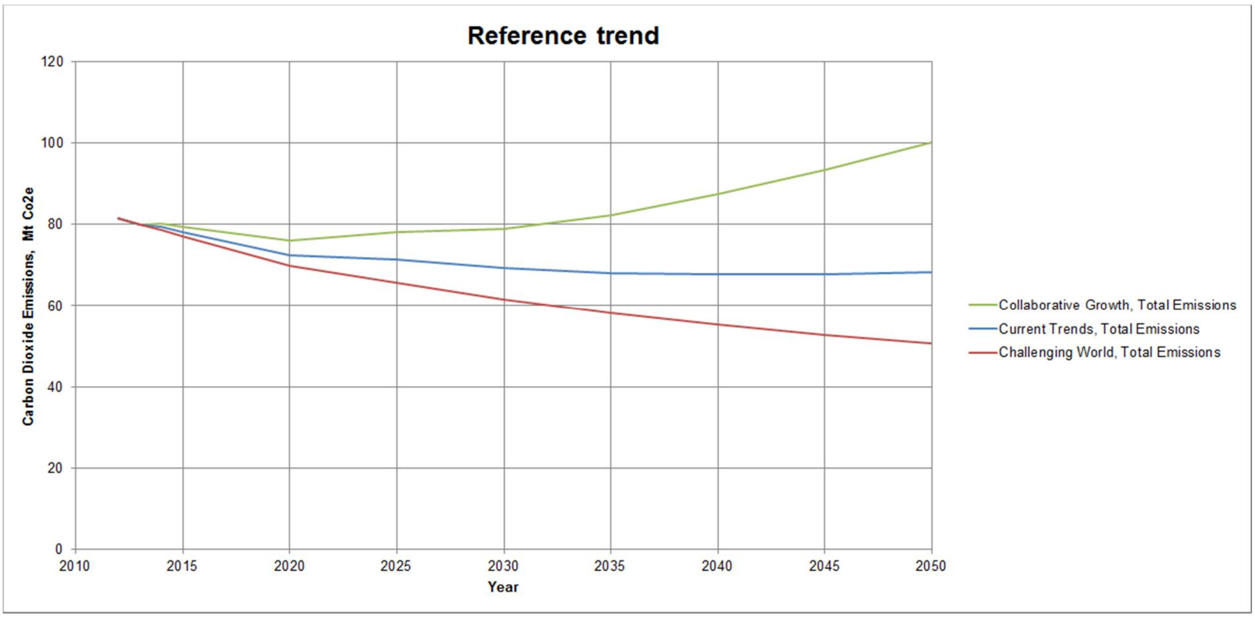

Figure 5: Reference trends

In Figure 5, two parameters – total sector output (which is assumed to be directly proportional to total emissions) and grid decarbonisation of electricity use in the reference year[5] – are combined for each of the three scenarios. The results provide an assessment of the possible quantitative impact of production and grid emission factors combined to 2050. In the 'current trends' scenario, changes in sector output and grid decarbonisation broadly cancel each other out, and sector emissions in 2050 are only slightly lower than in the reference year of 2012.

Figure 6 to Figure 11 below present the combined BAU, intermediate and Max Tech pathway results for all eight sectors for the current trends scenario which assumes modest sector production growth in most sectors (oil refining assumes modest production contraction) and DECC central assumptions for grid decarbonisation.

Figure 6 and Figure 7 below show the combined BAU pathway emissions reductions from **81 million tonnes of CO_2 in 2012 to 58 million tonnes of CO_2 in 2050**. This is a result of progressive grid decarbonisation of 2012 electricity use (62% of total emissions reduction relative to 2012 base year), continuing investment in 'incremental' energy efficiency measures (23%) and increased use of biomass (7%).

[5] Future changes in electricity consumption (e.g. increased electricity use) are assessed as part of the option and pathway analysis.

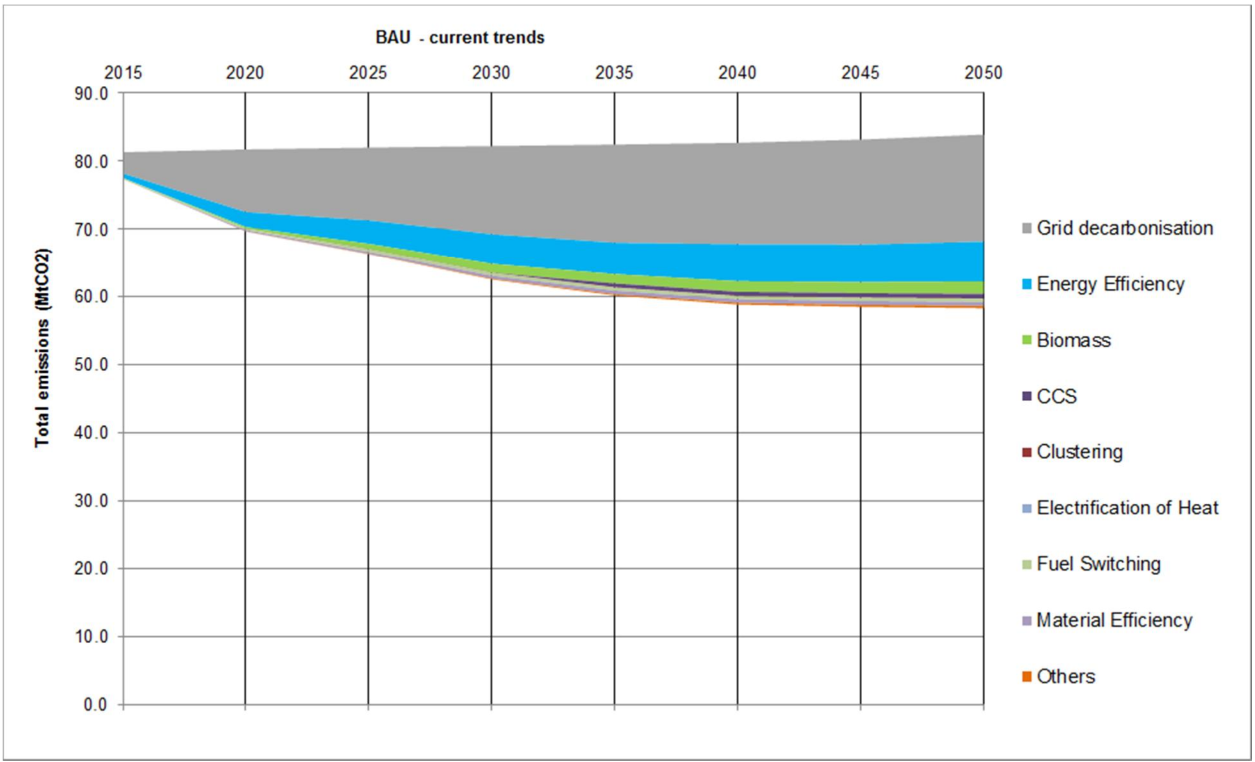

Figure 6: Combined BAU pathways in current trends scenario

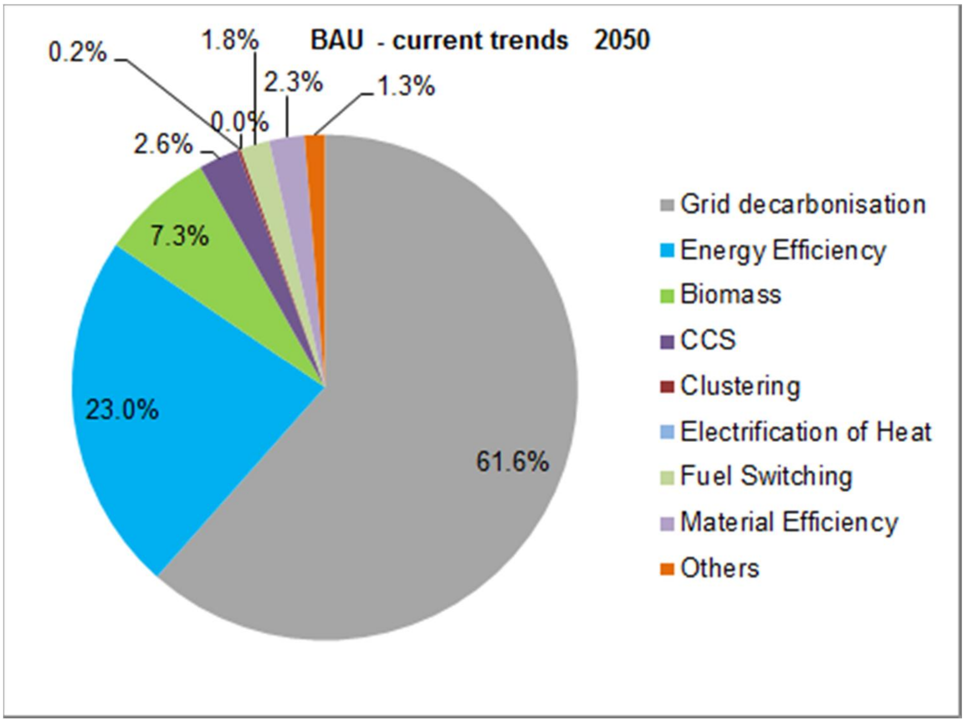

Figure 7: Combined BAU pathways in current trends scenario

Figure 8 and Figure 9 below show the combined intermediate pathways emission reductions from **81 million tonnes of CO_2 in 2012 to 42 million tonnes of CO_2 in 2050**. The technology groups giving the greatest reduction potential are impacts of electricity grid decarbonisation of current electricity use (37% of total CO_2

reduction in 2050 relative to 2012 base year), energy efficiency and heat recovery technologies (23%), carbon capture processes (18%) and biomass as both fuel and feedstock (13%).

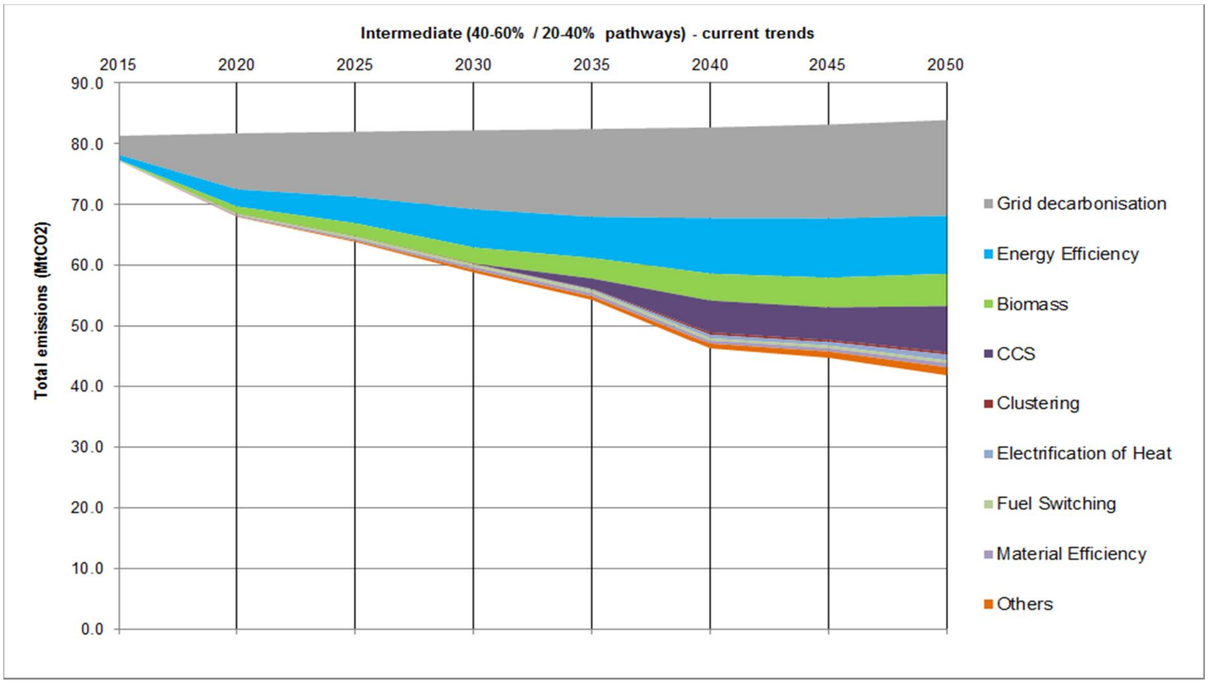

Figure 8: Combined intermediate pathways[6] in current trends scenario

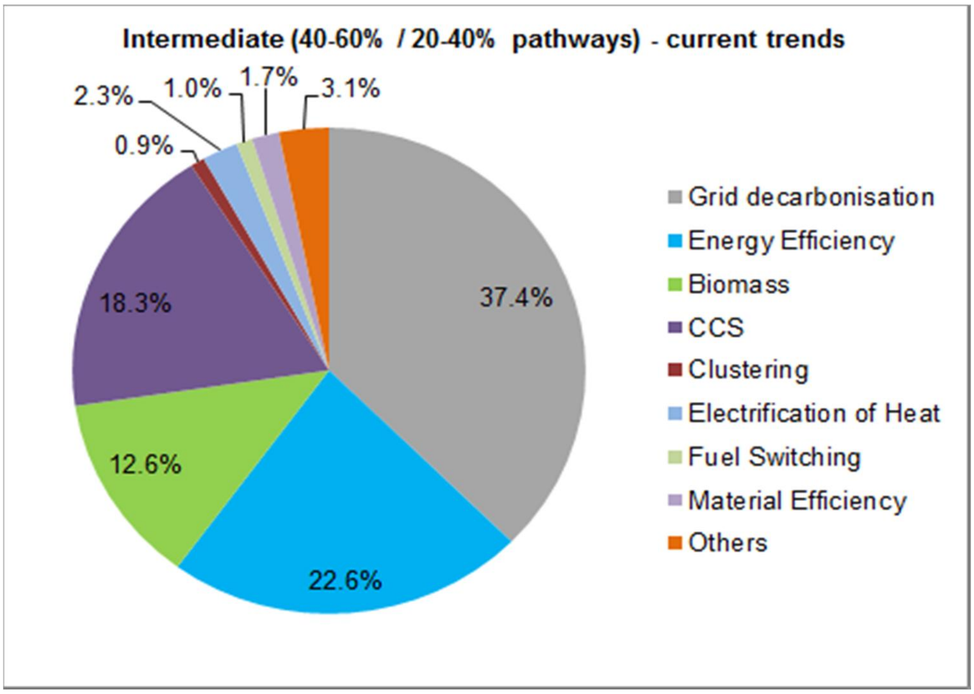

Figure 9: Combined intermediate pathways in current trends scenario

[6] '40-60% CO_2 reduction pathway', which represents a 40-60% CO_2 reduction in 2050 as a percentage of the base year with two exceptions: cement (20-40% CO_2 reduction pathway) and food and drink (60-80% CO_2 reduction pathway).

Figure 10 and Figure 11 below show the projected combined Max Tech pathways emission reductions from **81 million tonnes of CO_2 in 2012 to 22 million tonnes of CO_2 in 2050** (using the Max Tech pathways that maximise carbon capture deployment). The technology groups giving the greatest reduction potential are carbon capture processes (37% of total reduction in 2050 relative to 2012 base year), impacts of electricity grid decarbonisation on current electricity use (25%), biomass (as both fuel and feedstock, 16%), and energy efficiency and heat recovery technologies (13%).

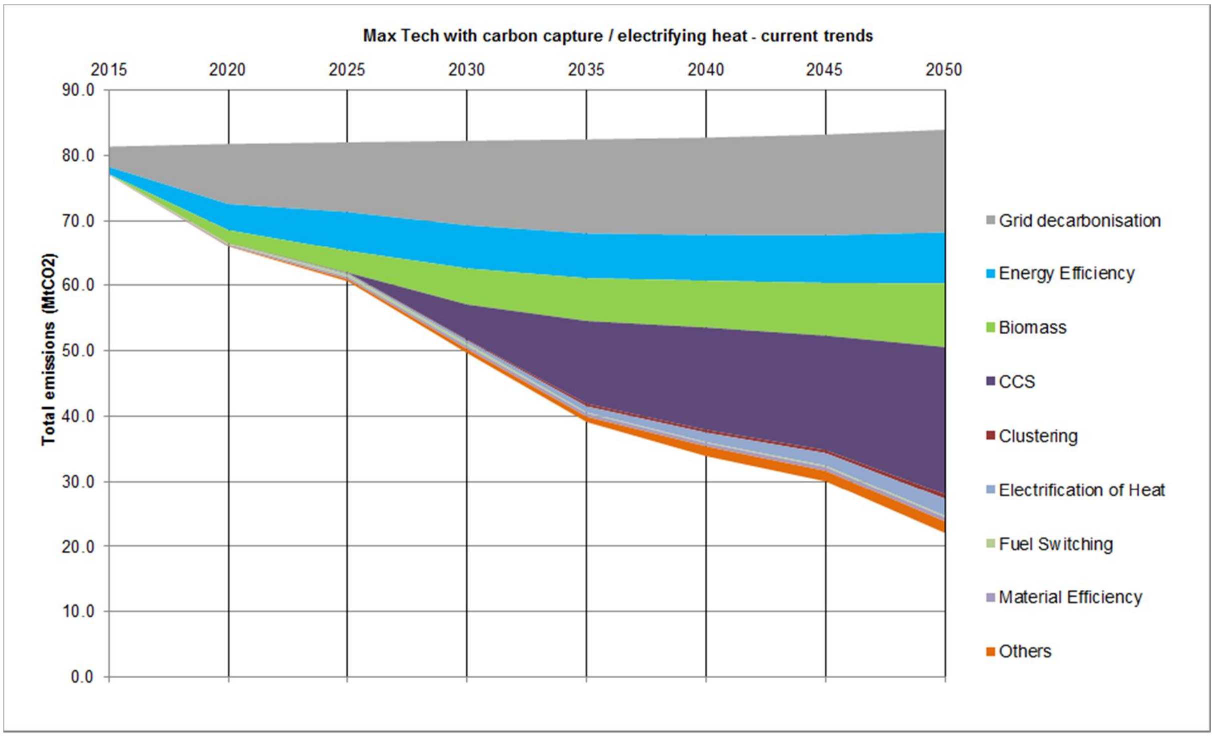

Figure 10: Combined Max Tech pathways in current trends scenario

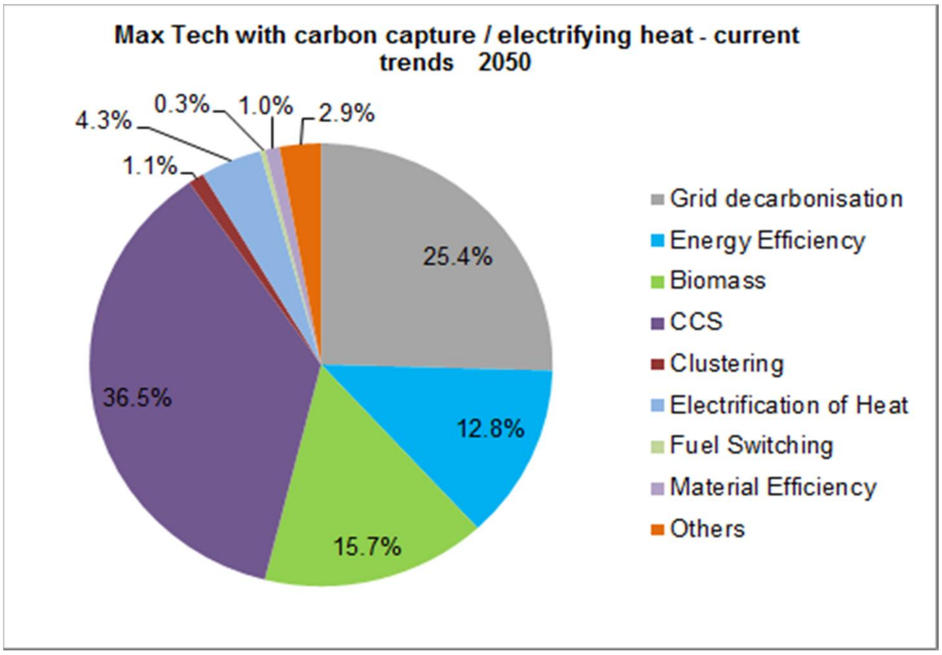

Figure 11: Combined Max Tech pathways in current trends scenario

2.2. Technology Development

The pathways analysis above includes technologies that have a range of technology readiness levels (TRLs) generally ranging from TRL4 (technology validated in the laboratory) to TRL9 (system proven in an operational environment)[7]. Given the diversity of manufacturing processes carried out in the eight sectors, it is important to recognise that a single technology group (e.g. carbon capture) may have different TRLs in different sectors, depending upon how the technology can be applied within that sector.

While the Max Tech pathway provides an assessment of a combination of carbon abatement options and energy savings that is both highly ambitious but also reasonably foreseeable, some options within Max Tech with lower TRLs still need extensive RD&D to enable their deployment. In addition, some options with lower TRLs are only included in the pathway analysis to a limited extent or not included at all (examples in each sector are included in Table 3 below). RD&D has the potential to help realise greater deployment of such technologies.

Sector	Lower TRL options in each sector
Cement	Oxy-combustion CO_2 capture technology and storage or use. Alternative cements based on non-traditional processes or raw materials. Use of hydrogen fuel
Ceramic	Electric kilns, gasification of biomass to fuel kilns, reduced number of firings, lower temperature processes, lower product weight
Chemicals	Carbon capture technology and storage or use. Hydrogen by electrolysis (ammonia and hydrogen production). Recycled plastics to syngas. Membrane separation technology.
Food and drink	Factories of the future, increased use of enzymes, microwave drying and heating, innovative packaging reduction.
Glass	Electric furnace technology, innovative furnace designs, use of hydrogen fuel.
Iron and steel	Advanced technologies with carbon capture and rebuild[8]
Pulp and paper	Two Team[9] project options (e.g. deep eutectic solvents and flash condensing with steam)
Refining	Carbon capture technologies and storage or use.

Table 3: Summary of lower TRL options

2.3. Material Efficiency

Research suggests that improvements in material efficiency could offer significant additional opportunities to reduce carbon emissions in manufacturing[10]. As noted in Table 1 above, the pathways analysis in this study included a limited assessment of material efficiency options and an evaluation of some simple sensitivity

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[7] See http://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf
[8] This includes HIsarna, Corex and Finex installed with carbon capture technology within a rebuilt integrated blast furnace site.
[9] CEPI's Two Team Project generated possible breakthrough technologies to deliver the CEPI goal of 50% more value from the sector's products by 2050.

[10] Information is available on material efficiency in industrial sectors, see for example : Allwood, J.M., Philosophical Transactions of the Royal Society A, Mathematical, Physical and Engineering Sciences, 371, Transitions to material efficiency in the UK steel economy, *p. 17*, 2013.

testing of the potential impact of reduced production quantities. Beyond this, material efficiency opportunities were not assessed within the pathways analysis. Further assessment of material efficiency potential could provide significant additional opportunities that have not been fully captured within the analysis carried out in this project.

2.4. Pathway Costs

An initial order of magnitude estimate of the net present value capital cost for the pathways, discounted at 3.5%, and aggregated across all sectors, gives a range in the current trends scenario of £6 billion (for BAU) to £16 billion (for Max Tech).

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

As stated above, 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. Given these limitations, there is a case for further work to investigate and analyse the cost impact of the pathways. Such techno-economic analysis on individual options or groups of options would enable improved validation of the indicative results presented above. This would provide an improved dataset to inform future priorities and action.

3. CROSS-SECTOR TECHNOLOGIES

This section provides a summary of six main technology groups that are common in the pathways in more than one sector. The six groups include four technology groups giving the highest decarbonisation potential in the analysis presented in section 2: carbon capture, electricity grid decarbonisation, biomass, and energy efficiency and heat recovery. Two additional technology groups (electrification of heat, and clustering) make a substantial contribution in at least two sectors and have potential to be used more widely.

The following summaries explain the various kinds of technology in each group (in order of their relative contribution to the combined Max Tech results), the group's significance to the pathways, which sectors the technologies are relevant for, and example actions to strengthen enablers and overcome barriers to effective deployment.

3.1. Carbon Capture

This technology group comprises the extraction of CO_2 from process streams or flue gas streams. CO_2 is either compressed and exported by pipeline (or liquefied for export by ship) for permanent storage in geological formations, or utilised as a feedstock for the manufacture of chemicals, fuels, fertilisers or other products. Each sector has considered potential deployment of carbon capture. Broad assumptions on possible transport and storage infrastructure or possible use have been made, and these are provided in the sector roadmaps.

As shown in section 2, carbon capture (as deployed in the Max Tech pathways) is the single largest contributor to decarbonisation in the combined results with a total emission reduction potential of 23 million tonnes of CO_2 per annum in 2050 (37% of the total combined reduction in Max Tech in 2050). It is a key decarbonisation technology in four sectors: cement, at 62%[11] of the total Max Tech reduction in 2050, chemicals (43%), iron and steel (45%) and refining (56%). In these four sectors, sensitivity analysis has shown that without carbon capture technologies, emissions reductions are projected to be much smaller and potential alternative technologies are currently considered to be limited.

Carbon capture was also included the assessment of two others on a smaller scale, glass at 39% of the total Max Tech reduction in the glass sector in 2050, and ceramic (17%). In both of these two sectors, alternative technologies (electric melting and electric kilns respectively) are potential alternatives to carbon capture within the Max Tech pathway.

While carbon capture technology has reached demonstration scale in the power sector, application in industry is less advanced. A range of technologies are under development, and currently at different technology readiness levels (TRL). Industry sector-specific technology development (e.g. oxy-combustion capture in the cement sector and top gas recycle with carbon capture in the iron and steel sector) would minimise the cost and efficiency penalties associated with implementation. Carbon capture transport and storage infrastructure investment is likely to benefit from economies of scale – large emitters such as iron and steel, refineries or power stations could provide the anchor load together with the addition of other clustered smaller emitters.

An in-depth analysis of projected CO_2 transportation infrastructure to identify which industrial sites and clusters will potentially have access to CO_2 pipelines would help enable development activity across multiple

[11] All values quoted for individual sectors exclude grid decarbonisation

sectors. This analysis could also explore the roles and responsibilities for government, transport and storage owners and industry, including strategy and infrastructure. The analysis could also inform the debate on issues of ownership and long-term liabilities of stored CO_2 and quantify potential benefits from clustering of industrial carbon capture and possible integration with carbon capture in the power generation sector.

Further desk-based studies would help to quantify potential for CO_2 utilisation to determine whether this is a significant outlet for captured CO_2. Carbon capture and utilisation is an area of interest for academic research: as breakthrough technology in this area, it could offer the potential for more commercially viable decarbonisation. While there is debate about the relative future scales of carbon capture and storage and carbon capture and utilisation, the current industry view is that carbon capture and utilisation will not be possible at sufficient scale to make a significant contribution to sectors such as refining, chemicals, cement and iron and steel. Further research and development could, however, change this balance.

The application of carbon capture increases both capital costs and operating costs for the industry. Policies to support industry to deploy carbon capture, such as an incentive mechanism, would facilitate implementation and avoid the UK industry being at commercial disadvantage to overseas competitors.

3.2. Electricity Grid Decarbonisation

Grid decarbonisation impacts the pathways in two ways: (i) through decarbonisation of imported electricity use from the base year and (ii) through deployment of options that involve electrification. As stated in section 1, scenarios were used to test the robustness of the different pathways and three scenarios for electricity grid decarbonisation were provided by DECC[12] as shown below.

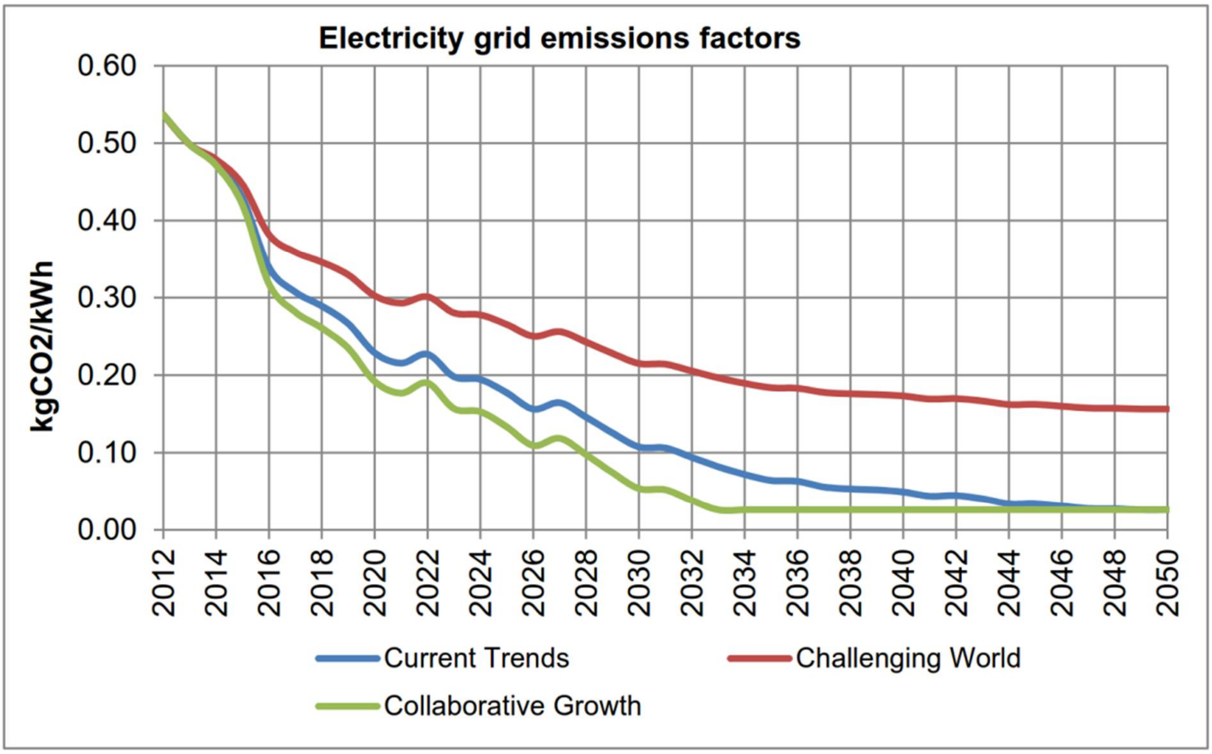

Figure 12: Scenarios for electricity grid decarbonisation

[12] Green Book Supplementary Guidance, 2013

While grid decarbonisation is outside the direct control of the industry, decarbonisation of the national electricity grid could provide a considerable contribution to the overall decarbonisation as shown in section 2. For the combined Max Tech pathway results, grid decarbonisation contributes a total reduction of 16 million tonnes of CO_2 in 2050 (25% of the total combined reduction in Max Tech in 2050). Grid decarbonisation has a significant impact in all sectors that currently import large quantities of electricity, which is all sectors except refining. For sectors that include options that rely on increasing use of (low carbon) electricity (food and drink and pulp and paper for lower temperature heat and iron and steel, glass and ceramics for high temperature heat), grid decarbonisation is also a key part of the equation.

Government's reforms of the electricity market are already driving electricity grid decarbonisation, and this study uses the assumptions of future electricity decarbonisation trajectories that are consistent with government methodology and modelling. Future policy work streams - regarding future electricity grid decarbonisation and changing configurations of generation, distribution and use - need to include assessment of the impacts of industry sectors such as food and drink, pulp and paper, glass and ceramic given the importance of grid decarbonisation for the electrification of heat option (see below). For example in the food and drink sector for the Max Tech pathway, grid decarbonisation coupled with electrification of heat is projected to contribute 6.5 million tonnes of CO_2 reduction in 2050 out of a total of 9 million tonnes in the base year of 2012 (72%).

Industry will need to be reassured by government and the grid operators that the grid decarbonisation plan is robust in terms of security and confidence of implementation. Future costs of decarbonised electricity will also be an important factor in order to realise the potential emissions reductions resulting from electricity grid decarbonisation while retaining competitiveness.

3.3. Biomass

Biomass technology for decarbonisation is the use of bio materials to provide a fuel or feedstock replacing current fossil fuel sources. Biomass absorbs CO_2 during growth, so there is the potential to reduce emissions compared to fossil fuel sources. However, there are many different sources of biomass (including within waste streams) that will have different emissions factors linked to their processing and transport.

As shown in section 2, biomass use could be a large contributor to decarbonisation across a number of sectors with a combined total emission reduction potential of 10 million tonnes of CO_2 per annum in 2050 (16% of the total combined reduction in Max Tech in 2050). It is a key decarbonisation technology in six sectors: pulp and paper, at 60%[13] of the total Max Tech CO_2 reduction in 2050, cement (28%), chemicals (37%), glass (27%), food and drink (22%) and ceramic (7%). Biomass use was assessed in iron and steel in a sensitivity case only.

Three main uses of biomass as a fuel have been identified in this study: combined heat and power (CHP), gasification and pyrolysis. CHP is an existing well proven technology whereas both gasification and pyrolysis have a lower technology readiness level. Biomass can also be used as a feedstock replacement, for example in the chemicals and cement sectors.

There are a number of complexities regarding biomass use as a decarbonisation option, from an industrial perspective: availability of different resource streams (and the related issue of competing demand for land), consistency of quality, carbon emission factors, price and policy support. As biomass also serves as feedstock for pulp and paper and the food and drink sector, it adds complexity to the question at hand. In

[13] All values quoted for individual sectors exclude grid decarbonisation

addition, biomass can be used in a range of applications outside of the eight sectors assessed here (e.g. electricity generation, transport and space heating).

Possible future actions to help with this complex issue would be more research into understanding the emission factors for different kinds of biomass, establishing how much biomass is actually available for use in industrial sectors, including what is currently being used in other sectors or for other uses, and the potential impacts of different deployment scenarios. An improved policy framework on waste and non-waste biomass - and the carbon emissions associated with them - could assist with addressing the complexities above. This would need to be linked to broader work on the waste hierarchy, for example, assessing how to define its best use (e.g. price paid or maximum overall decarbonisation potential) as an alternative to competition, and also taking into account non-industry competition for supplies. An example of the types of alternative uses for waste biomass is presented in the recent government publication: Building a high value bioeconomy: opportunities from waste[14].

3.4. Energy Efficiency and Heat Recovery

This group includes a range of options to increase energy efficiency through investment in state-of-the-art equipment, improved energy management and increased heat recovery. There are opportunities for increased energy efficiency in all of the eight sectors. As shown in section 2, energy efficiency and heat recovery contribute to decarbonisation with a combined total emission reduction potential of 8 million tonnes of CO_2 per annum in 2050 (13% of the total combined reduction in Max Tech in 2050). According to the pathway analysis, it is a key decarbonisation technology in all sectors as follows: pulp and paper, at 41%[15] of the total Max Tech CO_2 reduction in 2050, refining (43%), food and drink (36%), glass (16%), chemicals (9%), ceramic (9%), iron and steel (7%) and cement (5%).

Companies invest in new process equipment to stay competitive and new state-of-the-art equipment is typically more energy efficient than the equipment they replace. There are also opportunities to manage energy more systematically on sites. This includes improved automation and process control, monitoring, planning, and maintenance. As these interventions use highly developed technologies, they could be implemented in the short term, and since the investment costs can be low and energy efficiency saves operational costs, many of them can be funded locally. It is important that, with increasingly lean organisations and sometimes a lack of skilled labour, that when upgrading industrial plant, energy efficiency and decarbonisation are both considered as a high priority and suitably resourced in the project development process.

In addition to improved energy efficiency, increased heat recovery is an opportunity in all eight sectors. Most of the available heat to recover is lower grade heat[16]. To use it effectively, there needs to be either matched heat sinks near the plant or the heat needs to be upgraded to higher grade heat or electricity. Industrial clustering could help co-locate industries that use lower grade heat (food and drink, semiconductor manufacturing etc.) with industries that have low grade heat available (iron and steel, pulp and paper, etc.). Low grade industrial waste heat could also be used in district heating schemes to provide heat local housing or non-domestic buildings.

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[14] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/408940/BIS-15-146_Bioeconomy_report_-opportunities_from_waste.pdf

[15] All values quoted for individual sectors exclude grid decarbonisation

[16] https://www.gov.uk/government/publications/the-potential-for-recovering-and-using-surplus-heat-from-industry

3.5. Electrification of Heat

Substantial electricity grid decarbonisation would provide a further opportunity to decarbonise UK industry through the electrification of processes that are currently powered by fossil fuel combustion. This will only provide overall emissions reductions where the use of electricity is a lower-carbon option than the current energy source, i.e. as the grid becomes decarbonised, more processes could have a reduced carbon impact through electrification.

As shown in section 2, electrification of heat contributes to decarbonisation with a combined total emission reduction potential of 3 million tonnes of CO_2 per annum in 2050 (4% of the total combined reduction in Max Tech in 2050). It is a key decarbonisation technology in five sectors as follows: pulp and paper, at 22%[17] of the total Max Tech CO_2 reduction in 2050, food and drink (45%), glass (37%), and ceramic (59%). Increased use of electric arc furnaces in steel production was assessed as a sensitivity analysis.

Electric melting for glass manufacturing, electric kilns in the ceramic sector, and an increased proportion of steel production via electric arc furnaces, EAF, (although scrap price and availability constraints might limit this option) are key decarbonisation technologies. For the food and drink and pulp and paper sectors, electrification of heat is an important decarbonisation option. Compared to other sectors, the food and drink and pulp and paper sectors have a large part of their heat demand at fairly low temperatures and this could enable these sectors to shift towards electrification more easily. For other sectors, using electricity as their energy source is possible at higher temperatures but equipment (e.g. electric kilns) is not developed at scale and lower efficiencies can result compared to using other fuels. Electricity price projections relative to counterfactual fuels (e.g. gas) will be a key consideration in any investment decision.

Electrification of heat could be considered when replacing equipment, but the extent to which investments in electrified technologies are made will depend on firms' confidence that there will be secure, affordable decarbonised electricity in the future. The decision to electrify is an extremely significant step for companies to make, hence a clear plan will be needed that takes into account technology development, risks, costs and security /cost of supply.

DECC forecasts suggest substantial decarbonisation can be made from electrification, as long as prices are competitive to alternatives. Large-scale electrification of heat would increase overall electricity use, and therefore the impact of its deployment on the development of electricity generation, transmission and distribution capacity should be investigated.

3.6. Clustering

Clustering for decarbonisation benefits is the integration between industrial sites to deliver energy savings. It can reduce emissions by optimising the use of resources (waste- or by-products such as CO_2 from one process to be used beneficially by another process), while costs are shared, heat is used wisely and other benefits increase. Many of the decarbonisation options identified for the eight sectors - such as improved site and sector integration, carbon capture and biomass - could be enabled by further industrial clustering. It also allows the development of labour market expertise and skills in a cluster area, alongside research and innovation facilities. Waste heat recovery can bring further energy efficiency benefits through re-use of low-grade heat by other heat users outside of the sector producing that waste heat.

[17] Excluding grid decarbonisation

Clustering is a long-term, gradual option that requires new or replacement plants to be encouraged to locate where clustering benefits can be realised, and existing plants to maximise local opportunities. The barriers to clustering are generally related to organisational collaboration and include the perceived risk of becoming reliant on a partner who may not be present in the long term. Relocating many plants within the eight sectors is unlikely due to the scale of operations and size of sites but other industries could locate themselves around them.

According to our analysis, clustering could result in significant decarbonisation in the pulp and paper and chemicals sectors, but most sectors could benefit from increased clustering.

To support further development of clustering, a high-level feasibility study on the potential across different UK sectors should be executed, including a forecast of possible markets or customers for the waste- and by-products. This study could help mitigate the risks associated with clustering, and support planning and incentive policies by government - both central and local - to encourage clustering. Infrastructure investments (in roads, ports, pipelines, etc.) would strengthen existing clusters and enable new ones to develop.

4. CROSS-SECTOR STRATEGIC CONCLUSIONS

The pathways analysis and wider evidence suggests that there is substantial scope for collaboration between industry, government and others to take steps in the short term that could enable industry sectors to make deeper emissions reductions over the longer term while staying competitive. This section draws strategic conclusions organised under eight themes that are common to many of the sector roadmaps.

These conclusions have been developed by analysing the main enablers and barriers in each sector with input from a cross-sector workshop held in February 2015. The section includes a brief overview of each strategic conclusion, its links with the other strategic conclusions and examples of current best practice and potential next steps. The eight strategic conclusions cover:

1. Strategy, leadership and organisation
2. Business case barriers
3. Future energy costs, energy supply security, market structure and competition
4. Industrial energy policy context
5. Life Cycle Accounting
6. Value Chain Collaboration
7. Research, Development and Deployment (RD&D)
8. People and skills

4.1. Strategy, Leadership and Organisation

This theme applies at a UK, sector and company level. It articulates the case for action and therefore links to all other conclusions and technologies. At a national level, we identified the need to emphasise why energy intensive industries are important for the UK economy, and on the need for some technological changes to take place in the energy system itself (e.g. grid decarbonisation). In addition, some major technology groups like carbon capture, whilst site-specific, are not likely to be taken forward by industry alone.

At sector level, a number of the strategic conclusions and technologies will benefit from the development of a clearly defined strategy and leadership for its implementation – either as part of collaboration with government or other sectors, or within the sector. While technology development and future policy will be developed in partnership and with consultation, future results will depend upon individual action at company level, for example through the implementation of corporate sustainability targets. The need for business strategies (which are based on commercial considerations of profitability and cost reduction) to place decarbonisation high on the agenda was identified as a key enabler, as was the willingness and commitment of senior management to actively decide to drive programmes of action.

A range of good practice with respect to decarbonisation and innovation was identified during the course of the roadmap project such as “ULCOS” in the iron and steel sector and “Two Team” in the pulp and paper sector. The opportunity for UK companies and sites together with their corporate headquarters and R&D centres to collaborate with technology companies, academia and other stakeholders could lead to considerable strategic benefits. For example, consortium teams from groups of the sectors studied on this project could enter European Commission funding competitions to demonstrate the range of technology groups discussed in section 3.

We also identified the need for strong and clear communication on the rationale for decarbonisation. For example, many sectors mentioned that clear messages on the benefits of decarbonisation to consumers can help enable action and pull demand through the supply chain. Clear communication across government, research communities and corporate R&D centres could result in effective future RD&D projects.

4.2. Business Case Barriers

Businesses are driven by financial and commercial imperatives, decarbonisation and energy efficiency improvements can be made through the implementation of specific projects on individual manufacturing sites where a viable business case which satisfies internal criteria can be made. Companies and sites are usually aware of a range of potential projects that will reduce carbon dioxide emissions and improve energy efficiency, but the chances of implementation relate to the project business case and wider business conditions and market confidence. The research, development, demonstration and commercial deployment of major technologies requires significant capital expenditure as well as potentially incurring additional operating costs.

Industrial stakeholders reported a number of barriers to implementation of energy efficiency and decarbonisation options under this theme, including payback periods that are longer than company-defined thresholds, competition for corporate funding and shortage of technical or managerial resource. There are also technical risks to the manufacturing process itself (both real and perceived) that can hinder project implementation such as potential negative impacts on output and product quality. Therefore projects that link decarbonisation with other business benefits such as output and quality will have a better chance of moving forward.

The EU Emissions Trading System (EU ETS) has created a market that aims to incentivise and improve the business case for 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, further policy incentives could support investments including accelerated depreciation, interest free loans, an enhanced capital allowance scheme and support for the scrapping of less efficient technology.

Development capital could be considered for more uncertain projects with higher potential for decarbonisation. Recycling of energy-related policy costs back to energy efficiency projects in industry might be one way to provide a direct incentive for companies to invest. More generally, the investigation of different sources of finance may assist companies to invest in projects, for example, equipment manufacturer packages or ethical investment funds.

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

All sectors operate within markets that are evolving and these changes can present opportunities for decarbonisation and energy efficiency more broadly, as well as challenges within each sector (e.g. online newspapers reducing demand for paper products, electric and hybrid cars reducing demand for refined fuels). Many sectors within this project operate in highly competitive markets. Competitiveness of UK firms is dependent on a range of factors including but not limited to energy costs and energy security. The UK Government has taken significant action to reduce the cost impact of climate change policy on energy intensive industry by introducing a compensation scheme which, when fully implemented, will cover in the region of 80-85% of the pass-through costs of policy.

Some of the key technological options considered by the pathways, such as carbon capture (plus storage or use), will require significant capital investment without associated direct business benefits. While many of the options covered in the roadmaps would increase energy efficiency, it is also recognised that other options will lead to higher energy consumption and increased operating costs. Any additional costs will reduce the overall cost-competitiveness of sectors compared to businesses overseas, unless the same measures are taking place at the international level as the result of multilateral action or global agreement.

4.4. Industrial Energy Policy Context

This strategic conclusion builds on the section above regarding potential competitive disadvantage for UK sectors, and covers UK, EU and global policies and agreements (for example policy relating to carbon pricing, energy efficiency, biomass and waste). There are concerns in industry that the long-term direction of energy and climate change policies and regulations in the UK, or uncertainty about their direction, may put at risk international competitiveness. Uncertainty (perceived or real) weakens investors' confidence and reduces the ability of sectors to justify the business case for major investments in energy efficiency and decarbonisation technologies in the UK. This risk applies to any industry in whichever national regulatory regime it is operating, so there is a case for more analysis on whether the reported additional risk of UK policy uncertainty is real or perceived for these sectors.

The policy context needs to carefully balance industrial regulation and investment support. Many in the sectors have emphasised that a long-term energy and climate change policy framework alongside policy support for industrial competitiveness is key to investor confidence

This links to the business case barriers identified above: the business case for investment needs to be strong and to include risk identification and effective risk mitigation and control measures. Related to the point about competitiveness is the fact that rising energy costs and carbon costs in a particular country should not be assumed to lead automatically to more investment in energy efficiency, because there is often a viable alternative of moving production and investment to a different country with lower operating costs. The long term trajectory of higher CO_2 costs presents a clear challenge for the European and particularly UK sectors until there is a global climate change agreement and a multilateral commitment to CO_2 pricing.

4.5. Life Cycle Accounting

All sectors use raw materials from and provide products to other parts of the economy. A standardised and quantifiable means of understanding the overall carbon impact of the entire product life-cycle could put a value on life-cycle (carbon) benefits of both the sector's manufacturing and product performance[18]. This could better align industry incentives for generating revenue and maintaining competitiveness with societal incentives for decarbonisation by helping to build the case for investment in decarbonisation.

The interactions involved are complex – for example, producing biomass absorbs carbon; if this carbon is then 'sequestered' in a plastic derived from this biomass there might be a long-term societal carbon benefit, but this will depend on factors such as how the biomass is produced, the end-of-life disposal or re-use of the plastic and the alternative materials that the plastic may be replacing. There are also interactions with products from other sectors that need to be taken into account. This accounting would also help to determine, for example, how to compare the uses of a limited resource such as biomass (i.e. as a feedstock or a fuel) by assessing the overall life cycle carbon impact compared to that of alternatives (e.g. the continued use of fossil hydrocarbons) with or without carbon capture. Other examples that illustrate this complexity include cases where improvements produced with additional emissions in one sector deliver carbon benefits in other sectors.

This theme links to value chain collaboration described below. Work to develop standardised methodologies will benefit from involving academia, industry and government, as well as the value chain.

[18] See existing UK and related standards, such as PAS 2050 [Carbon Footprints of Goods and Services], PAS 2060 [Carbon Neutrality] and ISO TS 14067 [Carbon Footprint of Products]

4.6. Value Chain Collaboration

All sectors are part of value chains that link raw materials through production[19] to customers and consumers. The possibility to develop an entire supply chain analysis per sector could highlight 'carbon hotspots' and inform research activities. Hence, through value chain collaboration, opportunities to decarbonise and improve energy efficiency can be realised. For example, material efficiency explores opportunities to deliver the same quality of services for downstream industries with fewer material inputs (e.g. light-weighting in the iron and steel, ceramic and food packaging sectors), but requires engagement with the value chain to realise product or specification changes. Recycling presents an opportunity in the glass sector by increasing the use of recycled glass (cullet).

Creating markets for low carbon products is another opportunity that could be realised through value chain collaboration. At present, it is perceived that the majority of customers and consumers do not preferentially choose a low carbon product over a similar product manufactured to lower environmental standards. However, if consumers put a value on low-carbon products and were prepared to pay for this feature, this could address some of the business case barriers (see above) and help fund energy efficiency and CO_2 reduction. For example, creating markets for low carbon glass products would improve the business case for investing in additional environmental projects.

4.7. Research, Development and Demonstration

In order to realise the 40-60% reduction or Max Tech pathways, deployment of medium to longer term innovative technology is needed, which will require further technology development and demonstration before commercial scale deployment can be considered and costs fully understood. It is intended that the pathway information in the sector roadmaps will be used to inform technology innovation strategies for government and companies.

Evidence from the sector roadmaps has shown that RD&D is, in itself, an enabler to deployment of technology. For example, lack of demonstration of potentially beneficial technologies is a barrier to their use by companies. However, 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, and it is concluded that a collaborative approach is likely to be the most effective.

Examples of specific technologies that are included in the pathway analysis that require some level of RD&D are summarised below:

- **Carbon capture technologies,** suitable for different types of emissions in the cement, chemicals, iron and steel and refining sectors – and to a smaller extent, ceramics and glass. For example, the RD&D of oxy-combustion CO_2 technology is considered the most appropriate way forward in cement while the demonstration of capture technology in chemicals and refining needs to consider higher CO_2 concentration gas streams from ammonia and hydrogen production (in chemicals), more complex gas streams from fluid catalytic cracking (in refining) and blast furnace gas (in iron and steel). The RD&D of storage and/or use options including infrastructure required will need to progress alongside capture technologies.

- **Biomass technologies**, this includes the RD&D of advanced gasification and feedstock replacement in the ceramic, chemicals and glass sectors, as well as investigation of the future role (from a technology point of view) of biogenic materials in the cement, iron and steel and refining

[19] This project analysed carbon dioxide emissions from production only.

sectors. The 'biorefinery' is a concept that links clustering with a number of sectors including, for example, pulp and paper, chemicals and food and drink to power generation and the waste sector.

- **Electrification**, there is scope for **high temperature electrification** in the ceramics and glass sectors and **lower temperature electrification** in the food and drink and pulp and paper sectors.

- **Energy efficiency and heat recovery.** This is an active area of current RD&D. There are a wide range of variants of this technology group within the pathway analysis,– for example, ways of converting waste heat to electricity and improved monitoring and sensors for process control.

Innovation in technologies as they approach commercial scale requires very significant investments. Given the scale of investment need, alternative approaches to funding technology innovation are required. 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 can be an area where companies can collaborate (for example at pre-competitive stage such as the ULCOS programme that provided a focus for cross-company and cross-border collaboration within the European steel industry). European funding sources, and joint funding models could 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 sectors 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 could benefit the UK economy through global market opportunities for the technologies developed.

4.8. People and Skills

An ageing workforce and shortage of engineers were identified as challenges in several sectors, and this is likely to present a barrier to finding innovative ways to decarbonise (as well as the many other activities that sector resources are needed for). A highly educated workforce who can tackle new challenges including implementing advanced decarbonisation and energy efficiency technologies will be required. Lack of knowledge about the options and the routes to develop a company's energy efficiency program can be a barrier.

This agenda links to a range of existing initiatives that industry and government already support, for example the Science Industry Partnership, which helps to fund employer-led skills programmes in the chemicals and life sciences sectors.

Some sectors are also reported to lack diversity which not only reduces the talent pool but also reduces the attractiveness of the sector overall. Paired with a shortage of marketing and communication skills, other career paths may appeal more to graduates.

Based on evidence collected in the roadmaps, there are shortages or limited availability of a range of skills that can enable decarbonisation and energy efficiency progress:

- Operational and maintenance skills which can enable incremental improvements in energy efficiency;
- The ability to develop projects including articulating a viable business case;
- RD&D skills including the development of successful links with equipment manufacturers, technical centres and academia;

- Technical and engineering skills relating to specific processes and technologies identified in the pathways analysis such as combustion specialists (for example in cement, ceramics, glass and iron and steel), electrification (ceramics, glass, food and drink and pulp and paper) and chemical engineering (for example in those sectors where carbon capture could play a significant role);
- engagement with senior leaders, so that they understand the challenges in terms of skills and how they can develop and deploy the skills needed to tackle the challenges ahead.

4.9. Next Steps

The roadmap reports are intended to provide an evidence-based foundation upon which future policy can be implemented and actions delivered. The way in which the reports have been compiled is designed to ensure they have credibility with industrial, academic and other stakeholders and are recognised by government as a useful contribution when considering future policy. They will be successful if, as a result, the government and these sectors are able to build on the evidence and analysis to deliver significant reductions in carbon emissions, increased energy efficiency and a strong competitive position for UK energy intensive industry in the decades to come. In doing so, collaboration, leadership, innovation and coordination will be needed by industry, government and other experts.

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