Decarbonisation of heat in industry

A review of the research evidence







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Contact:

Heather Haydock
Ricardo-AEA Ltd
Gemini Building, Harwell, Didcot, OX11 0QR
t: 01235 753518
e: heather.haydock@ricardo-aea.com

Ricardo-AEA is certificated to ISO9001 and ISO14001

Lead authors:

Heather Haydock (Ricardo-AEA) and Tamaryn Napp (Imperial College)

Approved By:

Mahmoud Abu-Ebid

Date:

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Signed:

Executive summary

This is the final report from an evidence review on the decarbonisation of heat in industry by Ricardo-AEA and Imperial College for the UK Department of Energy and Climate Change (DECC) between January and March 2013. The review focused on the decarbonisation of energy use associated with heat in six sectors: refineries, metals (iron & steel, aluminium), non-metallic minerals (cement, ceramics, and glass), paper & pulp, chemicals, food & drink.

The evidence review addressed a series of research questions around:

- Key technologies applicable to each sector in the short- and longer-term
- The technical potential and associated costs of these technical measures
- The factors surrounding UK industry's investment in decarbonising heat, including economic and organisational drivers and barriers
- The effectiveness of current policy interventions
- The strength and transferability of the evidence base

Study methodology

The review followed a Rapid Evidence Assessment methodology in accordance with the guidance provided by DECC. Papers and reports were collected using a systematic search of relevant academic literature databases, a targeted search of the grey literature and requests for suggestions from relevant industry associations. Database search terms were chosen systematically and agreed upon in discussion with DECC. A total of 527 papers were collected using this search methodology. All papers were categorised and split according to sector and topic (i.e. technology, policy or organisational focus). The quality, source and objectivity of each paper were analysed and the papers were further filtered according to category-specific relevance criteria. The quality of evidence was assessed by examining the methods used, judging their robustness and the strength of conclusions drawn from them.

Experts from Ricardo-AEA and Imperial College were assigned to review the literature according to their background and expertise. In order to ensure a consistent approach across all reviews, experts were given guidance and templates to complete. All high relevance papers were read and assessed in depth. Experts also consulted the medium relevance papers where the evidence based on high relevance papers appeared to be insufficient. In some cases, additional papers were added to the database during the literature analysis phase based on following citation trails, expert knowledge and further targeted searches and recommendations.

Technical potential for decarbonisation of heat in UK industry

The evidence suggests there are some short-term opportunities to reduce carbon dioxide (CO_2) emissions in many sectors in the UK, for example through the further uptake of Combined Heat and Power (CHP), heat integration and heat networks, and in the longer term deeper emissions cuts will be possible through the introduction of novel technologies and fuel substitution. However, for many of the measures the evidence was incomplete on both the applicability to the UK and the carbon savings that could be achieved. The following paragraphs summarise our findings on the measures and technical potential for each sector.

<u>Refineries</u>

Significant technical potential exists for decarbonisation in the refinery sector between now and 2050. However, it is difficult to determine the exact scope for potential decarbonisation in the UK without detailed knowledge of current heat integration within UK refineries. It is possible that reanalysis and optimisation of existing heat exchanger networks could yield energy savings.

The most significant long-term savings in CO_2 could be made by implementing Carbon Capture and Storage (CCS) technologies within refineries, though these are in the process of development. Because refineries are extremely complex, there are a wide variety of potential energy saving technologies available. Research is on-going in the USA into a number of potential techniques such as the use of membranes in distillation, which could yield significant improvements in distillation efficiency of up to 33%.

Industrial ecology, including considerations of heat flow between different industries (which would need to be co-located in the future) could yield significant savings in overall heat use of between about 25% and 70%[1].

Chemicals

In the near term there is some technical potential for savings through process control and distillation column design. However, much of the literature reviewed referred to other countries and was not specific to the chemicals sector in the UK.

In the longer term, significant technical potential exists for decarbonisation in the chemicals sector to 2050, particularly from the application of advanced membrane, solvent and catalyst technologies to replace or enhance standard processes such as distillation. The slow rate of replacement of capital-intensive equipment and the high cost of research, development and demonstration of new technologies is a barrier to the implementation of these technologies in the UK. CCS is also an important abatement opportunity for certain parts of the chemicals industry in the longer term[2].

Iron and Steel

In the near term there may be some technical potential for savings through increased heat recovery/reuse through CHP and district heating. However, much of the literature reviewed which identified these technologies referred to other countries and was not specific to the iron and steel sector in the UK. It is the author's opinion that much of the short term opportunity has already been realised as a result of policies such as CCAs and the EU ETS.

Significant technical potential exists for longer-term decarbonisation in the iron and steel sector to 2050, particularly from technology under development focusing on the replacement of and retrofitting to existing blast furnace processes.

A potential barrier to the uptake for a number of these longer term technologies is that only a marginal increase in steel consumption in the UK/EU is forecast and it may be possible to meet future demand by increasing the productivity of existing blast furnaces. Furthermore as the majority of the technologies are aimed at replacement or retrofit of existing blast furnaces in the UK, such changes would need to be factored into the planned refurbishment/shutdown schedule for existing plant.

Aluminium

In the near term, the literature reviewed identified some technical potential for savings through increased heat recovery at primary production sites and through increased recycling. There is little potential for uptake of primary heat recovery in the UK due to the down-scaling of primary production caused by the closure of the Lynemouth Smelter in May 2012. In the UK 70-80% of aluminium scrap is already recycled so there is limited further opportunity from increased recycling.

There is much reduced potential for longer-term decarbonisation of the UK aluminium sector since the closure of the Lynemouth Smelter. Primary production is now restricted to the remaining smelter at Lochaber, which operates on a much smaller scale and uses hydropower. Lochaber therefore has relatively low emissions and limited potential for savings as fuel switching is not an option. Other long term abatement measures such as anode and cathode opportunities are very much at the development stage.

Paper and Pulp

[1] This upper limit was based on a single case, highly academic study, and may not be achievable in practice,
[2] DECC and BIS are funding separate research on industrial CCS and so we did not use CCS as an active search term for this project.

The CO_2 reduction opportunities in the paper sector include specific measures for reducing the energy use of the drying process such as on-line moisture measurement, pre-dryer dewatering, laser-ultrasonic stiffness sensors, and advanced fibrous fillers, and more significant changes to the process such as hot pressing, gas fired drying, Taking the paper production process as whole, there is potential for energy and carbon saving through process integration both within the plant and within the local area, through heat recovery, and through the use of low carbon energy supplies.

According to one report, there is the technical potential to reduce emissions by up to 23%[3] from the UK paper sector through the adoption of good practice and a range of innovative technologies, particularly relating to drying processes. However it is also reported that UK industry is reluctant to invest in unproven technologies or measures with a payback of more than a year, which suggests much of this potential may not be realised.

<u>Food and Drink</u>

Significant technical potential exists for decarbonisation in the food and drink sector to 2050, particularly from the application of dielectric heating technologies, CHP and heat pumps. The implementation of novel technologies such as high-pressure processing and pulse electric field is likely to be expensive, though new companies in this sector are considering such technologies.

Technologies like dielectric heating and ohmic heating show potential for short term decarbonisation in UK but the scale of their current deployment in the UK could not be determined. These electromagnetic technologies in food processing have gained increased industrial interest and have potential to replace, at least partially, the traditional well-established preservation processes within this sector.

<u>Cement</u>

The main near-term opportunities to reduce CO_2 emissions from the cement sector involve the use of kiln pre-calciners and preheaters and a greater use of alternative fuels and clinker substitute materials. The current uptake of each of these measures in the UK cement sector could not be determined from the literature. Fuel related CO_2 savings per unit of cement that occur because of an increased use of clinker substitute would reduce the CO_2 savings per unit of cement for other fuel related opportunities.

Cement systems other than Ordinary Portland Cement offer significant technical potential to reduce CO_2 emissions associated with cement manufacture in the longer term. However, there are issues to do with market acceptance and production scale up that would hamper the realisation of this potential. CCS is also an important CO_2 abatement option for the industry in the longer term.

<u>Ceramics</u>

Closing the gap between current practice and best practice in the bricks sub-sector has the potential to reduce CO_2 emissions associated with heat generation by 5%. Insufficient evidence is available to estimate the equivalent figure for other sub-sectors of ceramics.

The key long term CO_2 abatement opportunities in the ceramics sector are better heat integration, the use of syngas or biogas and greater use of electric kilns. However, the literature reviewed did not provide information to allow these opportunities to be quantified in the UK context.

<u>Glass</u>

There are a number of near term opportunities identified for reducing CO_2 emissions in the glass sector but the literature is unclear about the potential in the UK context. For example, it is not clear why oxy-fuel firing is not used more widely or what the remaining, feasible

[3] This figure was based on a single source; there was limited other UK-relevant evidence with which to validate it.

potential for increased cullet use is in the UK. Availability of cullet is a complex issue, and is influenced by waste policy.

Longer term opportunities covered in the literature are concerned with technologies rather than fuel switching from gas to syngas or biogas, and it is not understood why this opportunity is not covered.

Abatement costs

A relatively small number of reports, typically produced by consultancies for public sector clients, formed the bulk of a limited evidence base on the costs and cost-effectiveness of abatement options in the UK. These reports typically focused on a single sector or subsector in some detail or provided an overview of the likely future costs of a range of technologies and fuels by collating available cost data and applying extrapolations and expert judgement. A number of relevant reports prepared for and by international bodies such as the International Energy Agency (IEA) provided additional technology and sectorial coverage, but were not UK-focused.

There was a particular lack of useful data on the costs of mitigation measures in the academic literature, even for shorter term technologies, with sporadic cost data often quoted as a single capital cost (Capex) or as cost-effectiveness (£/tCO_2) without corresponding information on the baseline or discount rate applied. Where costs were available, they often related to application of technologies in other countries and so were not necessarily applicable to the UK context. This made it very difficult to validate or supplement the cost data in consultancy reports with data from the academic literature.

As a result we were unable to draw robust conclusions on short- or long-term abatement costs based on the literature reviewed.

Organisational barriers to uptake of abatement options

A number of studies have been done on the barriers to and drivers for the uptake of energy efficient technologies in the industry sectors addressed by this evidence review. The majority of these studies are based on surveys of companies in order to determine which barriers and drivers are considered the most important. Based on the literature reviewed, the key drivers are cost and threat of rising energy prices and willingness of top management to make climate change a priority. The key barriers are risk of disruption to production, lack of resources, both in terms of time and capital; and, closely related, lack of prioritisation. Continuity of production is of primary importance to firms. This is one of the reasons that energy efficiency technologies tend to have more stringent economic criteria compared to investments that are more closely related to the core business. There is limited evidence regarding how the drivers and barriers vary by company size and type and geography. In general, however, smaller companies and those that are less energy intensive typically have more barriers and have fewer drivers than larger, more energy intensive companies.

There is very limited UK specific research in this area. Additionally, in much of the literature only a descriptive analysis of the data was presented with only very few full regression analyses carried out. This limits the level of conclusions that can be drawn from the literature. One key area of weakness is that only one paper considered how to overcome the barriers and reinforce the drivers.

Effectiveness of existing policy mechanisms

The evidence of the effectiveness policies that apply to energy-intensive industries in the UK was reviewed. Currently, industries in the UK are subject to a wide range of policies, both nationally and at EU level. Whilst there is evidence in the literature indicating that the energy- and CO_2-intensity of these industries has decreased in recent decades, it is uncertain whether this was directly as a result of policy interventions.

The policy evidence base is very weak and it is difficult to summarise a consistent message across the evidence. The two major papers on the effectiveness of the Climate Change Agreements (CCAs) come to different conclusions. For example, modelling indicates that the

CCAs resulted in most industries achieving and even surpassing their targets by 2002. In contrast, a study that compared firm-level energy use found that the energy intensity of firms was higher with the CCAs than would have been expected without the policy. Regarding energy taxes combined with voluntary agreements, the majority of the literature supports the view that these schemes are effective and help uncover energy efficiency options, but there are several papers, which question whether the asymmetry of information between governments and industries means that they are deliberately underestimating their energy efficiency potential. The evidence on impact of the EU ETS and related competitiveness issues is also contended. In general, industry associations estimate much higher potential leakage rates (based on bottom-up analysis of cost increases) compared to energy and macro-modelling exercises.

Coverage and Strength of the Evidence Base

The majority of the papers and reports entered into the database had a technical focus. The majority addressed industry as a whole and did not refer to specific sectors. Of the papers that referred to specific industrial sectors, non-metallic minerals and iron and steel were the most well represented sectors in terms of the quantity of literature, each with around 100 papers. However, many of these papers were found not to be highly relevant on closer inspection. Food and drink, chemicals and refineries were the least well-covered sectors in terms of numbers of papers. Most of the literature was either not geographically specific or concerned industry on a global level, with only 37 papers focussed specifically on the UK. Out of all the papers collected in the database, 27% of papers were considered to have high relevance to the study based on the initial categorisation.

Table ES1 summarises the quantity and strength of the evidence base by sector and technology, and for the economic/organisational behaviour and policy themes. The table also shows the numbers of highly relevant papers and reports that were obtained from academic literature searches, directed searches of web sites, suggestions by sector stakeholders and from additional sources suggested by our expert reviewers. The literature provided information on potential CO_2 savings from a range of short- and longer-term decarbonisation technologies in all of the sectors covered by this study. However, for some sectors much of the information was based on non-UK case studies and so its relevance to the UK context may be limited. The academic literature tended to focus on a single technology in a single application while reports from international bodies and consultants were more comprehensive but may not have been subject to rigorous peer review.

Gaps in the evidence base

Analysis of the existing evidence base against the research questions for this project suggested a number of gaps in the evidence:

- The extent to which certain key short-term measures are really applicable in the UK. For example, what level of clinker substitution in cement production and fuel substitution in steel production is possible without adversely affecting product quality and customer confidence.
- The remaining potential for technology improvements and increased uptake in the UK of crosscutting technologies such as energy efficient boilers, burners and insulation.
- The longer term (post 2030) potential for electrification and hydrogen to affect deep cuts in CO_2 emissions in UK industry.
- The likely capital and operating costs of abatement technologies in different sectors and on different timescales, using a systematic approach to ensure comparability.
- The potential for application of CHP with novel technologies such as fuel cells and Carbon Capture and Storage (CCS).
- The scope for further improvement of heat integration through co-location of different industry sectors and with power generation, e.g. co-locating power generation with CCS with cement works or refineries.

- The barriers to and drivers for the decarbonisation of industrial heat within a UK context, together with an understanding of the key factors which determine the most important barriers and drivers for a company.
- The effectiveness of current policies in addressing the technical, economic and organisational barriers to the adoption of low carbon technologies in UK industry.

Table ES1: Summary of strength of evidence on industrial decarbonisation of heat

Sector/ Technology/ Theme	Number of high relevance papers reviewed					Strength of the evidence			
						International		UK-specific	
	Academic database searches	Directed website searches	Suggested by sector stake-holders	Expert reviewer additions[4]	Total[1]	Evidence on potential	Evidence on costs	Evidence on potential	Evidence on costs
Refineries	11	0	3	16	30 (26)	Strong	Medium	Medium	Weak
Chemicals	9	1	4	2	16 (6)	Strong	Medium	Medium	Weak
Iron & Steel	16	0	5	3	24 (6)	Medium	Strong	Strong	Medium
Aluminium	3	0	2	1	6 (5)	Medium	Medium	Weak	Weak
Paper & Pulp[2]	22	0	4	0	26 (8)	Medium	Weak	Weak	Weak
Food & Drink	6	1	2	5	14 (7)	Strong	Medium	Weak	Weak
Cement	8	0	9	3	20 (9)	Strong	Medium	Strong	Medium
Ceramics	5	0	5	1	11 (4)	Strong	Medium	Strong	Medium
Glass	3	0	1	4	8 (6)	Weak	Medium	Medium	Medium
Energy efficiency[3]	15	6	6	0	27 (3)	Medium	Weak	Weak	Weak
Biomass	6	2	9	2	19 (2)	Strong	Medium	Medium	Medium
CHP	10	1	1	3	15 (3)	Strong	Medium	Medium	Weak
Electrification	4	2	3	0	9 (2)	Weak	Weak	Medium	Weak
Hydrogen	2	2	2	2	8 (2)	Weak	Weak	Weak	Weak
						Evidence on barriers and drivers		Evidence on barriers and drivers	
Organisational	14	1	0	1	16 (13)	Medium		Weak	
						Evidence on effectiveness of interventions		Evidence on effectiveness of interventions	
Policy	26	1	8	1	36 (18)	Medium		Medium	

[1] First number is total number of papers rated as highly relevant during the categorisation process; of these only a few papers (represented by the number in brackets) were actually found to contain useful information by the expert reviewer. Note that, the initial categorisation was made based on a brief skim-read of the papers, hence when there was uncertainty over the ranking of the paper, the reviewers tended towards a higher ranking in order to avoid potentially excluding an important paper. As a result, when the high relevance papers were read in more detail a number were found to be less useful.
[2] Paper & pulp papers addressing chemical processing of pulp were excluded from this review as this is not done in the UK and is unlikely to be applied in the future.
[3] Crosscutting energy efficiency technologies only; sector-specific technologies are addressed under sectors.
[4] Assumed to all be high relevance

Key: Strong evidence = multiple papers written since 2010 that provide consistent, detailed and evidenced information on potential or costs
Medium evidence = multiple papers giving broadly consistent information or one credible recent paper with detailed and evidenced data
Weak evidence = some evidence but with inconsistent or missing data; or credible but very dated information
No evidence = no papers found that provide this information even after gap-filling with medium priority papers and secondary references

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Appendices

1 Introduction

This is the final report from a Rapid Evidence Assessment of the decarbonisation of heat in industry by Ricardo-AEA and Imperial College for the UK Department of Energy and Climate Change (DECC) between January and March 2013.

The aim of this review is to gather evidence that will help Government understand the opportunities and challenges associated with the decarbonisation of heat, as it relates to industrial enterprises. This evidence is required to suitably inform the development of a policy framework that drives the required levels of decarbonisation of industrial heat, but at the same time maintains a prosperous and competitive industrial sector such that high quality manufacturing jobs are preserved in the UK and carbon leakage does not result.

In order to achieve this aim, the evidence review addressed the following nine research questions:

1. TECHNICAL POTENTIAL: What existing research is there on the technical potential for decarbonising energy use associated with heat, and in particular heat demand in industry to 2050? What generic and specific technical measures including heat demand, production of heat and recycling/reuse of heat within a process or site does decarbonisation involve, and which heat-intensive industries are those measures applicable to?
2. TECHNOLOGY COSTS: What research is there on the costs of these technical measures, and what does it tell us?
3. DRIVERS: What does research tell us about the economic and organisational drivers for industrial organisations in the six sectors[4] to decarbonise their heat use? What are the perceived benefits for industrial organisations to decarbonise their heat use?
4. BARRIERS: What does research tell us about the economic and organisational barriers for industrial organisations in the six sectors limiting effective decarbonisation of their heat use?
5. POLICY EFFECTIVENESS: What evaluations exist of the effectiveness of past and present interventions (including UK government policies) in influencing industry decision making to drive decarbonisation of heat in the six sectors? Which interventions have been most effective and why?
6. INDUSTRY INVESTMENT: What are the factors surrounding UK industry's investment in decarbonising heat uses – in particular regarding competitiveness issues?
7. FRONT RUNNERS: What does research tell us about the similarities or differences across organisations making headway in decarbonising heat (for example geography, company size, other contextual factors), and how headway is baselined e.g. with respect to production output (in which case noting assumptions used if products change)?
8. INNOVATION: What is the 'state of the art' innovation for lower carbon industrial process heat use, and the context leading to innovation in UK or abroad?
9. EVIDENCE BASE: How robust is the evidence and what gaps are there in evidence on the above points? How transferable is evidence between sectors and outside these sectors to the medium energy intensive, and across geographies.

Rapid Evidence Assessments (REA) use the principles of systematic review but are constrained to a particular topic or key question(s). The aim of an REA is to give a quick overview of the existing research on a topic. In order to successfully conduct an REA within a

[4] Refineries, metals (iron & steel, aluminium), non-metallic minerals (cement, ceramics, glass), paper & pulp, chemicals, food & drink

short timescale it is crucial that the searching, screening and filtering stages are carefully planned to ensure that key papers are not overlooked, whilst at the same time excluding irrelevant information. A structured and systematic approach was developed; guided by the scope of the review as defined in Table 1. The full methodology is outlined in Section 2.

It is important to note that given the short timescale of an REA it is possible that not all relevant papers are captured. However, the REA should be sufficiently widespread to gain an overview of the strength of evidence on a particular topic. This report, therefore, refers only to the papers found in the process of this REA, i.e. where the report refers to 'the literature' this should be understood as 'the literature collected here'.

Table 1: Scope of the review

	Details
Main focus (i.e. these topics were actively searched for):	• Energy efficient heat generation (i.e. heat integration, lagging, avoiding heat loss) • Fuel switching - technical potential, technology readiness, downsides/barriers • Alternative fuels: Waste, biomass, biogas, electricity, to gas from coal, burning of by products, refinery fuels and others, hydrogen, ammonia, borates (future potential in industry, energy storage options?), hydrogen-gas blend • Heat networks - industrial clustering and heat integration • CO_2 only
Secondary focus (i.e. these topics were not actively searched for, but relevant points were drawn out of the selected literature):	• Process emissions reduction options • Feedstock substitution options • Carbon Capture and Storage (CCS)
Excluded:	• Energy efficiency in electrically driven equipment (e.g. motors, compressors, pumps etc.) • District heating networks • Non-CO_2 emissions (e.g. refrigerants, methane, PFCs, NO_X)

This report begins by describing the study methodology in Section 2. The research findings addressing research questions 1) to 6) are discussed in Section 3. A high level summary of the evidence including a discussion of the strength of the evidence base (research question 9) is provided in Section 4. Section 5 gives an overview of the remaining gaps in the literature, based on analysis of the metadata and expert review. The conclusions from the study are presented in Section 6. Finally the references are presented in Section 7 and further details of the methodology, including search criteria, are provided in appendices.

2 Methodology

The research questions identified for this project were grouped according to **Figure 1**. The research has three key areas of focus, namely: 1) technology focus which covers questions 1, 2 and 8; 2) Drivers and barriers analysis covering questions 3 and 4; and 3) Policy and intervention focus answering questions 5 and 6. In addition, research questions 7 and 9 were answered by examining the full evidence across all three of the focus areas.

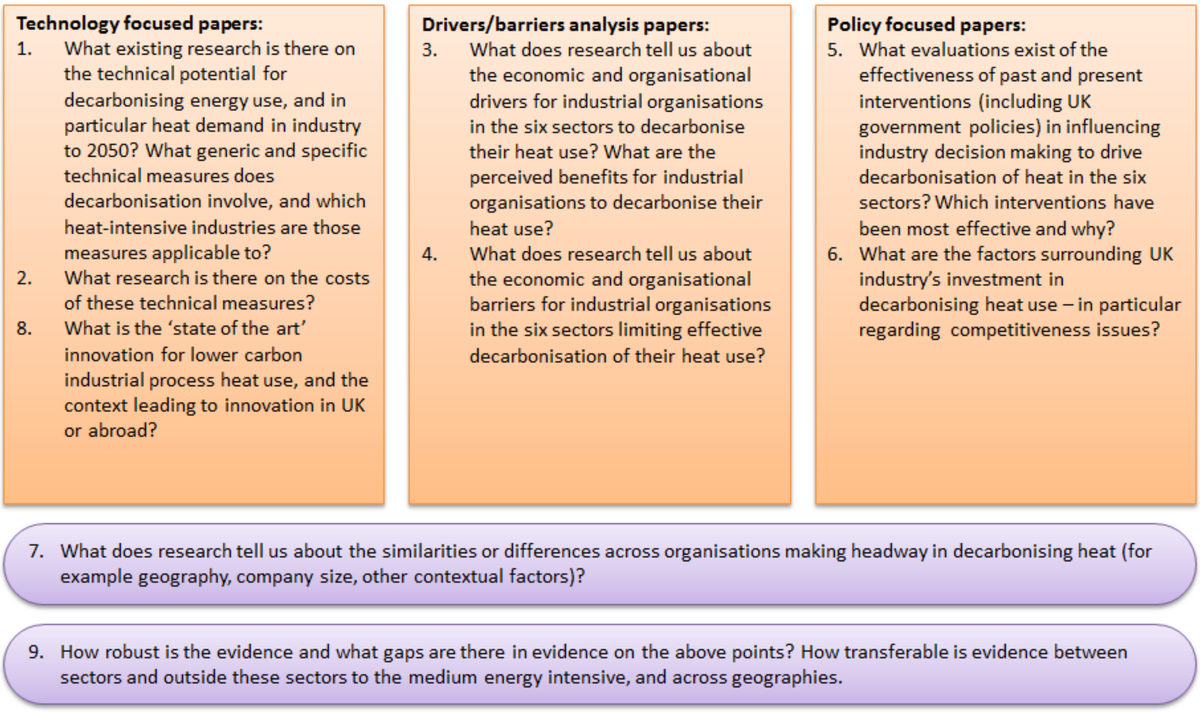


Figure 1: Schematic of the analysis of the literature, and questions, which will be addressed

The research was conducted in three phases: 1) A literature review and data collection phase, 2) a literature analysis phase and 3) a gap analysis phase.

The approach for the first phase is represented schematically in **Figure 2** below. Two main methods were used to collect papers: 1) a systematic search of the academic literature databases and 2) a targeted search of the grey literature by approaching industry contacts, trawling relevant websites and using industry networks to identify key papers. A number of online scientific databases were identified and these were categorised by priority according to the type of journals that they covered (refer to Appendix 1). Only the 'high priority' databases were consulted due to the short timescale of the project. Search terms were chosen systematically and agreed upon during early-stage discussions with DECC (These are shown in Appendix 2). For all searches, the search date, results (i.e. number of hits) and the number of papers retained, were recorded (a full table of results can be found in Appendix 3). Based on a brief scan of the title and abstract, the papers were filtered according to the chosen high level selection criteria (Appendix 4). Retained papers were saved to a database. The literature obtained through the targeted search approach, included a variety of reports written by industry, industrial organisations, consultancies and government. These were combined with the literature from the systematic search and saved to the database. All papers were then broadly categorised according to their general focus, i.e. whether the paper is largely 1) technology focussed, 2) driver/barriers focussed or 3) policy focussed. The papers were then skim-read and categorised using the form given in Appendix 5. Details of the category-specific relevance criteria, which were applied to determine how relevant the paper was to the research questions, are shown in Appendix 6. The quality criteria that were applied to the literature are also provided in Appendix 6. In particular, the quality of literature was assessed by examining the methods used, and judging their robustness and the strength of conclusions drawn from them. Based on this, each paper was given an overall relevance rating of high, medium, low or no relevance. The breadth of the evidence including key findings and meta-data are presented below.

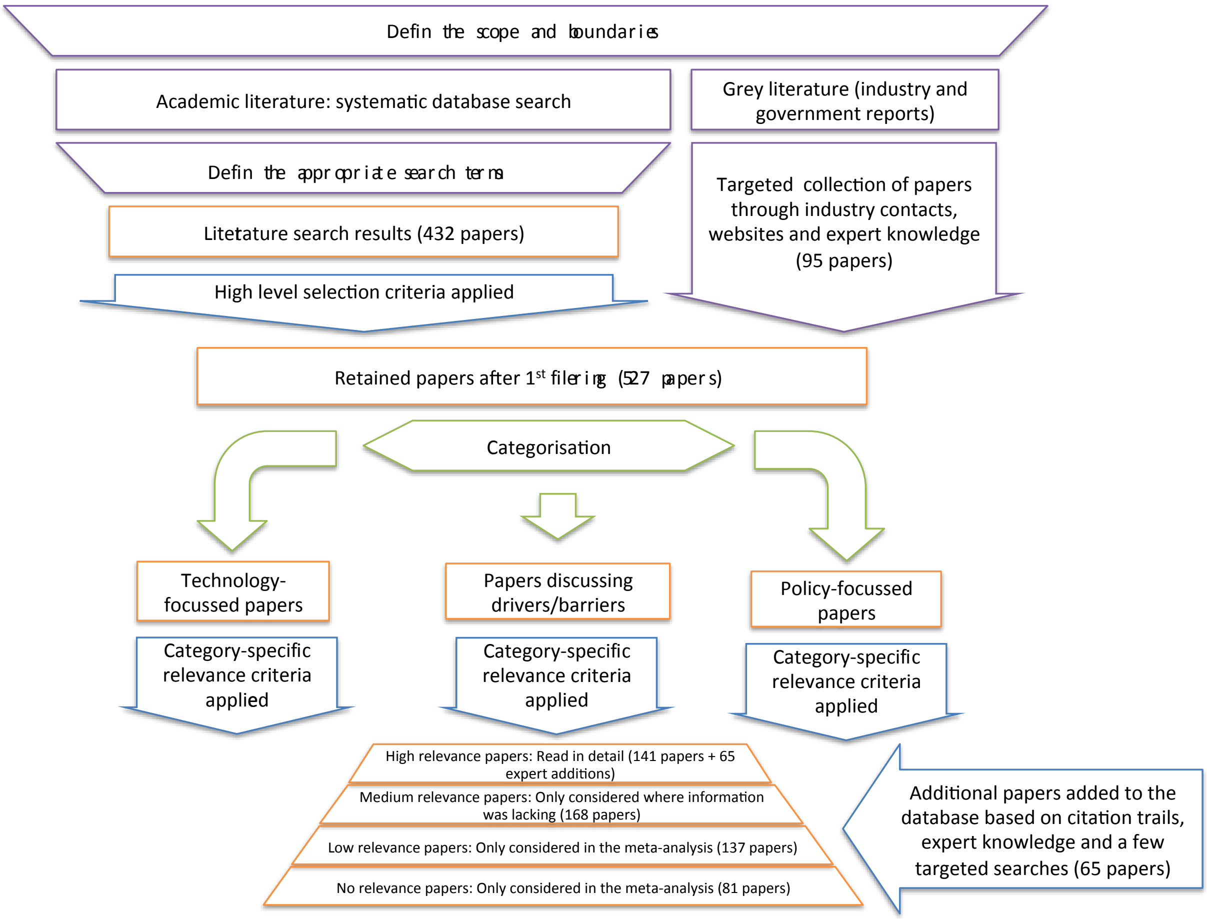


Figure 2: Diagram of the approach to selecting and categorising literature

Using the categorisation information, the papers were split according to sector, technology, policy and organisational focus as shown in **Figure 3**. Experts were assigned to review these papers according to their background and expertise. In order to ensure a consistent approach across all reviews, experts were given guidance as shown in Appendix 7.

All high relevance papers were read and assessed in depth. It is important to note that, the initial categorisation was made based on a brief skim-read of the papers, hence when there was uncertainty over the ranking of the paper, the reviewers tended towards a higher ranking in order to avoid potentially excluding an important paper. As a result, when the high relevance papers were read in more detail a number were found to be less useful. For sections where the evidence based on high relevance papers appeared to be insufficient, experts consulted the medium relevance papers before making a final conclusion, however in all cases no additional useful information was found. During the review process, the experts also added papers to the database by following citation trails, expert knowledge and further targeted searches and recommendations – these were automatically assumed to be high relevance papers.

Figure 4 gives an overview of the literature database, which was surveyed. The majority of the papers (70%) had a technical focus. Out of the all of the papers, 203 papers addressed industry as a whole and did not refer to specific sectors. Of the papers that referred to specific industrial sectors, non-metallic minerals and iron and steel were the most well represented sectors, each with around 100 papers. Food and drink, chemicals, refineries were the less well-covered sectors, but still had over 50 papers each. Most of the literature was either not geographically specific or concerned industry on a global level. The EU was well represented, with over 100 papers covering research in the EU. By comparison, there were only 37 papers that focussed specifically on the UK. Based on the relevance criteria outlined in presented in Appendix 6, papers were categorised according to overall relevance to the study. Out of the papers collected in the database, 27% of papers were considered to have high relevance to the study, 32% medium relevance, 26% low relevance and 15% were excluded at this stage.

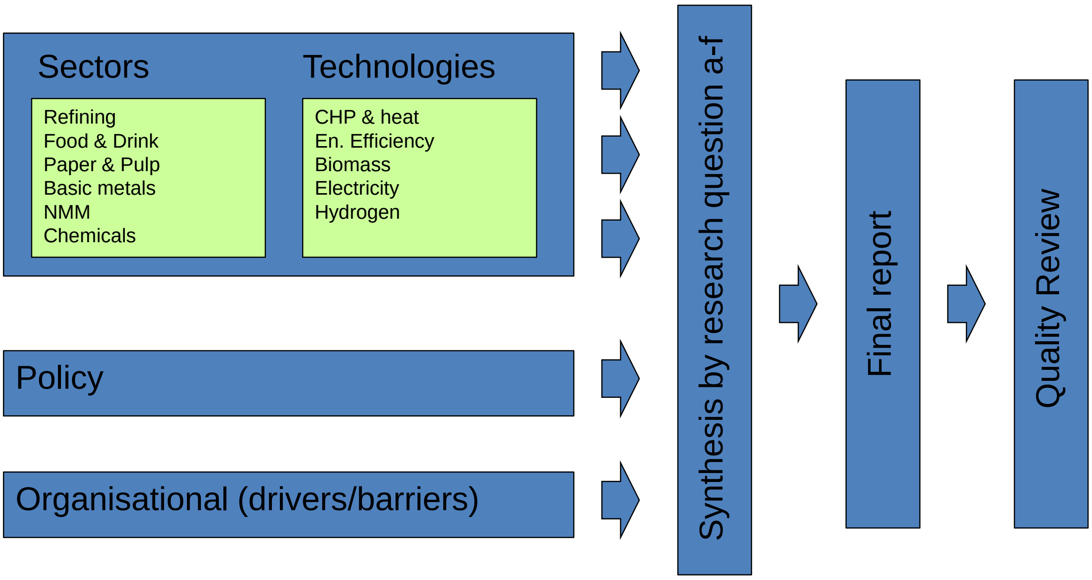
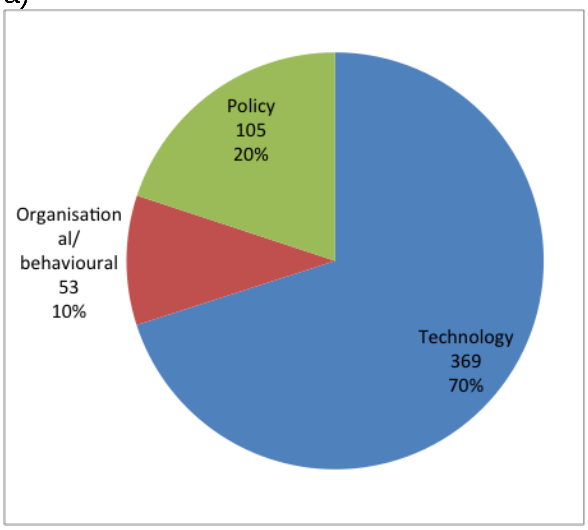


Figure 3: Diagram of information flow for the assessment of evidence

a)



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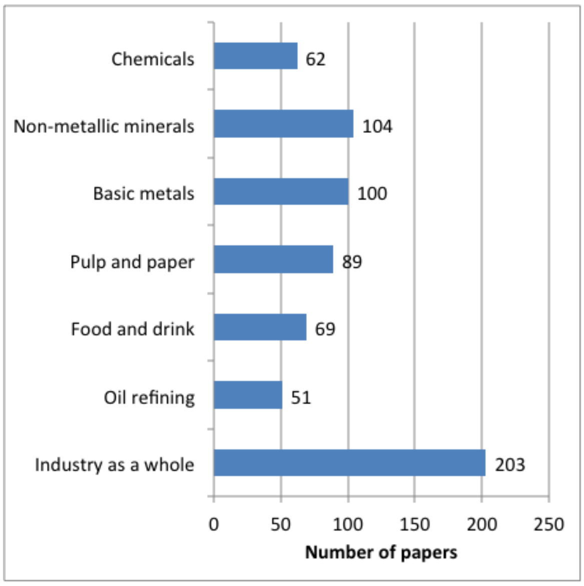

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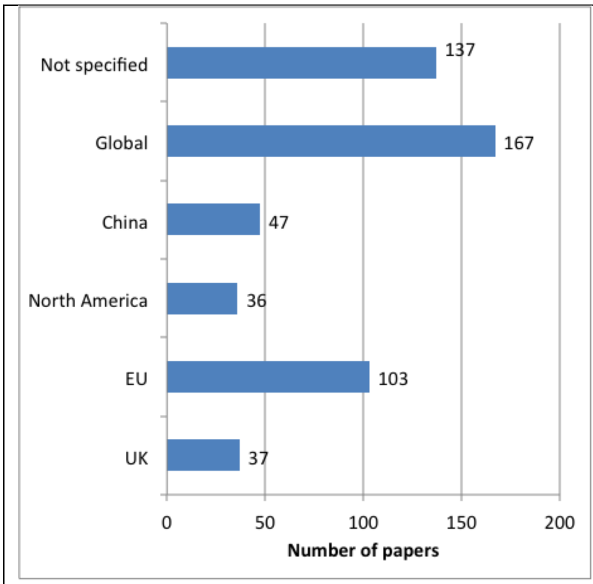


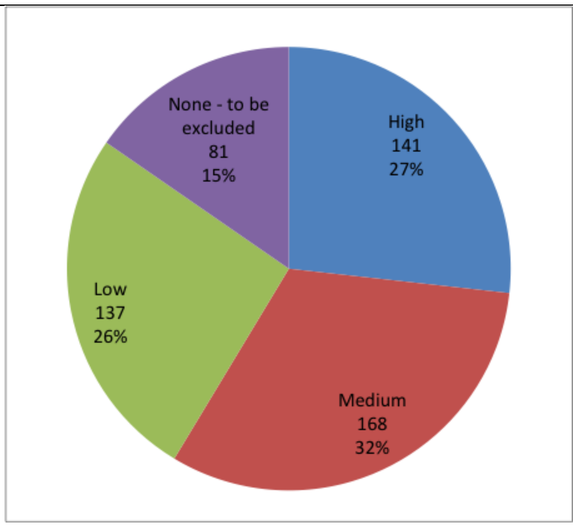


Figure 4: Overview of the literature collected (all papers). a) Breakdown of all papers by focus topic, b) Breakdown of all papers by industrial sector, c) Breakdown of all papers by geographical region of the research focus and d) Breakdown of papers by relevance

3 Research findings

This section presents findings from the review of papers and reports conducted by Ricardo-AEA and Imperial College experts. It starts by discussing decarbonisation options by sector for each of nine major emitting industry sectors (Section 3.1) and then reviews the evidence on crosscutting technologies (Section 3.2) such as CHP and biomass. This is followed by a review of the evidence on drivers and barriers to decarbonisation of heat in industry (Section 3.3) and finally a discussion of key policies and their effectiveness (Section 3.4).

We have referenced statements and data throughout, making it clear where any information is based on the author's opinion rather than evidence in the literature. The strength of the evidence in the literature is discussed in the summary of the evidence and gap analysis sections (Sections 4 and 5).

3.1 Sectoral analysis

This section presents our findings from the evidence review on decarbonisation potential and associated costs for short- and long-term technology options in each of nine industry sectors: refineries, chemicals, iron & steel, aluminium, paper and pulp, food and drink, cement, ceramics and glass. Short-term options are defined as those available now or before 2020 while long-term options will not be available until later decades.

For each sector we present a short discussion of the key findings on decarbonisation technologies, costs and sector-specific barriers followed by a table providing more detailed information on selected key technologies for that sector.

A large part of the information useful for answering the research questions on technologies, abatement options and costs found in the so called meta-documents, that is those documents that were already syntheses of peer reviewed academic literature and other reports produced by consultancies and sector associations. Although both academic literature and meta-documents identified the opportunities for CO_2 abatement, only the meta-documents provided data on costs. In the sections that follow, we have tried to make it clear what information comes directly from the literature and where our experts have used their judgement or opinion to add context or fill gaps.

3.1.1 Refineries

Key Findings

Significant technical potential exists for decarbonisation in the refinery sector between now and 2050. However, it is difficult to determine the exact scope for potential decarbonisation in the UK without detailed knowledge of current heat integration within UK refineries. It is possible that reanalysis and optimisation of existing heat exchanger networks could yield energy savings (author's opinion, based on publications relating to other countries). If scope was found in UK refineries for improvement, payback times can be short (3 – 12 months) ([3],[4]).

The most significant long-term savings in CO_2 can be made by implementing carbon capture and storage technologies within refineries [5], though these are in the process of development. Because refineries are extremely complex, there is a wide variety of potential energy saving technologies available, these have been investigated in detail as part of the US ENERGY STAR ® program [13]. Research is on-going in the USA into a number of potential techniques such as the use of membranes in distillation [6], which could yield significant improvements in distillation efficiency of up to 33% [6].

Industrial ecology, including considerations of heat flow between different industries (which would need to be co-located in the future) can yield significant savings in overall heat use – between 25% (author's opinion, readily achievable) and 71% (single case, highly academic study, may not be achievable in practice) [7][8].

There is technical potential for increased use of hydrogen in refineries as part of a wider hydrogen economy, though care is necessary to ensure that overall well-to-wheels lifecycle efficiency is not compromised. There is limited scope for electrification in this industry, when consideration is made of wider efficiency grounds (author's opinion).

Petroleum refineries in the UK produce a variety of products including petrol (26%), diesel (32%), jet fuel (8%), fuel oil (10%) [9] and a range of other products including lubricants and bitumen [9]. These are produced through distillation of crude oil (heating, to separate by differences in volatility) and a number of other chemical processes such as catalytic cracking (transformation of larger and heavier oil fractions into smaller and more valuable ones). Since these processes generally involve the application of heat, CO_2 emissions from refineries worldwide are dominated by those produced by boilers and furnaces as shown in **Figure 5**. The main source of direct process emissions is the regeneration of catalyst from the catalytic cracker.

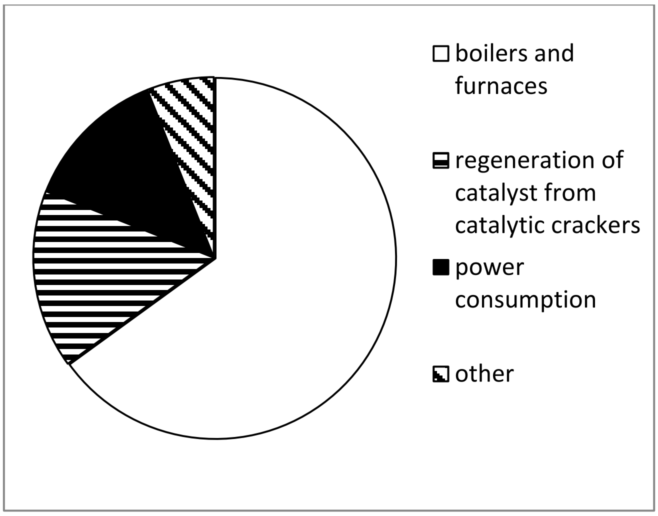


Figure 5: Sources of CO_2 emissions from refineries [9].

This discussion will therefore focus on improvements to heat production and utilisation, with a brief consideration of other areas. The findings of this report are similar to those of a previous report for the Committee on Climate Change [10]. The most significant areas for short-term energy savings are by optimisation of heat utilisation (heat exchanger network optimisation and fouling mitigation), and for the future in improvements in distillation technology and through carbon capture and storage (CCS).

Table 2 at the end of this section shows a summary of the key technologies, abatement potential, costs and barriers for the refineries sector from the literature.

3.1.1.1 Short term decarbonisation opportunities: potential and costs

Energy efficiency: Significant reductions in CO_2 emissions can be achieved from optimising the energy efficiency of the systems in use. Heat exchangers are a key example, moving heat from process streams that require cooling to those that require heating. There are many heat exchangers in a typical refinery. However, it is possible (author's opinion, based on similar cases discussed below) that as a refinery has grown, the addition of new heat exchangers to the network has been done in a sub-optimal manner, prioritising short-term throughput improvements over long-term energy savings. This can be an outcome of incremental engineering projects, which are done piecemeal because of the industrial annual budgeting process. Furthermore, during operation, heat exchangers become less efficient, owing to the build-up of deposits within them (fouling). Since fouling mitigation (for example, by cleaning off deposits) requires the heat exchanger to be taken off-line, shutting down the associated process equipment, there is a trade-off between energy efficiency and plant throughput. Furthermore, fouling can be accelerated by the processing of lower quality crudes – a decision that might appear attractive in the short-term.

Reanalysis and improvement of the heat-exchanger system can yield a ~ 25% saving in fuel energy use (comprising ~ 93 % of the energy use in the refinery, with the remainder being electricity) [3]. Branco et al. [11] evaluated abatement costs for thermal energy management such as improvements to heat exchanger networks and fouling mitigation in Brazilian oil refineries. Results show relatively high costs for introducing these measures of 20.2 to 77.3 $ US/tCO_2 for thermal energy management and 115.6 to 210.8 $ US/tCO_2 for fouling mitigation. Savings from improved heat exchanger networks depend mainly upon whether the system was optimised properly to start with, and whether subsequent additions have also been carefully integrated. If they have, the savings may be significantly lower: "Given the more energy-efficient refinery industry in Europe, it is reasonable to assume that it has a lower energy saving potential for heat integration and waste heat integration than the US petroleum industry."[7]. Where opportunities exist (for example, where poorly optimised heat-exchanger systems are in place), there is the potential for extremely rapid payback times – two or three months ([3],[4]). However, without specific information for UK refineries, it is not possible to determine if such opportunities exist. The evidence therefore suggests that there are significant technical potential savings of up to 25 % of fuel used through heat optimisation, though this will depend upon the initial efficiency of UK refineries.

Others have suggested more significant activity, such as retrofitting furnaces to be more efficient [12].

One significant survey of a number of potential energy savings as part of the US ENERGY STAR® program [13] found 10–15% savings in energy use are justified by the economics [13]. The document is a detailed analysis of many technologies for refining, running to 100 + pages. The major technologies discussed include thermal energy management (improved heat exchanger networks, as discussed above), power recovery via turbo-expanders, elimination of flaring (and recovery of hydrogen from streams where it is present but not required for the process and improvements to hydrogen production units), improved process control at a variety of locations within the plant, including the fluid catalytic cracker, improved steam production and better matching between steam production and utilisation pressure, reducing heat exchanger fouling (as discussed above) and air preheating and improved burners for process heating, and better motors, pumps, fans and compressors, including improved maintenance. In addition, it was noted that over-purification of products (for example, refining a product to 99 % purity when 95 % is acceptable) can lead to significant energy costs. Furthermore, changes to cooling processes in the distillation column, upgrading column internals and improved distillation chains were also discussed, alongside CHP and improvements to power generation. A summary of all technologies discussed is found on pages 81 – 82 of the document [13]. There is significant evidence that there are a large number of potential energy savings possible in refineries in general, but the potential savings in a UK context will depend upon how many of the particular technologies are already being applied.

There is one issue, as discussed in Johansson et al. [7] "many economists argue that analyses that show strong profitability for energy efficiency must have overlooked some real costs (but perhaps intangible) for consumers or firms, otherwise such strategies would already have been implemented" ([14],[15]). Of course, capital expenditure may be delayed in any particular jurisdiction (including the UK) if a more profitable expenditure can be made elsewhere. In general the evidence, as well as the author's understanding, indicates that improving plant throughput is generally considered to be more important than energy efficiency. This finding is in line with that from [10]. Eldridge et al. [6] indicate that energy efficiency measures need to pay back within only 12 months for them to be implemented.

CHP and heat recovery: No papers in the evidence base specifically addressed CHP in refining, probably because it is normal practice to install CHP at refineries. In the UK most refineries have some sort of CHP; some have reached their maximum technical potential such as Humber refinery but the majority still have some potential for further capacity [16]. Heat from CHP systems can go both to and from a refinery (depending upon the temperature of the heat required and available), and optimising the integration of heat between different industries, including refining, and power generation can lead to improved overall efficiency (author's opinion).

Ricardo-AEA's recent study into the potential for CHP [17],puts the projected CHP capacity for the energy Industry at 4,590 MWe by 2030, This projected capacity, which includes existing capacity, is the economic potential capacity adjusted for barriers preventing the economic potential from being taken up[5]. Of this 4,590 MWe, 2,790 MWe is within refineries. The author estimates that the Good Quality CHP capacity at refineries in 2012 was about 2,100 MWe, implying an additional projected potential capacity of 690 MWe by 2030, which is both economic and realistic.

Putting these figures into context, the same report by Ricardo-AEA estimates an overall technical CHP potential by 2030 of 33,783 MWe covering all sectors including Refineries, LNG and Oil Terminals [17], with 20,138 MWe[6] of this capacity being economic and 12,128 MWe being projected (realistic) potential.[7]

3.1.1.2 Long term decarbonisation opportunities: potential and costs

Energy efficiency: There is potential for technical innovation in multiple areas. Combined distillation and membrane separation [6] was highlighted by the US DoE (33% saving). The Institute for Sustainable Process Technology (wwww.ispt.eu) in the Netherlands is a multi-million Euro public-private partnership undertaking research, development and technology transfer in the area of energy-efficient separation technologies. There is scope for increased electrical efficiency in some rotating machinery, especially compressors, using variable speed drives for example (author's opinion and from discussions with Shell). An advanced pumping system might have an efficiency of 72%, compared to a conventional system's efficiency of 31% [18]. The evidence shows that further research and development of novel technologies for separations could yield significant (though challenging to quantify) returns in terms of future energy and decarbonisation targets, and potentially increased profitability.

Co-location of industries: The ideal way to reduce energy usage is to extract the maximum possible utility per unit of heat. This means that industries that use high temperature heat should be integrated with those requiring medium temperature heat, and these in turn should deliver heat to low-grade heat applications. Although no specific evidence was collected, it seems likely that it would require significant effort to encourage industries to work in this manner (author's experience from other industries with similar potential integration), but the potential savings are very large. Johansson et al. [7] indicates a technical potential of 20 – 25% energy saving in a study focussing on refining in the EU and Norway, whereas Hayakawa and Suzuoki [8] analysed heat flows and determined that were existing industries in three Japanese prefectures integrated in this way, there would be potential energy savings of up to 37%, 24% and 71% respectively, in each prefecture. Costs were not calculated. It has been estimated that industrial ecology in the Kalundborg eco-park (Denmark) saves between $12 million and $15 million per annum [19], together with more than 150,000 tonnes of CO_2 per annum. Assigning cost and CO_2 savings in an interconnected industrial system is challenging, since it is possible for e.g. a refinery to take heat from a power station at one temperature and return it at a different temperature, yielding an overall reduction in heat use for both, but different potential accounting methods can be employed (frequently based on heat, exergy or economic value, though such a discussion is beyond the scope of this work).

[5] E.g. aversion to risk, hurdle rates in some sectors being higher than that assumed in the economic modelling and problems with access to finance
[6] Assuming a Discount Rate of 15%
[7] Projected (realistic). Takes into account other barriers to the implementation of the economic potential identified, including aversion to risk, hurdle rates in some sectors being higher than that assumed in the economic modelling and problems with access to finance.

The evidence therefore shows that this concept has been applied in some locations (outside the UK), and that the potential for savings is large, provided that hurdles can be overcome in terms of industries working together.

Hydrogen: Refineries already use significant quantities of hydrogen in hydrotreaters and hydrocrackers [20], and it is likely that these uses will increase with time given the likelihood for more stringent fuel quality regulations. While there was no evidence in the literature on the burning of hydrogen to provide heat in refinery operations, it is understood that this is normal practice where there is *excess* hydrogen in the refinery, with the hydrogen usually fired in boilers (author's opinion). It is unlikely that extra hydrogen would be produced in order to fire boilers. This is because technologies such as steam-methane reforming are required to produce the hydrogen; a typical reforming process is around 70% efficient [21] without CCS, and will be lower if CCS is applied. Assuming similar combustion efficiencies, it would be more sensible to burn methane directly in the heater and to capture the CO_2 from this process, since this eliminates the inefficient and unnecessary reforming step. The addition of a large-scale gasifier within a refinery might service such a need, but again requires a CCS system to be CO_2 neutral. The author is aware that this would entail a very high capital cost. However, as part of a wider industrial system based on hydrogen in a low-carbon economy, refineries could in principle increase their use of hydrogen in heat generation and co-generation activities (author's opinion), for example if a large gasifier were to be built locally to produce hydrogen for power applications, there could be scope for off-peak utilisation of H_2. The evidence demonstrates that where excess hydrogen is available in or close to a refinery, it might be fired within it. However, producing extra hydrogen specifically for use in a refinery would in the opinion of the author make little sense on the grounds of efficiency. Further evidence is required to conclusively settle the matter.

Electrification: This review of the literature has found limited evidence for the potential for electrification in refineries. This is in full agreement with [10]. Electrification would require a decarbonised electricity source to produce heat. Only around 50% of the chemical energy in the fuel will be transformed into electricity, which can be used in the refinery (on-site CHP can be used, but (author's opinion) significant advances in technology will be required to allow the production of heat above ~ 150^{o}C). This means that a more efficient use of the fuel would be to directly fire a process boiler. Furthermore (with the exception of fuels for large trucks and aviation), the end-use of the fuel or electricity used has to be considered. The electricity used in the refinery to produce high-temperature heat could otherwise be used to directly charge an electric vehicle, and without any tailpipe emissions.

CCS: Carbon Capture and Storage is possible in many refinery locations, with potential costs from 38 - 134 $\$_{2011}$ / ton of CO_2 avoided [5]. Another study has identified technical abatement potential from CCS in the UK refineries sector of about 6 $MtCO_2$/year by 2030 in a cost range of 88-107 $£_{2010}$/tonne CO_2 [10].

3.1.1.3 Sector-specific barriers

The evidence suggests that the CO_2 price required to make refinery owners invest in CO_2 mitigation is quite high ([7] discusses findings from [22]): "Similarly, in a study of the Brazilian oil refining industry in which the impact of CO_2 taxation on the configuration of new refineries was investigated", results indicated that measures to reduce emissions in new refineries require a CO_2 price of about 100 \$/tCO_2.

Table 2: Summary of key technologies, potential, costs and barriers for the refineries sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings found in specific studies – not UK specific	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
Optimising heat exchange in refinery – can be a reanalysis of current heat exchange strategy	Commercial	Short term	20 – 30% energy efficiency improvement [3],[4]. Perhaps 10 – 15% justified by economics [13]	Negative cost [12], through to 20.2 - 77.3 $\$_{2011}/tCO_2$ [11]. Some claim a cost of $\$100/tCO_2$ is required to influence investment [22]	Global, but not always implemented	No evidence for UK	Low
Heat cascading: Optimisation of heat utilisation by co-location of different industries[8]	Commercial	Short term	20 – 25% [7] up to 71% [8] of energy	Estimated **saving** of $12 – 15 million / yr for Kalundborg [19]	The Netherlands, USA (trials), Denmark (established) [19].	N/A	Desire of individual industries not to be tied to other industries.
Other Improvements in heat utilisation: Improvements to boilers, reactors, etc. [12]	Various	Short term	Various	Unclear	Unclear – scope for improvement depends on the baseline technology	No Evidence	Cost [12] Other barriers including costs for management, potential for system shutdown, etc.
Next generation distillation e.g. combined membrane and distillation.	Development	Long Term	33% energy saving [6]	Unclear	None / research globally.	None	Basic research needs to be done / implemented
Carbon capture and storage (CCS)	Development / Deployment	Long term	80% emissions avoidance	A range, from 38 $\$_{2011}$ to 134 $\$_{2011}$ per ton of CO_2 depending on location and technology [5].	Storage Demonstrations in Norway, Algeria, USA/Canada. Capture in a number of locations	None so far – demonstration planned	Lack of demonstration

[8] For example, Kalundborg situates a refinery and a power station with other industries

3.1.2 Chemicals

Key Findings

In the near term there is some potential for savings through process control and distillation column design but much of the literature reviewed referred to other countries and was not specific to the chemicals sector in the UK, where it is the author's opinion that a number of the identified opportunities for decarbonisation have already been carried out, as a result of policies such as Climate Change Agreements (CCA) and the EU Emissions Trading System (EU ETS).

In the longer term, significant potential exists for decarbonisation in the chemicals sector to 2050, particularly from the application of advanced membrane, solvent and catalyst technologies to replace or enhance standard processes such as distillation. The slow rate of replacement of capital-intensive equipment and the high cost of research, development and demonstration of new technologies is a barrier to the implementation of these technologies in the UK.

CCS is an important abatement opportunity for certain parts of the industry in the longer term, in particular for ammonia production and steam-methane reforming hydrogen plant, where the concentration of CO_2 in the separated gas streams approaches 100%.

In the UK, the chemicals sector accounts for 18% of total industrial CO_2 emissions (34.8 $MtCO_2$), equivalent to approximately 10% of direct emissions (9.3 $MtCO_2$), with a trade surplus in 2006 of £4.4bn and a strong record of innovation [23]. There is a wide range of production processes and of technologies that can be applied to decarbonise these processes. There are key technologies that can be applied to stages and processes common to a number of different chemical production processes, both short-term and long-term, and which are consistently reported in the major reports on technology opportunities [10], [24–26]. Table 3 shows a summary of the key technologies, abatement potential, costs and barriers for the chemicals sector.

3.1.2.1 Short term decarbonisation opportunities: potential and costs

Improved Separation (new designs, process control, new solvents, membrane technology): Separation accounts for 60% of chemicals energy use worldwide and distillation accounts for 95% of the energy in separation [6]. The ways in which separation can be made more energy efficient include:

- Improving distillation through new designs of distillation column, e.g. divided wall columns, or new distillation sequences
- Improved process control of distillation
- Use of more efficient solvents to speed distillation
- Using membranes for separation in place of distillation

All of these technologies are in use to some degree already (e.g. membranes used for monomer recovery in polymer plants) but the major savings are likely to be longer-term, particularly for membranes [10], [24–26].

Cumulative net savings potential of £3.0bn in carbon abated and energy saved by 2050 is given for improved membrane separation in the chemicals sector in the UK [24] but no savings figure in CO_2 terms is given. Improvements to distillation columns can also achieve large savings in energy and carbon but are case specific – up to 22% reductions in CO_2 are reported [27]. As the opportunities are process specific, there will be a mixture of short term and longer-term activities.

Waste Heat Recovery/Process Integration/Process Optimisation: Large carbon savings can be made through improved utilisation of heating and heat recovery, often as an integral part of a CHP system. Distillation is the workhorse of chemical process industries. Gadalla et al [27] have shown that, for example, reductions of up to 22% in CO_2 emissions from a crude oil[9] distillation column can be achieved through process optimisation (e.g. by optimising the feed-in temperature, the liquid flow rate and the steam flow rate) and an extra 48% when coupled with a gas turbine. They have also shown that heat integrated distillation systems, coupled with a gas turbine, can reduce the CO_2 from the reboiler by 83% compared to a simple conventional distillation column and by 36% compared to a heat pump design. Similarly, savings of approximately 20% in energy costs have been reported from utilisation of flue gas exhaust heat for air preheating [12]. It is worth noting, however, that these papers ([12], [27]) are already quite old and in the author's opinion, based on experience from the CCAs programme, much of these measures have already been implemented by most of the industry in the UK. Nothing more recent was available in the literature.

In general it has been estimated that the potential total energy savings from heat recovery in chemicals in the UK is between 5-10%, based on 2005 data [28].

<u>Process Intensification:</u> Process intensification is defined as improving the efficiency of a chemical plant by optimisation of the process through the use of novel techniques (e.g. miniaturisation, synergy between reaction and separation) [29]. It is highly process specific and diverse and often comprises a set of radically innovative principles in process and equipment design, which can improve energy efficiency. There are limited examples of process intensification in the literature, although more than 60 technologies have been identified [29] which can contribute to energy savings in the next 10 to 40 years, with potential energy savings of 5% in the next 10-20 years and 20% in the next 30-40 years [29].

<u>Process Specific Savings:</u> There are a number of process-specific saving opportunities as listed below:
Ammonia production: Opportunities have been identified by [30] to reduce energy consumption at various stages in the ammonia production process, though no specific timescales or savings are provided:

- In the steam reforming stage – reduction of flue gas temperature; improved furnace insulation to reduce heat loss; increased pre-heat temperature for feed, steam and air used; increased operating pressure and reduced steam to carbon ratio
- New measures (beyond 2020) include - gas-heated reformers with smaller surface areas, palladium membrane units for H_2 separation, new high temperature catalysts for the 'shift' stage of production, new solvents and membranes (to replace distillation) in the CO_2 removal stage of production

Steam cracking options – higher-temperature furnaces, gas-turbine integration, advanced distillation columns and combined refrigeration plants – total worldwide potential saving of 24 Mtoe from existing to best-available technologies [31].
N_2O reduction from nitric and adipic acid production – this gives greenhouse gas savings but not CO_2 savings so is outside the scope of this report [10].

3.1.2.2 Long term decarbonisation opportunities: potential and costs

<u>More efficient use of hydrogen in the Chlor Alkali production process [24]:</u> This involves the more efficient use of the hydrogen by-product from the chlor alkali process. Net savings potential of £0.09bn in carbon abated and energy saved by 2050 is given for the UK [24].

<u>Improved Separation (new designs, process control, new solvents, membrane technology)</u>: Potential savings from using membranes are large, from 20% energy savings [29] to as high as 30-40% energy savings [26] by 2050, but this will not be fully commercial until after 2030. Considerable research is required into new and cheaper membrane technology (currently reliant on expensive metals like palladium) to demonstrate the validity of these savings [29].

[9] This is given as an example of savings in distillation, which is the most important energy-using activity in chemical process industries

Bioprocessing/Biocatalysts: Bioprocessing/bio-catalysts require long lead times and major changes to existing facilities. Total potential savings have been identified from bioprocessing/bio-catalysts in the UK of 0.1 $MtCO_2$ by 2030 [10]. It is estimated that the potential savings from the use of biopolymers worldwide rises from 0.05 $GtCO_2$ p.a. in 2015 to 0.3 $GtCO_2$ p.a. in 2050 at a cost falling from \$15k/tCO_2 to \$5k/tCO_2 (at 2008 prices) [31].

CCS: The viability of CCS is highly dependent on the chemical process being considered, due to the composition of the flue gas and partial and total pressure of CO_2 within it. In the chemicals sector the concentration of CO_2 in the separated gas streams can reach nearly 100% (as shown in the table below). Where large volume concentrated sources exist (such as in ammonia and steam-methane reforming (SMR) hydrogen plant), the only equipment required would be relatively low cost compressors, drying equipment, pumps, coolers and separators [10], resulting in cost estimates for CCS ranging from £10-20 /tCO_2 for ammonia and ethanol production [26], [29].

Typical content of CO_2 in gas streams [32]

Sector	% CO_2
Ammonia	~100%
Hydrogen	10 to ~100%
Ethylene oxide	~100%

3.1.2.3 Sector-specific barriers

The main sector-specific barrier to implementation of decarbonisation opportunities in the UK is the high level of sunken capital investment and the slow rate of replacement, in common with other OECD countries [29]. This means that the more advanced measures, such as membrane technology, are only likely to be implemented when existing plant is replaced. Another major barrier is the large cost of research, development and demonstration required for new technologies and the perception that the ‘first-mover’ is disadvantaged by bearing these costs. Other barriers, such as a low and unstable carbon price and the lack of a stable policy regime, are common to many sectors.

Table 3: Summary of key technologies, potential, costs and barriers for the Chemicals sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
Improved separation (new designs, process control, new solvents, membrane technology)	Commercial/ Demonstration/ Development	Short/Longer term	Varies e.g. 20% [29] in energy	~£3.0bn net savings in UK by 2050 [24]	Insufficient evidence	Insufficient evidence	High level of sunken capital investment/slow rate of replacement. High cost of RD&D/ 'first mover' disadvantage
Waste Heat Recovery/Process Integration/Process Optimisation	Commercial/ Demonstration/ Development	Short/Longer term	Varies: e.g. 22% saving [27] in carbon 5-10% saving for waste heat recovery [28] in energy	No evidence	Insufficient evidence but widespread.	No detail but widespread.	Lack of local use for waste heat
Process intensification	Some commercial, but mainly development	Mainly Longer term.	No evidence	No evidence	Insufficient evidence	Insufficient evidence	Insufficient evidence
Advanced recovery and recycling	Demonstration	Short term	20-30% [29]	No evidence	Insufficient evidence	Insufficient evidence	Insufficient evidence
More efficient use of hydrogen in Chlor Alkali production	Development	Longer term	Insufficient evidence	~£0.09bn net saving in UK by 2050 [24]	Insufficient evidence	Insufficient evidence	Insufficient evidence
Improved Reaction	Some commercial, but	Mainly	Insufficient	Insufficient	Insufficient	Insufficient	Insufficient evidence

Technologies	mainly development	Longer term.	evidence	evidence	evidence	evidence	
Bioprocessing/ biocatalysts	Mainly development	Longer term	~0.1 to 0.3 $GtCO_2$/yr by 2050 worldwide [31]	$1-5 /tonne of CO_2 saved (2008 prices) [31].	Insufficient evidence	Insufficient evidence	Insufficient evidence
CCS	Development	Mainly longer term	~4.3$MtCO_2$ [10]	£10-20/tCO_2 [26]	Insufficient evidence	Insufficient evidence	Insufficient evidence

3.1.3 Iron and Steel

Key Findings

In the near term there may be some potential for savings through increased heat recovery/reuse through CHP and district heating. However, much of the literature reviewed which identified these technologies referred to other countries and was not specific to the iron and steel sector in the UK. It is the author's opinion that much of the short term opportunity has already been realised as a result of policies such as CCAs and the EU ETS.

Significant technical potential exists for the longer-term decarbonisation in the iron and steel sector to 2050, particularly from technology under development focusing on the replacement of and retrofitting to existing blast furnace processes. These technologies are consistently identified and reported in the major reports on technology opportunities [10], [24], [25].

A potential barrier to the uptake for a number of these longer-term technologies is that the increase in steel consumption in the UK/EU is forecast to be marginal [34], and it may be possible to meet future demand by increasing the productivity of existing blast furnaces. Furthermore as the majority of the technologies are aimed at replacement or retrofit of existing blast furnaces in the UK, such changes will need to be factored into the planned refurbishment/shutdown schedule for existing plant (author's opinion).

In the UK the majority of crude steel is produced using the Blast Furnace – Basic Oxygen Furnace primary route (BF-BOF), where steel is produced through a chemical process at temperatures up to 2000^{o}C. The remainder is produced using the Electric Arc Furnace route (EAF), where scrap is melted at approximately 1600^{o}C. Average carbon intensity in the UK is currently around 1.7 – 1.8 tCO_2 per tonne of steel. Whilst this is higher than some countries, e.g. Brazil (1.25 tCO_2) and Korea and Mexico (1.6 tCO_2), it is much lower than a number of other economies such as India and China (3.1 – 3.8 tCO_2) [26]. However as the UK and EU blast furnaces are operating very efficiently within the constraints of their existing technology, there is limited scope for efficiency gains without a major step change in technology. Table 4 shows a summary of the key technologies, abatement potential, costs and barriers for the Iron & Steel sector.

3.1.3.1 Short term decarbonisation opportunities: potential and costs

Increased heat recovery/reuse – a range of different methods of heat recovery and reuse are proposed by Johansson and Soderstrom [35] for the Swedish Steel industry, including:

- CHP and district heating
- Export of heat to other industries (see also Hayakawa and Suzuoki [8])
- Thermal energy storage (TES) transporting waste heat to domestic consumers, via sorption technology, Phase Change Materials (PCM) or chemical storage.
- Heat recovery from water-cooling using in casting, rolling and shaping.

Johansson and Soderstrom [35] estimated that 30%-40% of the heat used in the Swedish steel industry could be recovered, but a lower estimate of 20% is reported by McKenna and Norman [28]. Neither of these authors estimates the likely costs involved, but the Centre for Low Carbon Futures [26] reports that discussions with industry indicate that there was limited room for further efficiency gains without a major step change in technology.

Power generation from waste heat - Several possibilities are explored for the Swedish Steel Industry by Johansson and Soderstrom [35], including:

- Top pressure recovery turbine (TRT)
- Organic Rankine cycle (ORC) and Kalina Cycle, (a thermodynamic process for converting thermal energy into usable mechanical power, thought to increase thermal power output efficiencies by up to 50% in suitable installations, and considered suited for applications including steel production plants)

- Thermophotovoltaic (TPV) conversion recovering heat radiation from blast furnace slag and slabs, continuous casting, blast furnace, roof and sides

Top pressure recovery turbines have been recently been installed on Blast Furnace 4 at Port Talbot and may also be applied to Blast Furnace 5 at this site.

Fuel Substitution – replace coal with biomass or waste plastics. These options are discussed by Johansson and Soderstrom [35] for the Swedish steel industry, and could be retrofitted to UK blast furnaces, although some applied research would be needed to verify that product quality can be maintained before deployment can occur, and there are reservations over insufficient quantities of supply and the cost [25].

3.1.3.2 Long term decarbonisation opportunities: potential and costs

Blast Furnace Top Gas Recycling: currently in the demonstration phase of the ULCOS (Ultra Low CO_2 steel production) a European wide cooperative research programme. Top Gas recycling is in the small-scale demonstration phase at the LKAB plant in Sweden. It is an option for new plants and an option for retrofit of existing blast furnace plant. The process itself does not give a net reduction in energy consumption as reduced coke consumption is balanced by an increased electric power requirement for CO_2 separation. CO_2 emissions are reduced through sequestration and this process can lead to up to a 50% reduction compared to EU average specific emissions [34]. The estimated total capital expenditure (capex) for UK rollout is £2.5 billion; this assumes 100% replacement of the current blast furnace fleet.

Smelt reduction (Coke free steel making): HIsarna technology uses a bath-smelting technology and produces a more energy efficient and less carbon intensive steel. It combines a number of processes, preheating of coal, partial pyrolysis in a reactor, an ore melting cyclone and a vessel for ore reduction. These are all proven technologies on a small scale, but HIsarna brings them together in an integrated way. As part of the ULCOS project Tata commissioned a pilot plant in the Netherlands in 2011. As the process does not require the production of coke from coal, and iron ore sintering savings of 20% CO_2 emissions have been forecast, these rise to 80% when combined with CCS [26]. The technology requires the replacement of existing blast furnaces, and cost analysis relative to the EU average for blast furnaces indicate that both capital and operational expenditure would be lower. Capital costs are estimated at 75% (greenfield site) and 65% (Brownfield site) with operational cost expenditure at 90% of current blast furnace costs.

Fastmelt: Uses a completely redesigned blast furnace in the form of a rotary hearth furnace, which is more efficient in reducing iron ore. Direct energy consumption is 10% lower on average as compared with an EU blast furnace. Fastmelt offers CO_2 savings of 55% when combined with CCS (5% without CCS). Capex is estimated at 200% relative to current blast furnaces, (assumes a greenfield site with no CCS) and operational costs are estimated at between 80 – 90% of equivalent plant [26].

Gas-based Direct Reduction of Iron (DRI): Already a commercially viable technology, though best suited in countries with a readily available and cheap source of natural gas, it is an alternative method of reducing iron ore into metallurgical iron. In DRI, iron ore is reduced in its solid state, unlike the blast furnace process where a liquid metal is formed during reduction. DRI can then be transformed to steel in electric arc furnaces (or used in blast furnaces as a high grade feedstock that increases hot metal yield per batch). DRI production is common in the Middle East, South America, India and Mexico [26]. DRI offers an attractive option due to its small-scale low capital investment requirements and its suitability to local raw material situations. The MIDREX process is the most globally widespread technique and a MIDREX-EAF plant can emit 50% less CO_2/t than the traditional blast furnace plant.

A total roll out and conversion of the UK primary steel making industry to DRI-EAF based steel production would cost £1.5 billion with the potential for approximately 10Mt of CO_2 abatement. However, the small scale of EAF operations can also act as a barrier for energy efficiency investments, as up to 10 EAFs would be required to produce a similar production level of steel to that resulting from the use of a single large blast furnace. The high cost of gas and electricity in the UK would also make it commercially unattractive to operate the DRI process in the UK [26].

CCS: Although not a focus for this study, CCS has potential as a key abatement technology for the steel sector as it has the potential to increase the potential for CO_2 reduction when combined with other long term opportunities, e.g. top gas recycling or Fastmelt, as discussed above. CCS can also be considered in combination with waste heat recovery with and without CHP, see Section 3.2.2.

3.1.3.3 Sector-specific barriers

A potential drawback to the uptake for a number of these technologies is that as the increase in steel consumption in the UK/EU is forecast to be marginal [34], it can be met by increasing the productivity of existing blast furnaces. Furthermore as most of the technologies are aimed at replacement or retrofit of existing blast furnaces in the UK, such changes will need to be factored into the planned refurbishment/shutdown schedule into existing plant (author's opinion). Steel producers tend to overhaul existing blast furnaces every 15 years or so to increase plant lifetime, costs amount to approximately 50% of the investment for a new blast furnace, the rate of replacement of existing facilities is expected to be slow and determined by existing blast furnaces reaching the end of their lifetime [34].

Table 4: Summary of key technologies, potential, costs and barriers for the iron and steel sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
Increased heat recovery/reuse through CHP, district heating, and range of thermal energy storage techniques.	Mostly commercial, some still in development	Mostly short term	Estimated 20% by improved energy efficiency in UK [28], but 30-40% identified in Sweden [35] using more innovative technologies	Worldwide -50 to +50 $\$_{2009}/tCO_2$ [25]	Varying levels of uptake worldwide.	UK is considered to be one of most energy efficient steel producers, relative to competitors offering similar products. In the author's opinion there is some potential for additional uptake in the UK as part of normal replacement cycles.	Limited capital available for investment in UK, as more attractive returns available to non-UK owners worldwide, and higher investment levels would make UK industry less competitive in EU.
Power generation from waste heat via top pressure recovery turbines organic rankin cycle and Kalina cycle, and thermophoto-voltaic conversion.	TRT is commercial, others at R&D stage.	Mostly short term	Estimated [35] at 4%-12% potential energy saving, but not clear how much is already include in increased heat recovery /reuse.	As above.	TRT is used in many larger steel mills worldwide, other technologies at small-scale demonstration.	New TRT recently installed at Port Talbot Steel works.	Pressure too low on older blast furnaces to be economic for retrofit.
Fuel Substitution – replace coal with biomass or plastics	Development	Short term	10% potential energy saving [35]	Not quantified	Already used in other countries.	No uptake [25]	Insufficient supply of biomass materials in UK
Top gas recycling blast furnace (TRG-BF)	Development	Longer term (post 2030)	50-60% reduction in carbon emissions possible when used with CCS	£$_{2011}$1.5 to 2.5 billion [26]	Part of EU funded ULCOS Project. Pilot plant stage.	No uptake	Still at pilot plant stage

			($12MtCO_2$/year).				
Smelt reduction (coke free steel making)	Development	Longer term (post 2030)	20% reduction in carbon emissions (80% with CCS)	$£_{2011}$ Between 65 – 75% relative to EU average for Blast furnace [26]	Part of EU funded ULCOS Project	No uptake	Requires replacement of entire blast furnace.
FastMelt	Development	Longer term (post 2030)	5% reduction in carbon emissions (80% with CCS)	200% higher capital cost than alternatives [26]	Being promoted by Kobe Steel, Japan [26]	No uptake	Higher capital costs than alternatives selected for ULCOS>
Gas-based Direct Reduction of Iron (DRI) – combined with Electric Arc Furnace (EAF)	Commercial	Longer term (post 2030)	50% reduction in carbon emissions ($10MtCO_2$/year).	$£_{2011}$ 1.5 billion for UK rollout [26]	Used at various locations around world - where natural gas is plentiful & cheap.	No uptake	Cost of gas & electricity too high in UK – not commercially viable. (Require 10 EAFs to replace 1 blast furnace).

3.1.4 Aluminium

Key Findings

In the near term the documents reviewed identified some potential for savings through increased heat recovery at primary production sites and through increased recycling. There is limited potential for uptake in primary heat recovery due to the recent down scaling in UK primary production due to the closure of the Lynemouth Smelter. In the UK 70-80% of aluminium scrap is already recycled, hence there is limited opportunity for decarbonisation in the UK aluminium sector through application of to this technology.

Prior to closure of the Lynemouth smelter in May 2012, significant longer term potential existed for decarbonisation in the UK aluminium sector to 2050. This potential was dependent on the further development and implementation of inert anodes and wet cathodes technology. These key technologies were consistently identified and reported in the major reports on technology opportunities for the sector [10], [25]. The major barrier to implementation of these technologies in the UK is now the limited potential for their uptake due to the closure of the Lynemouth Smelter. Primary production is now limited to the remaining smelter at Lochaber, (Fort William), which operates on a much smaller scale, uses hydropower and therefore has relatively low emissions and limited potential for savings as fuel switching is not an option and long term anode/cathode opportunities are very much at development stage.

The manufacture of primary aluminium consists of three steps: bauxite mining, alumina production and electrolysis through the Hall-Héroult process. Four tonnes of bauxite are needed to produce two tonnes of alumina, which then produces one tonne of aluminium. Aluminium is formed at about 900^{o}C, but once produced it has a melting point of 660^{o}C, this means that recycling requires significantly less energy and is more cost effective than primary production. The smelting of the aluminium is the most energy intensive stage of production (120 GJ/t) [26], this is four times more than the refining stage of the bauxite, hence the technological development and research within the industry has focussed on this stage. The literature reviewed for the industry was all published pre 2012, at which time the UK primary aluminium industry consisted of two smelters. Firstly, Lynemouth for which electricity was supplied by its own on-site coal fired power station (420MW) but closed in May 2012. The remaining smelter at Lochaber, (Fort William), uses hydropower and therefore has relatively low emissions. Table 5 shows a summary of the key technologies, abatement potential, costs and barriers for the aluminium sector.

3.1.4.1 Short term decarbonisation opportunities: potential and costs

Prior to its closure in May 2012, the Lynemouth smelter concentrated on improving its efficiency via a focus on increased efficiency of its power plant, (from 36% to 39%) and the introduction of co-firing of the power station with 2.5 – 3% biomass fuel (wood pellets and olive residue). It is estimated that implementing these measures saved approximately 40,000 tCO_2 per annum [26].

3.1.4.2 Long term decarbonisation opportunities: potential and costs

Wetted drained cathodes: In existing Hall-Héroult cells, the molten aluminium collects at the bottom of the cell on top of the carbon cathode lining, before it is removed periodically. To avoid shorting the anode is required to be some distance from the aluminium surface, (electrical forces cause the aluminium to undulate resulting in an uneven surface). Wet cathodes can potentially reduce energy consumption by allowing the continuous draining of the aluminium, which therefore presents a flat stable surface, resulting in a reduction of the anode – cathode distance, which reduces the resistance and required energy. Energy savings are estimated at up to 20% [25] compared to a modern Hall- Héroult cell, cost data were unavailable.

Inert anodes: As part of the current (Hall-Héroult) process, the carbon anodes are consumed, so periodic replacement is required. This anode changing upsets the stability, production and energy efficiency of the cell. These problems could be avoided by the use of inert anodes, which would also eliminate process-related PFCs and CO_2 emissions. Despite extensive testing at lab and batch scale, there was no recent information available concerning industrial scale testing. Theoretically the use of inert anodes in conjunction with a wetted drained cathode should match the energy performance of the best cells in operation today and result in a reduction of CO_2 emissions of up to 40% compared with current levels [25]. Capital costs for cell replacement are estimated at $1-2 million per cell and there is an estimated 3% reduction in operating costs [35].

3.1.4.3 Sector-specific barriers

With the closure of the Lynemouth Smelter, primary production is limited to the remaining smelter at Lochaber, (Fort William), which uses hydropower and therefore has relatively low emissions and very limited potential for further savings since fuel switching is not an option and long term opportunities are very much at the development stage (author’s opinion).

Table 5: Summary of key technologies, potential, costs and barriers for the aluminium sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
Increased heat recovery	Various	Mostly short term	15% of energy use could be recovered at primary production sites [26]	No evidence	No evidence	No uptake	Remoteness of UK primary production.
Increased recycling	Commercial	Mostly short term	Could recycle a further 7% of waste aluminium [26]	No evidence	No evidence	70-80% of aluminium scrap recycled [36]	Technical limit reached in UK.
Fuel switching	Commercial	Short term	None, since closure of Lynemouth 2012	No evidence	No evidence	No uptake	No scope – primary production powered by hydro-electricity.
Inert anodes and wet cathodes in Hall-Héroult cell.	Development	Longer term	40% reduction in carbon emissions	$1-2 million per cell [35].	No uptake	No uptake	Not known as yet.

3.1.5 Paper and Pulp

Key findings

The UK paper sector emits around 4.7 million tCO_2 per annum (38), and there is the technical potential to reduce emissions by up to 23% (38) through the adoption of good practice and a range of innovative technologies, particularly relating to drying processes. The evidence suggests the available measures have a range of paybacks of between 18 months and 5.5 years (where paybacks are given).

The CO_2 reduction measures range from smaller measures for reducing the energy use of the drying process such as on-line moisture measurement, pre-dryer dewatering, laser-ultrasonic stiffness sensors, and advanced fibrous fillers, and more significant changes to the process such as hot pressing, gas fired drying, Taking the paper production process as whole, there is potential for energy and carbon saving through process integration both within the plant and within the local area, through heat recovery, and through the use of low carbon energy supplies.

However it is reported that UK industry is likely to be reluctant to invest in unproven technologies or measures with a payback of more than a year [37].

Much of the international literature on this sector is not relevant to the UK context because it addresses combined pulping and paper facilities, which are not used in the UK, and the opportunities from using the by-products of the pulping process for the production of heat for use in the rest of the facilities.

The paper and pulp sector was not addressed by either of the two recent AEA (now Ricardo-AEA) studies for the Committee on Climate Change (CCC) [10] [21] and was only briefly addressed by the Centre for Low Carbon Futures report [26]. This is probably because paper and pulp is not such a major energy-using sector as in Scandinavia and North America, for example. Much of the literature derives from those regions and addresses abatement options associated with the chemical processing of pulp. There is only limited pulp processing in the UK and it is all-mechanical rather than chemical processing [26], so much of the international literature is not relevant to the UK context.

The only UK-specific paper on abatement options in the paper and pulp sector in the literature was the 2011 Carbon Trust Industrial Energy Efficiency Accelerator (IEEA) Guide to the Paper Sector [37]. The other key reference for this section is the US Energy Star Guide to the Paper and Pulp Industry prepared by the Lawrence Berkeley National Laboratory (LBNL) [38]. This guide provides detailed technology potential and cost data but from a US perspective and therefore the potential savings and payback times for UK industry may be different.

Paper and pulp is also examined in Horizon 2050 [34] where it is claimed that emissions can be largely eliminated. However the paper is focussed on the European industry as a whole, and the basis for the large reduction of emissions is the use of by-products from chemical pulping as fuel, which is not relevant to the UK. The other major sources of emission reductions proposed are advanced drying technologies.

3.1.5.1 Short term decarbonisation opportunities: potential and costs

Boiler efficiency and heat recovery: The LBNL guide [38] advises that boiler energy efficiency can be improved by upgrading burners and burner controls by around 2.4% with a simple payback of around 19 months, and further improvements in boiler energy savings of around 3.5% can be achieved using flue gas economisers. A Swedish study on the utilisation of excess heat in the pulp and paper industry found there was potential for the use of mechanical and adsorption heat pumps with a payback of 1.7 to 2.7 years [39].

On-line moisture measurement: On-line moisture measurement and control using microwave sensors has the potential to save energy by preventing over-drying and reducing product wastage, at a payback of 2-3 years [37]. However initial trials of this technology at a UK site indicated a need for further research and development to overcome concerns over the accuracy of the sensor technologies employed and the resulting effects on product quality due to over- or under-drying [37].

3.1.5.2 Long term decarbonisation opportunities: potential and costs

Heat Sharing and Heat Recovery: There is potential for heat integration both within paper facilities and also in area wide schemes across different industries. Energy savings are application specific but typically can be of the order of 10% to 35% in the US [38], with applications limited by the site/area requirements for low-grade heat. No specific data on the potential in this area in the UK.

Gasification of paper waste: Waste materials from the paper process can be gasified and used as part feed to the steam boilers for the process. The UK potential for CO_2 reduction is put at 50,000 tonnes of CO_2 over 10 years at a cost of £10/tonne CO_2 saved [37].

Optimisation of Dryers: There is potential to reduce dryer energy use by up to 50% through reduction of water content, optimisation of drying process, and heat recovery. On a typical paper mill this would lead to savings of 22,000 tonnes of CO_2 after 5 years and 55,000 tonnes of CO_2 in the UK after 10 years with a payback of 1.5 to 4.5 years [37]. A gas fired paper dryer is at the demonstration stage and has the potential for energy savings within the drying process of 10% to 20% [38].

Hot pressing: Hot press systems being trialled in the Netherlands have the potential to deliver 68,000 tonnes of CO_2 savings in the UK over 10 years at an average cost of £7.50 per tonne of CO_2 saved by increasing the solids content of the paper as it enters the dryer [37]. However there is uncertainty over the impact of higher operating temperatures on the fibre surface.

Pre-dryer dewatering: By reducing water content of the paper with pre-dryer dewatering a reduction in the in the drying energy requirement of 10% can be achieved. This technique is under development [38].

Laser/Ultrasonic web-stiffness sensor**:** By continuously measuring the stiffness of the pulp/paper a reduction of 3% in dryer energy use can be achieved [38].

Advanced Fibrous Fillers: Advanced fillers are being developed which can reduce the pulp content of paper and hence reduce the energy use/carbon. Potential savings of 25% of the drying energy requirement are reported [38].

3.1.5.3 Sector-specific barriers

The main barriers to innovation in the UK paper industry were identified in the IEEA guide [37] through discussion with industry stakeholders and are summarised below.

Cost Effectiveness - Increasing competition driven by imports and overcapacity has reduced the margins available to the manufacturers and has limited capital availability. This has led to a reluctance to undertake investment with a payback of more than 12 months.

Conservatism - There is a degree of risk aversion in the sector, which is understandable, as technological failures would have a significant impact on business performance. This implies that new technologies need to be evolutionary rather than radical, or need to have been established in other sectors.

Operability – if any technology contains uncertainty regarding the impact on machine operability this would be a major barrier to its adoption.

Operational Costs - the sector is under severe pressure on margins, so even if energy efficiency or fuel switching measures would reduce fuel costs they may still not be taken up if they are accompanied by increases in maintenance costs for the equipment installed.

Table 6: Summary of key technologies, potential, costs and barriers for the paper and pulp sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
Mechanical and adsorption heat pumps	Commercial	Short term	Variable	Payback of around 1.7 to 2.7 years. [39]	No evidence	No evidence	No evidence
Boiler efficiency - upgrading burners	Commercial	Short term	2.4% reduction in fuel use [38]	Payback of around 19 months [38]	Widespread	Widespread	No evidence
Boiler efficiency – flue gas economisers	Commercial	Short term	3.5% reduction in fuel use. [38]	Information not given	Widespread	Widespread	No evidence
On-line moisture measurement	Commercial/ Development	Short term	10,000 tonnes of CO_2 after 5 years. 19,600 tonnes of CO_2 after 10 years. [37]	2.5 years payback. £12.60 per tonne of CO_2. [37]	No evidence	Some take-up but technology is continuing to develop.	1) Concerns regarding the long term durability of the sensor technologies deployed; 2) Impacts on quality during commissioning and control loop tuning; 3) Inherent conservatism of industry [37]
Heat sharing, heat recovery, area wide process integration (pinch analysis),	Commercial	Longer term	Variable depending on scheme. Pinch analyses can lead to energy savings of 10-35% in the pulp and paper industry [38]	Variable depending on size of scheme.	No evidence	No evidence	Lack of suitable sites with potential for integration/heat sharing (reviewer input).
Low carbon energy supplies (extended biofuel combustion)	Commercial /development	Longer term	UK potential: 50,000 tonnes of CO_2 after 10 years [37]	£10/tonne of CO_2 saved. A 5MW gasifier would have capital costs of £10M to £15M.	No evidence	No evidence	i) The high temperature of the generated syngas may make the modification of the burner pipe work system more difficult than anticipated. ii) The lack of gasifier

				[37]			expertise/resources may be difficult to secure. [37]
Optimisation of dryers (including process control	Demonstration/ development	Longer term	Reduction in electricity consumption of an estimated 50% (higher due to friction effects). On a typical paper mill this would lead to cost savings of £350,000 / year. 22,000 tonnes of CO_2 after five years. 55,000 tonnes of CO_2 after ten years [37]	[37] 1.5 to 4.5 years payback	No evidence	Inertia in sector due to fears of moisture condensation in the hood and the impacts of drips onto the paper. Also concerns about long term reliability of humidity sensors	1. Concerns regarding the long term durability of the sensor technologies deployed; 2. Downtime necessary for major hood engineering changes 3. Impacts on quality during commissioning and control loop tuning. [37]
Hot Press	Development/ Demonstration	Longer term	68,000 tonnes of CO_2 after 10 years. Payback 3 years. [37]	1.5 to 3.5 years. [37]	No evidence	No evidence	The uncertainty with hot pressing is the impact of higher operating temperatures on fibre surface properties and the ultimate impact on the mechanical and finish properties of the final product.
Gas fired paper dryer	Demonstration	Longer term	10 to 20% of the drying energy requirement [38]	No evidence	No evidence	No evidence	No evidence
Pre-dryer dewatering	Development	Longer term	10% reduction in drying energy requirement. [38]	No evidence	No evidence	No evidence	No evidence
Laser-ultrasonic web stiffness sensor.	Demonstration/ development	Longer term	3% of the drying energy requirement [38]	No evidence	No evidence	No evidence	No evidence
Advanced fibrous fillers	Development	Longer term	25% of the drying energy requirement [38]	No evidence	No evidence	No evidence	No evidence

3.1.6 Food and Drink

Key Findings

Most of the academic research papers in the literature addressed energy consumption in the food and drink sector of countries like Taiwan and Brazil, which are very dissimilar to the UK with regards to food production. In addition, for measures involving electrification of processes, the energy or carbon savings reported in some of the research papers could not be directly applied to the UK context as the electricity supply mix is different. Overall, therefore, the academic literature provided little information relevant to the research questions. Therefore the findings in this section are primarily based on a small number of relevant reports and papers from non-academic sources that discussed new technologies deployed in the food industry, including Carbon Trust Industrial Energy Efficiency Accelerator (IEEA) guides on various industry sub-sectors.

Significant potential exists for decarbonisation in the food and drink sector to 2050, particularly from the application of dielectric heating technologies, combined heat and power and heat pumps. The implementation of novel technologies such as high-pressure processing and pulse electric field is likely to be expensive, though new companies in this sector are considering such technologies.

Technologies like dielectric heating and ohmic heating show potential for short term decarbonisation in UK but the scale of their current deployment in the UK could not be determined. These electromagnetic technologies in food processing have gained increased industrial interest and have potential to replace, at least partially, the traditional well-established preservation processes within this sector.

There was very limited information on the costs of individual technologies or energy efficiency measures in the literature. The capital expenditure required for short term decarbonisation measures can vary significantly and there is a lack of complete and consistent information on which to judge cost effectiveness. For example a bakery could adopt improved combustion efficiency for about £80,000 or a heat pump stove for up to £800,000, and it is not clear whether the latter would deliver ten times the energy or carbon savings. In the UK food and drink sector is the third largest emitting industry with significant abatement potential estimated by the Carbon Trust. The sector uses heat for various processes like melting, cooking and boiling, baking, roasting, frying, pasteurisation, sterilisation and drying. The academic research papers identified alternative heat technologies but were very specific to the region of study (e.g. Brazilian sugar industry) and the quantified values cannot be directly applied to the UK food and drink sector. The key technologies that would benefit this sector were consistently discussed in other reports ([24], [25], [40], [41]). In the UK anaerobic digestion (e.g. brewing sector and dairy plants) and biomass are widely deployed but there was no specific evidence found within the academic literature.

3.1.6.1 Short term decarbonisation opportunities: potential and costs

<u>Dielectric heating (Radio frequency (RF) and microwave (MW) heating):</u> Dielectric heating implies the interaction between an electromagnetic alternating field and the dipoles and ionic charges contained within a food product that enables the volumetric heating of the product. It is used in pasteurisation, sterilisation and drying processes of food production. Microwave heating has found many applications in the food processing industry, including tempering of frozen foods for further processing, pre-cooking of bacon for institutional use, and finishing drying of pasta products. In the UK confectionary and stoving sector, MW drying technology can save 607 Kg CO_2 per tonne of water evaporated with an investment cost of £500k for a 240 kW unit [42].

<u>Ohmic heating:</u> Heating occurs when an alternating electrical current is passed through a food resulting in the internal generation of heat due to the electrical resistance of the food. It

is used in pasteurisation, sterilisation and drying. Energy savings of at least 70% could be achieved [43] and the technology has been increasingly deployed since 1980 in the UK.

Combined Heat and Power (CHP): The literature highlighted that maltings sites have a typical heat to power ratio around 4.8 to 1 thus CHP offers carbon savings in order of 25-30% when compared with separate generation of heat and electricity. CHP can achieve overall efficiencies of up to 80% in industry, as well as reduced emissions. The capital cost of the CHP installation is in line with typical costs for reciprocating gas engines (£800-900/kWe installed). CHP can be deployed in 50% of the maltings sector in UK [41]. CHP is used in other sub sectors in UK (cereal manufacture) but there were little evidence in the academic literature. CHP units running on biomass residues could add significant carbon savings in this sector. The author's view (based on the UK statistics prepared by Ricardo-AEA for DECC) is that CHP is deployed in most of the food and drink sub-sectors (such as sugar, cereals, maltings, breweries, coffee, dairies, confectioneries etc.), and further CHP economic potential has been identified which could almost double current capacity by 2030 [16].

Other energy efficiency measures: Process optimisation measures in the brewing sector include:

- Reduce boil-off (Savings of 11,200 tCO_2)
- Increase high gravity dilution (Savings of 11,900 tCO_2)
- Optimise tunnel pasteurisers (Savings of 14,000 tCO_2)

Improving combustion efficiency in the bakery sector is expected to save 17,466tCO_2) at a cost of £40,000-£120,000 (average £80,000) [31].

3.1.6.2 Long term decarbonisation opportunities: potential and costs

UV pasteurisation: This is an alternative process technology to existing heating, cooling and cleaning process technologies. Ultraviolet (UV) radiation is an established disinfectant used to produce drinking water. UV pasteurisation can be used for both kegs and small packs in the UK brewing sector, saving up to 68,000t CO_2 with a payback of 6.5 yrs [40]

High pressure processing (HPP): The high-pressure treatment of foods involves subjecting food materials to pressures that typically range from of 100 to 1000 MPa. It inactivates vegetative microorganisms by using pressure rather than heat to achieve pasteurization. The technology can achieve reduction of 20% in total energy requirements. HPP cold pasteurization technology is increasingly applied throughout the world in the processing of a variety of product categories [43].

Pulsed electric fields (PEF): PEF technology is based on the application of pulses of high voltage (typically 20– 80 kV/cm) delivered to the product placed between a pair of electrodes that confine the treatment gap of the PEF chamber. It is less energy-intensive than traditional pasteurization methods, leading to potential annual savings of 791–1055 TJ per year of fossil fuel-equivalents [43].

Heat Pump: Enhanced and combined heat pump stoves cost £200k to £780k and can save 8,200 tonnes CO_2 per year with a payback period of 20 years [42].

3.1.6.3 Sector-specific barriers

The processes making up the food and drink sector are diverse in terms of energy consumption and application. The following barriers were described in the literature as being relevant for smaller companies. It is possible that these barriers are less relevant for larger companies in more energy-intensive food industries such as sugar, breweries, maltings, dairies and cereal manufacture, which are more likely to deploy energy efficient technologies (author's opinion).

- Cost-effective energy efficiency measures are often not undertaken as a result of lack of information and indifference toward environmental problems on the part of the managers [44].

- Managers do not consider energy efficiency as a ‘‘core’’ business activity (note: evidence based on limited data) [45]
- Lack of investment in energy conservation, because it is considered to be more profitable to do nothing [45]
- Energy study results or data are not robust enough to support investment decisions [45]

Table 7: Summary of key technologies, potential, costs and barriers for the food and drink sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
Dielectric heating e.g. radio frequency (RF) and microwave (MW) heating	Commercial	Short Term	MW in UK Confectionary Sector can save 60,200 tCO_2	No evidence £150k – £300k [42]	No evidence	MW is unproven but can penetrate 70% in industrial confectionery stoving sector	Both RF and MW are within the radar range
Ohmic heating	Commercial	Short Term	Energy saving up to 70% [43]	No evidence	A number of suppliers in USA and Italy and significantly deployed	A number of suppliers in UK	Enables higher pasteurization temperatures due to rapid heating
High pressure processing (HPP)	Commercial/ Development	Longer Term	reduction of 20% in the total energy requirements	No evidence	Japan, USA and Europe, worldwide take-up increased exponentially since 2000	Commercial suppliers are available, uptake in UK unknown	No evidence
Pulsed electric fields (PEF)	Commercial/ Development	Longer Term	The electricity savings of PEF can be up to 18%	Operation costs in the range of 1–2 €-cents per litre, about 10 times higher than those needed for conventional thermal processing	Europe and USA	Commercial suppliers are available but uptake in UK unknown	No evidence
UV pasteurisation	Commercial	Longer Term	68,300 tCO_2 savings in UK Brewing Sector [40]	Site Capex (2,000,000 hl/yr site) £240k to	Mainly in USA	No evidence	High cost, health risk to industry workers

				£2,270k			
Alternative heat generation (biomass)	Commercial	Longer Term	c100 kgCO_2/tonne of product based on replacing gas, greater if off gas grid) [23] 38,000 tCO_2 savings by burning wood chips in UK maltings sector [41]	Savings potential £3.8–4.8 bn by 2050 in UK Implementation cost £21m	Europe, USA, Brazil	No evidence	Scarcity of biomass supplies
High Efficiency Combustion e.g. radiant burners for Bakery sector [46]	Development	Longer Term	No evidence	No evidence	No evidence	No evidence	Needs to be determined and likely to be applicable to new build
Heat Pumps	Commercial/ Development	Longer Term	Savings of 56,000 to 82,000 t CO_2 Savings of 33,000 t CO_2 o 115,000 t CO_2 for maltings sector	£135k – £780k [42] (depends on size and type) Similar cost for maltings sector	Europe	No evidence	No evidence
CHP	Commercial	Short Term	29,000 tCO_2 for maltings sector	£11.7m for maltings sector	Worldwide	2 Maltings sites in UK + other sub-sectors	See Section 3.2.2

3.1.7 Cement

Key findings

The main near-term opportunities to reduce CO_2 emissions from the cement sector involve the use of kiln pre-calciners and preheaters and a greater use of alternative fuels and clinker substitute materials. The exact uptake of the UK cement sector against each of these could not be determined from the literature. However, it is the author's opinion that this information is already known to DECC via its interactions with the industry.

Cement systems other than Ordinary Portland Cement (OPC) offer significant technical potential to reduce CO_2 emissions associated with cement manufacture in the longer term. However, there are issues to do with market acceptance and production scale up that would hamper the realisation of this potential. CCS is an important CO_2 abatement option for the industry in the longer term.

Overall, the near term potential for abatement in the cement sector sits within a relatively small number of opportunities that are to do with reducing the amount of clinker produced and fuel switching. Longer-term abatement potential sits with using cement systems other than OPC and with CCS. Work by the Cement Sustainability Initiative has been heavily relied upon for information on costs and abatement. This is likely to be reliable, as this is expected to be sourced from direct industry experience, where possible.

Fuel related CO_2 savings per unit of cement that occur because of an increased use of clinker substitute would reduce the CO_2 savings per unit of cement for other fuel related opportunities.

The most common type of cement, Ordinary Portland Cement (OPC), is made by heating calcium carbonate ($CaCO_3$) at a temperature of about 900°C to form calcium oxide (CaO) in a process known as calcination prior to high temperature heating in a kiln. This process generally takes place in a pre-calcining cyclone chain sitting outside the cement kiln, and leads to the evolution of CO_2. The CaO thus formed reacts with other materials at ~1450°C in the kiln to form clinker, the main component of OPC cement. Other, more minor components of OPC include gypsum and other cementitious material additions.

The production of cement therefore leads to direct CO_2 emissions from calcination (process emissions) and from the consumption of fuel to generate the heat necessary to calcine limestone and support the formation of clinker.

3.1.7.1 Short term decarbonisation opportunities: potential and costs

Energy efficiency: Pre-heaters and pre-calciners improve the energy efficiency of the thermal processes in the kiln and so their retrofit leads to a reduction in the thermal requirement per unit of clinker produced [10]. No data are available in the literature on the extent to which the UK cement industry has already deployed such technologies and how UK kiln energy efficiency compares with the Best Available Technology (BAT) level of 3.1 GJ/tonne clinker [47]. However, the authors believe that information shared between the Mineral Products Association and DECC via the CCA target negotiation process does establish the extent of pre-heater and pre-calciner uptake and can be used to determine a good estimate of the actual thermal performance of the kilns currently operating in the UK.

CHP and heat integration: CHP was not addressed in the literature reviewed for this sector. However, in terms of heat integration, one report suggested waste heat recovery in the cement sector could be a cost-effective option at a 4% discount rate [48] and another scoped out the technical feasibility of recovering waste heat from the clinker cooler and the raw meal pre-heater and the use of this waste heat for the generation of electricity via a steam turbine [49]. Other examples of where waste heat from the kiln exhaust (post pre-calciner and pre-heater) and from the clinker cooler are given in the relevant BREF document [47]. Note none of these examples is "conventional" CHP as the waste heat is a by-product of a thermal process and is used to generate electricity, rather than the waste heat being a by-product of electricity generation, which is subsequently used for a heating application. However, this would become CHP if any remaining waste heat after the generation of electricity was put to a useful purposes, as would be the case, for example, in the desorption step of post combustion carbon capture.

Clinker substitution: This involves reducing the amount of clinker per unit of cement by substituting the clinker with other cementitious materials such as pulverised fuel ash, a by-product produced by coal-fired power stations. Such substitutions avoid the process emissions described above. Cement producers in South Africa use 40% clinker substitutes[10]. It is the author's opinion that this is higher than in the UK, suggesting that there may be scope for higher clinker substitute uptake in the UK if barriers can be overcome – see below. Such abatement is likely to be cost-effective [48]. DECC has, via the submission of CCA performance data, an approximate value of the proportion of cement leaving clinker producers that is clinker and that which is other materials. It should be noted, however, that there is a move in the UK towards the use of stand-alone cement blending plant, i.e. plant sitting on sites removed from the production of clinker. These sites are not covered by CCAs and so information on the nature of production is more limited. This means that determining the actual ratio of clinker to cement consumed would require further literature investigation.

Fuel switching to waste or biomass: Significant CO_2 savings can be achieved by switching from conventional fuels (coal, coke) to alternative fuels such as waste and biomass. Savings will depend on the CO_2 intensities of the conventional and alternative fuels. Alternative fuels provide about half the fuel input in Austria and Germany [25] but it is the author's opinion that in the UK this is nearer to one third. The IEA [25] suggests there is potential for alternative fuels to provide up to 80% of fuel input to the cement kiln. DECC has data that establishes the extent of alternative fuel consumption in UK cement kilns, but not data on how much of this is biomass and how much is waste.

Fuel switching to natural gas: Switching from other fossil fuels, e.g. coal to natural gas for firing the kiln could save 20-50 $kgCO_2$ per tonne of clinker [50]. To put this into context, this is a 40% saving in fuel related CO_2 emissions if the switch is from coal to natural gas. This would require capital expenditure of over €5m and also increase operating costs [50]. There is no information in the literature on the extent of fuel switching to natural gas in the UK or internationally, although DECC has the data on the fuel types used for generating heat in cement kilns gathered via the CCA reporting process. Furthermore, if natural gas supply is limited, there may be other uses with significantly better CO_2 savings – particularly considering the potential for alternative biogenic and waste fuels to be used in the kiln.

3.1.7.2 Long term decarbonisation opportunities: potential and costs

Energy efficiency: Replacing a conventional rotary kiln with a novel fluidised bed kiln (FBK) would reduce heat-related emissions but increase electricity consumption [51]. The overall carbon savings would depend on the technology being replaced and on the carbon intensity of electricity supply. No data on the likely capital costs of FBKs could be found in the literature.

Different cement systems: There are a number of alternative cement systems in development that do not involve a calcination process and therefore do not produce CO_2 process emissions. Magnesium oxide (MgO) systems are attracting particular interest because they require a much lower temperature of about 700°C to form the required phases, thus reducing fuel-related emissions by about 50%, as well as avoiding the process emissions associated with OPC production [52]. However, it is noteworthy that a major company involved in the production of Magnesium-based cements (Novacem, a spin-out from Imperial College) has recently gone into administration.

Other lower CO_2 cement system options, which emit calcination-process CO_2 emissions and fuel-related CO_2 emissions but to a lower extent than in OPC production, include the belite-

[10] Based on conversations with the CEO of the Association of Cementitious Material Producers (ACMP); no data available in the literature.

aluminate system, which uses 12% less fuel and 8% less limestone than OPC [52], and the sulpho-aluminate system which uses 40% less fuel and generates ~50-60% less calcination related CO_2 per tonne of clinker produced than OPC clinker.

Hydrogen: The use of 30% hydrogen blended with 70% natural gas was briefly discussed as a potential fuel in one report [21] but no detailed assessment of potential or costs were provided there or elsewhere in the literature.

CCS: CCS is a key abatement technology for the cement sector as it has the potential to abate the process CO_2 from calcination as well as fuel-related CO_2 emissions [53], [54]. This is in contrast (author's knowledge) to pre-combustion CCS, which is not suitable for cement production, as it would leave the process emissions unabated, so the preferred technologies are post-combustion and oxyfiring CCS. There are other potential advantages to oxyfiring, including potential for enhanced overall efficiency for the process (author's knowledge). The key messages from the literature (author's knowledge and [53], [54] is that post-combustion CO_2 capture using amines is likely to be significantly more expensive than more novel technologies such as calcium looping and oxyfuel-fired kilns, but that research is necessary to ensure that clinker produced by more novel technologies is of the same quality as that from traditional methods.

3.1.7.3 Sector-specific barriers

Clinker substitution: In the opinion of the authors, the construction industry may be reluctant to use unfamiliar cement systems and in the longer term clinker substitutes may be less available as coal-fired power generation declines. Cements with high levels of clinker substitute materials may not be applicable to all applications, owing to application specific requirements of rate of strength development, heat of reaction and durability.

Fuel switching to biomass: From conversations with the industry, the availability of financial incentives for using biomass in power generation and CHP is regarded as a potential barrier to the use of biomass in direct heat applications in the cement sector. This may also be a barrier in other sectors where biomass could serve as an alternative to fossil fuels for direct heat applications. Also, tailored fuel handling systems to support significant moves towards biomass would be required [25].

Fluidised bed kilns: FBKs may not be able to achieve the capacities that can be achieved with conventional rotary kilns [50].

Different cement systems: It is the author's opinion that the construction industry may be reluctant to use new cement systems without rigorous long-term testing. The availability of the raw materials required for different cement systems may also be an issue for the UK.

Table 8: Summary of key technologies, potential, costs and barriers for the cement sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
Increase use of clinker substitutes	Commercial	Short term	260 kgCO_2/tonne of cement produced (based on move from 0.88 to 0.6 tonne clinker per tonne cement) [10]	€-25 to -30/tCO_2 [48]	In South Africa clinker substitute levels of 40% have been reached [55]	Already used in UK; scope to further increase use of clinker substitutes	Reducing availability of clinker substitute material as coal-fired power generation decreases. Customer reluctance to use cement systems with different compositions.
Increase use of waste or biomass instead of coal, coke etc.	Commercial	Short term	Depends on CO_2 intensity of alternative fuels	Capital: €5-15 million for retrofit. Operational: €2-8/tonne clinker increase [50]	Alternative fuel use has reached a little over 50% in Austria and is at about 50% in Germany [25]	Already used in UK but at under 40% of fuel input currently (author's opinion). Could move to 60% (author's opinion) or even 80%	Competition for biomass; current incentives favour power generation not direct heat
Convert all other fossil fuels to natural gas for kilns	Commercial	Short term	20-50 kgCO_2/tonne clinker [50]	€5-15m Capex and €8-16 per tonne clinker Opex [50]	No evidence. Likely to be used in some parts of the world, such as Middle East	<1% in UK (author's opinion)	
Introduce fluidised bed kilns	Demonstration	Longer term	Carbon savings likely to be modest if replacing best practice rotary kiln, as there is an increase in electricity consumption that will offset the	No evidence on Capex. Opex: €0.3/tonne clinker increase [50].	Demonstrations have taken place in Japan (200 t/day) and China (1,000 t/day)	Not currently used in UK but technology is potentially applicable	Concerns about whether the technology can reach the present capacities achieved with conventional rotary kiln system [50].

			thermal savings to a degree [51].				
Use magnesium oxide (MgO) in place of calcium oxide	Development	Longer term	Fuel consumption and fuel-related CO_2 emissions reduced by 50%. All process related emissions (calcination of limestone) avoided.	£220,000 Capex for plant with capacity 0.5-1 million tonnes clinker [34]	None. Only very small scale demonstration.	None. Only very small scale demonstration.	Construction industry reluctant to use different cement systems without rigorous long-term testing. Potential issues with raw material availability.
Carbon Capture and Storage (CCS)	Development	Longer term	60 - 80 % CO_2 avoided. Oxyfuel and Calcium looping integrate best [53]. Potential for integration with power generation [54].	Abatement costs from $\$_{2011}$ 15 – 138 per ton of CO_2 [5] depending upon technology choice.	None	None	Small scale – requires tie-in to larger CO_2 transport network

3.1.8 Ceramics

Key findings

While the literature reviewed identified many of the near term and longer term opportunities to reduce CO_2 emissions from the UK ceramics sector, the literature reviewed only quantified these opportunities and estimated costs for the brick sub-sector. There is, therefore, an apparent gap in the literature relating to near term CO_2 abatement potential and costs for the rest of the ceramics sector. It is anticipated that the analysis underpinning the Cerame –Unie 2050 Road Map might provide more granular information on abatement potential and costs on a sector basis, possibly at the UK level, if this analysis became available.

The key long term CO_2 abatement opportunities would appear to be better heat integration, the use of syngas or biogas and greater use of electric kilns. However, the literature reviewed did not provide information that would allow these opportunities to be quantified in the UK context or the barriers to be considered in detail.

While there is agreement across sources about the actual abatement opportunities available to the ceramic sector, the detail on costs and actual abatement potential is not uniform - it is reasonably detailed for the brick sector and not detailed at all for the other ceramic sub-sectors.

Nominal CO_2 savings from opportunities associated with reducing the quantity of fuel combusted would not occur if that fuel were already biogas or syngas.

Ceramics production encompasses a wide range of product types, including the manufacture of bricks and tiles, sanitary ware, tableware, refractories and specialist technical ceramic materials

The manufacture of a ceramic component includes, in general terms: raw material preparation, green component formation, drying, firing in a kiln and finishing operations.

The majority (~70%) of direct CO_2 emissions associated with the production of ceramics are created in the firing process. These emissions come from both the combustion of fossil fuels for heat and the decomposition of carbonates in the raw materials.

3.1.8.1 Short term decarbonisation opportunities: potential and costs

While the short term opportunities for decarbonisation are well known and there is broad agreement across the literature about what these are (see table below), the literature review did not reveal information about the potential and associated costs across the whole of the ceramics sector. However, there was information found on the potential and costs for the UK brick sector. It is the author's opinion that the brick sector accounts for more than two-thirds of the direct fuel consumed by the ceramics sector in the UK.

Regarding the brick sector, closing the gap between current practice and best practice has the potential to reduce CO_2 emissions associated with heat generation by 5%. This 5% CO_2 saving comes from a number of individual abatement opportunities which have various costs associated with them [56]. The paybacks associated with these opportunities range from 1-10 years.

Other short-term decarbonisation opportunities include:

- Use of pulsed burners [57]
- Addition of materials to the raw material mix prior to firing such that the firing temperature is reduced
- Fuel switching from coal to natural gas
- Use of landfill gas
- Use of CHP to meet low and medium grade heat demands

Unfortunately, the literature review did not reveal data on the decarbonisation potential and costs associated with the above listed opportunities in the UK context. However, the potential for switch from coal to natural gas is known to be low in the UK, as, in the opinion of the author, natural gas already constitutes a very large proportion of fuel for heat.

3.1.8.2 Long term decarbonisation opportunities: potential and costs

The longer-term decarbonisation opportunities fall into three categories:

Recovery of heat at lower temperatures: There is potential for greater heat recovery than that which is considered best practice with current technology. This is the recovery below 200°C and requires developments in heat exchanger materials before it can be implemented, as recovering heat at these lower temperatures can lead to the condensation of acid gases which are not compatible with existing heat exchanger materials [58]. The potential and costs for this in the UK context are only given for the UK brick sector in the literature. There is potential to reduce CO_2 associated with heat generation by 5% at a capital cost of £400,000 per 1 MW of thermal input recovered [56].

Displacing current natural gas use with either syngas or biogas: This is a more favourable opportunity than the use of biomass, as in many cases syngas and biogas can be fed directly to existing burner systems. In the case of syngas, the level of substitution can be as high as 80% [59]. An estimated 28% of CO_2 associated with heat generation may be avoided by this opportunity in the UK brick sector, with an estimated capital cost of £2 million per 1 MW thermal input [56]. It should be noted that the relative costs of natural gas and biogas/syngas need to be taken into account in order to get a full picture of the economics of this opportunity. If biogas/syngas is more expensive than natural gas, then there will be an additional cost associated with this opportunity that will need to be taken into account.

Deploying electric kilns: The real decarbonisation potential associated with this opportunity depends on the CO_2 intensity of the electricity grid. The literature did not reveal the abatement potential for this opportunity in the UK context. However, the Cerame-Unie 2050 Roadmap indicates that the total abatement potential between 1990 and 2050 for the European ceramics industry is 68% without the deployment of electric kilns and 78% with their deployment. The costs associated with this were not found in the literature, but may be available in the analysis underpinning the Cerame-Unie Roadmap.

CCS – The relatively small scale of ceramics works mean that economies of scale may preclude CCS.

3.1.8.3 Sector Specific Barriers

Displacing current natural gas use with either syngas or biogas: In the opinion of the author, the availability of biomass and waste for on-site gasification to enable co-firing with syngas may be an issue, as there is likely to be competition for biomass and waste from electricity generators.

Electric furnaces – In the opinion of the author, the cost of operations will likely be high compared to the predominant natural gas alternative, owing to the historical relative costs of electricity and gas. It is not clear from the literature reviewed how much development work is required - and the likelihood of success of this work - to make available large, continuous electric furnaces, as would be required to support very high production rates at, for example, brickworks.

Recovery of heat at lower temperatures - Availability of materials for heat exchangers able to recover heat from waste streams <200ºC.

CCS – Scale of ceramic works may not be commensurate with cost effective CO_2 capture. Location of large ceramic works may not be commensurate with transport and storage of CO_2. Availability of capital is also a potential barrier.

Table 9: Summary of key technologies, potential, costs and barriers for the ceramics sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
General Energy Efficiency: Close gap between current practice and best practice	Commercial	Short Term	General Energy Efficiency: For UK brick sector, closing gap between current practice and best practice would save ~5% of CO_2 associated with heat generation	Various	No evidence	Partial	None
Pulsed Burners	Commercial	Short Term	No evidence	No evidence	No evidence	No evidence	Will have to wait until end of campaign or accept down time and lost production
Additions of materials to lower firing temperatures	Commercial	Short Term	No evidence	No evidence	No evidence	No evidence	Potential for loss of quality in the end product
Fuel switching from coal/oil to natural gas	Commercial	Short Term	In author's opinion, small in the UK, owing to high share of natural gas use	No evidence	No evidence	No evidence	Will have to wait until end of campaign or accept down time and lost production
Use of landfill gas	Commercial	Short Term	No evidence	No evidence	No evidence	No evidence	Site has to be co-located with a landfill site or gas transported
CHP for low and medium temperature heart demand	Commercial	Short Term	No evidence	No evidence	No evidence	No evidence	Site may be reluctant to take on the perceived technical risks associated with CHP
Waste Heat Recovery to lower	Development	Longer Term	For UK brick sector, about 5% of CO_2	Capex: £400,000 per 1 MW of	No evidence	No evidence	Development of heat exchanger materials

temperatures (<200°C)			associated with generation of heat can be avoided [56].	thermal input recovered			resistant to acid gas condensation at these lower temperatures [58]
Biomass for generating heat	Development	Longer Term	Depends upon the degree of replacement that can be sustained – nothing specific found in literature	No evidence	No evidence	No evidence	Would require new burners to be fitted (majority are natural gas) and temperature requirements will limit the amount of biomass that can be tolerated in the fuel mix.
Gasification of biomass or waste to syngas	Development	Longer Term	Can displace natural gas with syngas up to 80% [60]	Capex: £2 million per 1 MW of thermal input [56]	No evidence	No evidence	Availability of biomass and waste for gasification may be an issue and may make more economic sense to use syngas for electricity generation
Anaerobic Digestion (AD) to biogas	Development	Longer Term	Could displace natural gas by up to 100%	Insufficient evidence. Cost for syngas may be a guide.	No evidence	No evidence	Availability of biomass for AD may be an issue and may make more economic sense to use biogas for electricity generation
Electric Kilns	Development	Longer Term	Depends upon the CO_2 intensity of the grid at the time	No evidence	No evidence	Only for small-scale batch kilns.	High costs of electricity w.r.t. natural gas. Technical challenges with application to high throughput, continuous kilns

3.1.9 Glass

Key findings

Of the near term opportunities for reducing CO_2 emissions, the literature is unclear about the remaining potential for batch and cullet pre-heating and oxy-fuel firing in the UK context. It is also not clear why oxy-fuel firing is not used more widely, and this should be understood better in order to know the true potential for this in the UK context.

Increased cullet use, on the face of it, constitutes an easy abatement opportunity, but there was no information found on the remaining, feasible potential for this in the UK. Availability of cullet is a complex issue, which is influenced by waste policy.

Longer term opportunities covered in the literature seem to be concerned with technologies, rather than fuel switching from gas to syngas or biogas, and it is not understood why this opportunity is not covered.

Much of the evidence relating to costs comes from work done in the United States. While the authors believe that these cost estimates are as robust as they can be for the United States, care would be required in applying them in to UK context.

Savings from the increased use of cullet are additive to all of the other abatement opportunities. Savings associated with electric furnaces are not additive to savings that would be derived from opportunities concerned with reducing the quantity of fuel combusted, such as Oscillation Combustion and Submerged Combustion. The quantity of waste heat available for recovery would be lower from electric furnaces than for fuel-fired furnaces.

Glass production in the UK encompasses the production of container glass, flat glass, glass fibre and special/domestic glass. In the opinion of the author, container glass manufacture accounts for the majority of energy consumed in the glass sector (~65-70%), followed by flat glass (~30%) with the balance taken up by glass fibre and speciality/domestic glass. The overwhelming majority of direct fuel consumption (>70%) is in the melting process.

The production of the majority of glass takes place in furnaces that are constructed to continuously melt large quantities of glass over extended campaigns of 10-15 years. Accordingly, if the implementation of CO_2 abatement opportunities is to avoid interrupting the melting campaign and the associated down time and loss of production, it is necessary to wait until the end of the campaign when the furnace is renovated. As well as emissions from the combustion of fossil fuels for heat, CO_2 is emitted from the raw batch materials entering the glass furnace, which include sodium carbonate, limestone and dolomite.

3.1.9.1 Short term decarbonisation opportunities: potential and costs

The main short-term decarbonisation opportunities for the UK glass industry are:

<u>Increased use of cullet:</u> Increasing cullet use reducing the fuel required for melting. Increasing cullet use by 10% is estimated to reduce fuel consumption of the kiln by between 2-3.5% [61]. The current uptake of cullet use in the UK container glass sub-sector was estimated at 34% in 2008 [62]. The ultimate potential for this will depend on recycling rates and the degree to which recycled glass is diverted to other applications, such as aggregates.

<u>Batch and Cullet Pre-heating</u>: The preheating of batch and cullet reduces the fuel consumption associated with melting glass. An indication of the savings is that for a 50:50 mix of batch and cullet, preheating at 500°C reduces fuel consumption associated with melting by 8-12% [62]. The current extent of application of this opportunity in the UK was not found in the literature. The costs of this are estimated at Capex €1.5 million, Opex €120,000 p.a. for a 350 tonne/day cross-fired regenerator furnace container glass furnace [63].

<u>Oxy-fuel firing</u>: Oxy-fuel firing reduces the fuel for melting as it reduces the quantity of heat wasted in the exhaust as nitrogen is eliminated from the process. A higher flame temperature also promotes more efficient radiant heat transfer. The fuel savings are in the range 5-20% with respect to large, efficient regenerative furnaces [63].

Waste heat recovery for generation of electricity: This involves the recovery of waste heat from the regenerators or recuperators, typically in the range 300-600°C, and the generation of steam in a waste heat boiler for the generation of electricity via a steam turbine. Electricity so generated would displace a glass site's imports from the grid, and so the CO_2 abatement would depend on the CO_2 intensity of electricity on the grid. Capital costs are estimated at Capex €1.67 million, Opex €33,500 p.a. for a 300 tonne/day container glass furnace (end fired) with heat extracted after Electro-static Precipitator [63]. The extent of uptake in the UK was not found in the literature.

Direct Electric Melting: Electric melting is used in small batch glass furnaces in the UK. However, the very large container glass and flat glass furnaces are gas-fired. Replacing gas-fired furnaces with direct electric furnaces would save energy in that the latter are inherently more efficient. Whether this energy saving would lead to CO_2 savings depends on the CO_2 intensity of the electricity used. Large electric furnaces seem to be comparatively rare, but examples of their use in container glass applications have been found [64]. However, there have been high profile difficulties associated with their use, which may hinder the wider application. Electric furnace costs compared to a natural gas furnace with the same capacity was not found in the literature.

3.1.9.2 Long term decarbonisation opportunities: potential and costs

There are notable examples of longer-term abatement opportunities that could be deployed in the UK. While these are listed in the table below, two of these are briefly described below:

Oscillation Combustion: This involves the forced oscillation of the fuel flow rate to a furnace [65]. These oscillations create successive fuel-rich and fuel-lean zones within the furnace. A consequence of this is better heat transfer from the flame to the load. This decreases the heat up time of the furnace load, thereby improving furnace productivity and reducing fuel consumption.

Submerged Combustion Melting: This involves taking fuel and oxidant and firing them directly into the glass-melting tank [65]. The combustion gases created when the fuel and oxidant react bubble through the tank and create an intense transfer of heat between the combustion products and the molten glass. This also produces forced convection within the glass melt which, overall, improves the homogeneity of the temperature profile within the glass melt. Together these lead to a reduced fuel demand.

3.1.9.3 Sector Specific Barriers

The availability of good quality cullet will determine the degree to which melting energy can be reduced further. While container glass melting may be more accepting of mixed recyclate, flat glass manufacture is far more exacting in the origin of cullet. Further increases in the use of cullet may require glass manufacturers to intervene in the glass recycling business in order to secure cullet of the required quality, and the author, through his communications with British Glass, is aware of one container glass manufacturer doing this.

The implementation of opportunities requiring retrofit will either have to wait until furnace rebuild or experience unplanned downtime and lost production.

Implementation of electric furnaces may be hindered by the difficulties that have arisen through scale-up to higher capacities and the high profile failure of the 256 tonne/day container glass furnace at the Cameron Family Glass Packaging facility at Kalama, Washington State, United States [65].

Table 10: Summary of key technologies, potential, costs and barriers for the glass sector

Technology description	Development status	Short term (<2020) or longer term abatement option?	Energy and/or emissions savings	Costs	Uptake in other countries	Current uptake and potential in the UK	Barriers
Application of regenerative furnace design	Commercial	Short Term	15% fuel savings	Heavily dependent upon furnace size	In EU, overall uptake is 85% by melting capacity [63].	No evidence, but likely to be similar to the EU average	Implementation of opportunities requiring retrofit will either have to wait until furnace rebuild or experience unplanned downtime and lost production
Application of oxy-fuel firing	Commercial	Short Term	Between 5-20% of fuel savings compared to efficient regenerative furnaces [63], At least 15% more efficient than conventional air fired burner systems [62]	Dependent on the size of furnace	In EU overall uptake is ~4% by melting capacity [63]	Known to be used at one glass manufacture in the UK	Perceived technical risk and additional cost associated with construction of oxygen generating plant.
Increased use of cullet	Commercial	Short Term	Increasing cullet use by 10% reduces net energy consumption by 2-3.5% [61]	No evidence. (Manufacturer may have to undertake its own collection of recycled glass in order to have	Use of cullet in container glass manufacture is at an average of 60% in the EU and is as high as 95% in Belgium [66].	In container glass manufacture this is currently 34% in the UK [66].	Availability of recycled glass of the required quality (including colour). Availability of clear cullet can be particularly problematic.
Batch and cullet pre-heating	Commercial	Short Term	Pre-heating at 500ºC of a 50:50 Batch:Cullet mix gives fuel consumption savings of 8-12% [62]	Capex €1.5 million, Opex €120,000 p.a. for a 350 tonne/day cross-fired regenerator furnace container glass furnace [63]	No evidence	No evidence	Implementation of opportunities requiring retrofit will either have to wait until furnace rebuild or experience unplanned downtime and lost production

Waste heat recovery for the generation of electricity	Commercial	Short Term	Depends upon the grade of waste heat, which may be quite low if waste heat is already used for pre-heating batch/cullet	Capex €1.67 million, Opex €33,500 p.a. for a 300 tonne/day container glass furnace (end fired) with heat extracted after ESP [63]	No evidence	No evidence	Implementation of opportunities requiring retrofit will either have to wait until furnace rebuild or experience unplanned downtime and lost production
Direct electric melting	Commercial (just on a large scale)	Short Term	CO_2 savings only accrue if electricity is decarbonised	No evidence	Large furnaces in USA and Zimbabwe [64]	No evidence	High cost of electricity relative to natural gas. High profile failure at Cameron Family Glass Packaging 256 tonne/day container glass furnace may hinder uptake of electric glass furnaces
Oscillation Combustion	Development	Longer Term	Fuel savings of 2-5% [10]	-£183/tCO_2 to -£98/tCO_2 [10]	No evidence	No evidence	Downtime and lost production unless wait until opportunity for full rebuild arises.
Submerged Combustion Melting	Development	Longer Term	No evidence	-£89/tCO_2 to -£177/tCO_2	Use in the Ukraine in the 1990s [10]	No uptake	Not ready for full scale implementation at the current time

3.2 Cross-cutting technologies

In this section we discuss energy efficiency technologies, CHP and fuel switching to biomass, electricity or hydrogen. This section focuses on crosscutting applications such as boilers and burners that find application in numerous sectors. Sector-specific technologies for high temperature applications are discussed in Section 3.1.

3.2.1 Energy efficiency

Energy efficiency improvements from 1973 to 2006 have resulted in a de-coupling of energy consumption and economic growth. In OECD countries energy consumption would have been 63% higher in 2006 without these savings and the average rate of improvement is 1.7% a year over this period (though slowing down from a peak of 3.5% a year in 1973-1986 to less than 1% in 2006) [31], [67].

The focus on energy efficiency is much greater in energy-intensive industries where most of the potential savings have already been achieved. There remains considerable potential in less energy-intensive industries [31].

There is considerable discussion of energy efficiency in the literature but there is a tendency to treat it as a 'catch-all' term for all energy improvements. As such, future savings for energy efficiency given tend to double-count many of the savings attributed to individual sectors, as outlined elsewhere in this report.

There are two main areas of energy efficiency activity that apply to all sectors. These are generic technologies, such as boilers, burners, insulation and electric motors, and the use of energy management techniques.

The literature reviewed in this study provides very little information on the savings that can be achieved through the application of energy efficient boilers, burners and insulation. A savings figure of 2150 tCO_2 is attributed to heat recovery in boilers using economizers [68] but the baseline for this figure is unclear (as the paper refers to a study in Malaysia, so the figures are likely to be just for that country).

The use of efficient electric motors and variable speed drives (VSDs) is not an option for decarbonising heat in industry as it only reduces electricity consumption. However, using a VSD in a boiler fan can improve boiler efficiency by 2.5% [68], thereby reducing carbon emissions from fossil fuel use in the boiler. The same paper reports carbon savings from boilers due to reductions in fan motor speed. It is not clear in the paper, however, what the basis of the emissions is, though it is assumed to refer to Malaysia as the paper references another study from that country. VSDs have already been widely implemented in the UK, so available savings are likely to be less..

The use of energy management techniques is reported in the literature but with very limited information on savings attributable to these techniques. Park et al [69] describe how energy management is underpinned by international standards (e.g. ISO 50001) and includes:

Process design - building in efficiency from the start, including the design and layout of plant and the elimination of intermediate steps in process manufacture or transport.

Management and control systems – this includes the use monitoring and targeting systems and software to spot changes in energy use and minimise unnecessary use.

Elimination of unnecessary energy use - in particular during waiting time or start-up of equipment (savings of 10-25% have been made in Germany from machine tools previously left on stand-by).

Workforce training - promotion of energy saving through training and encouragement of workforce suggestions (Toyota used this approach to save 33% of energy costs between 1990 and 2003).

3.2.2 CHP

Key Findings

Combined Heat and Power (CHP) is a recognised technology that is delivering significant carbon savings in the UK and there is potential for further savings in all sectors. CHP applications are usually based on well-established and tested generation technologies such as gas turbines, steam turbines and internal combustion engines. Its application with fuel cell technology could bring additional carbon savings beyond 2030. There is a significant gap in the literature for novel techniques of application of CHP in sectors like food and drink and refineries. The academic literature identifies CHP technology as having significant carbon saving potential across most of the industrial sectors. Two of the high relevance academic research papers were relating to CHP application in the pulp sector, which has little significance in the UK. There was only one piece of academic literature that identified cooperation between industries and energy companies for deployment of CHP technology within Europe. Most of the carbon savings and figures have been reported in non-academic reports such as those produced for the Carbon Trust and IEA.

CHP technology generates electricity whilst also capturing usable heat that is produced during this process. CHP technology can be applied to both conventional fossil fuels, nuclear and renewable sources such as biomass. CHP offers the capability to make more efficient and effective use of valuable primary energy resources due to its higher efficiency when compared with separate generation of heat and electricity. A CHP system offers benefits in terms of:

- cost savings for energy consumer
- lower CO_2 emissions
- reduced reliance on imported fossil fuel
- reduced investment in energy system infrastructure

3.2.2.1 CHP Technologies

The vast majority of conventional CHP schemes are likely to be fuelled by natural gas. There are three main types of well-established gas-fired power generation technologies suitable for CHP:

1. Reciprocating Spark Ignition Gas Engines
2. Open Cycle Gas Turbines (OCGT)
3. Combined Cycle Gas Turbines (CCGT)

There are two main types of biomass power generators suitable for CHP:

1. Boiler-Driven Steam Turbines
2. Bio-liquid Engines

There are two main types of new technologies suitable for CHP which industry can apply:

1. Waste heat recovery for power generation (with Organic Rankine Cycle, ORC)
2. Fuel Cell with CHP

These technologies are described in Appendix 11.

3.2.2.2 CHP Potential

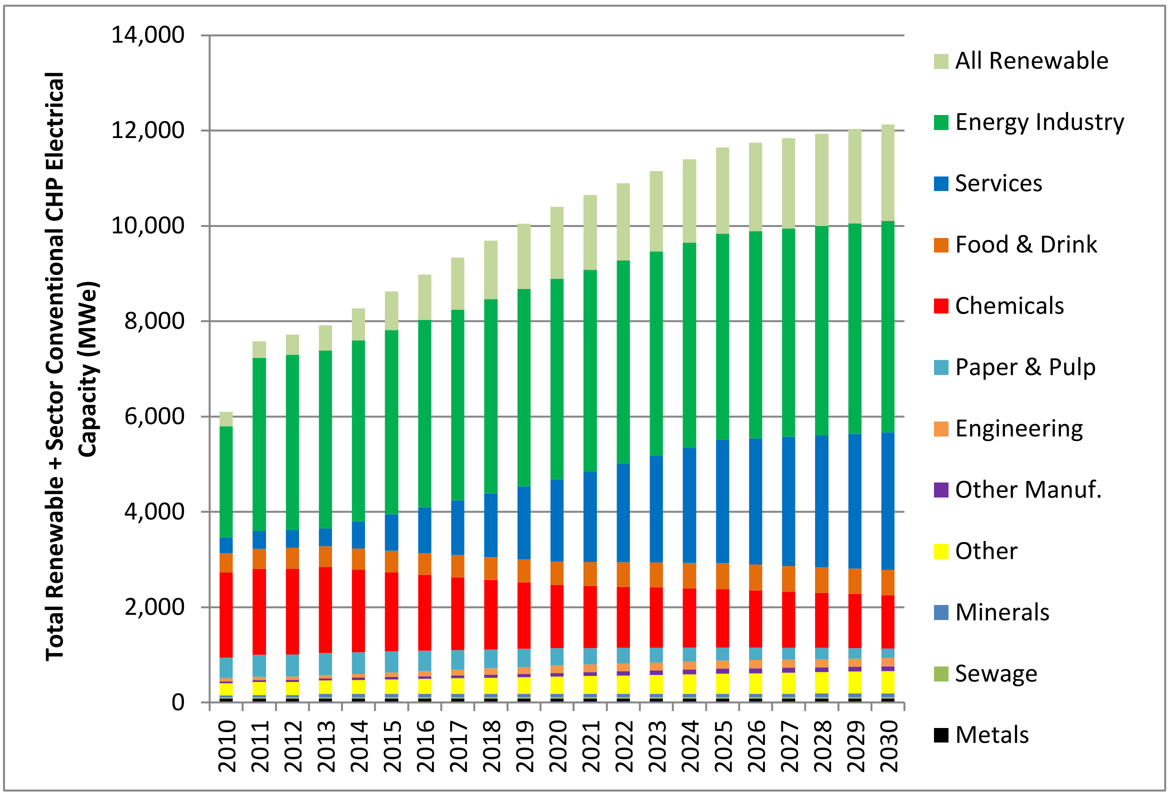
IEA analysis in 2006, estimated worldwide energy saving potential for CHP to be 4.5 EJ/yr [25]. CHP technology can be deployed across the industrial sector where the waste heat temperature and electricity price make this option viable.

- Ceramics Sector – cogeneration providing 32% of energy demand in Italy (similar trend in Spain) and gas-fired CHP is widely used in European ceramics manufacturing operations [57]

- Chemical & Petrochemical industry - could save 2 EJ/year from CHP, life-cycle optimisation by recycling and energy recovery from plastic waste [25] worldwide, where primary energy savings can be more than 20%. Based on the CHP economical potential 17] , CHP potential in the UK chemical and petrochemical industry could deliver energy saving of the order of 84 PJ/year by 2030.
- Pulp & Paper - BAT combined with CHP and additional recycling can provide 1.4EJ of energy savings worldwide, equivalent to 20% current energy use in the paper and pulp sector [25].

The evidence relating to CHP potential for UK was weak within the high relevance research papers. CHP technology is widely used in the UK food and drink sector but the reviewed papers for the technology sector had very little information relating to the potential of CHP technology in the UK. Ricardo-AEA has developed an economic bottom-up model that is used to assess the cost-effective potential of installing CHP for a number of sectors and size categories representing all energy demand in the UK [17]. The results from this model are shown in **Figure 6,** where the projected capacity shown for each sector included conventional and renewable capacity.   .

Figure 6: Good Quality CHP capacity projection, MWe *(Source: Ricardo-AEA)*



It can be seen that the industrial sector with the largest anticipated absolute growth in conventional CHP (and also the largest final capacity) is the energy supply sector whereas the chemicals sector is anticipated to have the largest absolute growth (and final capacity) in renewable CHP.

The ‘Energy Industry’ sector comprises oil and gas refineries and terminals including LNG. The ‘Other Manufacturing’ sector comprises the plastic, rubber, wood and textile industries.

The ‘Other’ sector comprises agricultural activities (Anaerobic digestion and greenhouses), district heating and the residential, sheltered housing sector (mainly communal heating and sports and leisure.

3.2.2.3 CHP Cost

The high relevance research papers have very limited information on cost for different CHP technologies. The Energy Technology Perspectives 2008 study [31] estimates the cost for bioenergy combustion for CHP technologies

- USD 3,333 to USD 4,320 per KW for plant capacity 0.1-1 MW and
- USD3,085 to USD 3,700/KW for plant capacity 1-50 MW

A study done by EUBionet estimates capital investment of USD 14.8 million for plants with 3.5-16 MW capacity and USD 40.1 million for plants with 17-40 MW capacity [31].

3.2.2.4 CHP Barriers

The barriers to CHP identified in this study are [25]:

- Electricity price – lower electricity price affects the viability of CHP projects
- High upfront costs compared to large power plants
- Difficulty in concentrating suitable heat loads
- Cost-effective grid access
- Non-transparent and technically demanding interconnection procedures

3.2.3 Biomass

Key Findings

Bioenergy is critical in meeting UK renewable energy targets and it could supply a significant proportion of the UK's heat, power and transport fuels. The use of biomass can deliver substantial reductions in carbon emissions but the main barrier is the high cost of such technologies. Co-firing of biomass is considered the most cost effective option and is widely deployed within UK. The academic literature did not adequately address this technology but significant abatement potential was identified in other literature.

There are a number of options for the use of biomass and these are:

- **Biomass heat – for heat only**. Biomass combustion is the typical technology used, although large-scale gasification to produce syngas for smaller combustors is an alternative. Examples of biomass boilers based schemes ranges from as low as 30 kW to 10's of MW serving individual buildings or sites (e.g. municipal buildings, hospitals, schools, apartment blocks or industrial sites) or in combination with district heating (DH) schemes.
- **Biomass electricity** – systems range in scale and technology and include co-firing and gasification. Co-firing has the largest current potential and may continue to be significant to 2030. Currently around 100 plants in Europe co-fire biomass. The current trend is for increased co-firing and biomass conversion, which would take most co-firing out of the medium and into the large-scale (>50MW) sector [31]. Major stand-alone biomass power generation uses wood as a fuel. However, other fuels, such as straw and other dry agricultural residues may be used.
- **Biomass CHP**: A significant proportion of bioelectricity generation at present is from CHP units. Many CHP plants are sited at industrial facilities and use waste products from that facility. The most commonly used biomass fuels are waste products such as black liqueurs, wood waste, bark and sawdust.

A variety of different biomass raw materials can be used for energy purposes. Many different conversion technologies are available to transform primary energy from biomass to heat, electricity or transportation fuels. IEA estimates that up to 150 EJ/yr of biomass energy would be required by 2050 worldwide. Biomass feedstocks include:

- Forestry residues

- Dedicated biomass
- Waste wood including sawmill residues
- Energy crops (perennial and annual)
- Organic waste and
- Biomass content within municipal solid waste

3.2.3.1 Biomass Potential

The IEA identified that biomass co-firing in modern coal power plants with efficiencies up to 45% is the cost-effective biomass use for power generation. Dedicated biomass plants for CHP, are typically of smaller size and lower electrical efficiency compared to coal plants (30%-34% using dry biomass, and around 22% for municipal solid waste) [70]. The industrial sector specific research papers identified biomass potential in nearly all sectors and some of the findings are given below:

- **Ceramics Industry -** the most promising way to reduce fuel emissions is to replace natural gas by biogas or syngas from biomass or waste. It is estimated that a substitution rates of up to 80% syngas could technically be possible in some kilns, with a potential reduction of running costs. This could reduce CO_2 emissions by over 30% [59].
- **Pulp & Paper industry** - 50% of its energy needs could come from biomass residue [31], which mainly comes from pulping process. UK has one pulping plant thus its use is limited to paper drying process
- **Cement Industry**: a kiln could be fired solely with a fuel mixture of biomass and natural gas [34].

3.2.3.2 Biomass Cost

The costs of bio-power vary widely because of the variety of feedstocks and processes. In Europe the cost relating to biomass production were [31]

- Operating a forwarder (vehicle for transporting logs) = USD 67 to 104 per hr
- Chipping = USD 148 to 213 per hour
- Loading/unloading = USD 40 to 83 per hour

The supply potential for UK feedstock is estimated to be around 450PJ at a price of £4/GJ in 2020 and could rise to 750PJ at the £10/GJ price point [71].

The investment costs relating to biomass technology were [31];

- Combustion for heat conversion Investment cost USD 370 – 990 per KW_{th}
- Combustion for power technology investment cost USD1,975 – 3,085 per KW (for 10-100 MW capacity plant)
- Combustion for CHP technology investment cost is provided in the CHP technology section above

Biomass co-firing in coal power plants requires limited incremental investment ($50-$250/kW) and the electricity cost may be competitive (US$ 20/MWh) if local feedstock is available at low cost [70].

3.2.3.3 Biomass Barriers

Barriers for biomass technologies are [70]:

- high costs when compared with conventional fuel technologies;
- low conversion efficiencies;
- additional transportation cost;
- feedstock availability (competition with industry and biofuels for feedstock, and with food and fibre production for arable land);
- lack of supply logistics;
- risks associated with intensive farming (fertilizers, chemicals, biodiversity);

- failure of the operators of businesses to utilise the biomass systems after installation (the author is aware of instances in large projects where "backup" natural gas systems are used as the primary boiler, because this is cheaper).

3.2.4 Electrification and hydrogen

The decarbonisation of the electricity supply provides opportunities to use electricity as a replacement for existing, fossil fuel driven, activities in industry. In most cases the technology applications already exist but are currently too expensive (and inefficient in terms of primary energy usage), when compared to natural gas for example, except in locations where there is a cheap supply of renewable electricity (e.g. hydropower) [26].

There is a wide range of possible uses of electricity as a replacement for existing technologies. Various applications are identified in the literature. The most widespread is the replacement of boilers and burners with electric equivalents for direct heat and steam generation [10]. However, this is highly inefficient in terms of overall energy usage. Similarly, heat pumps can be used instead of boilers for applications where temperatures of greater than 100^{o}C are needed, especially in food and drink production, or to upgrade low temperature heat to more useful levels [31], [72], [73].

There are also a variety of sector-specific applications of electricity identified in the literature including: washing, drying and air-conditioning, particularly in paper, chemicals and agriculture, UV pasteurisation in the food sector, the production of iron through molten oxide electrolysis in the steel sector and electrolysis in ammonia production (to replace cracking of natural gas) [10], [26].

Other applications are driven by increased recycling of product (which requires more electricity), e.g. increased use of Electric Arc Furnaces (EAF) in the iron & steel industry due to increased levels of recycling and electric melting of glass [10].

Carbon saving figures for electrification are sparse in the literature, and the costs for delivering them. Data tend to combine savings from both electrification and hydrogen, as one of the main uses of low carbon electricity is to produce hydrogen for other applications.

Very little was captured in the literature review concerning the scope for switching to hydrogen as a fuel for process technologies. The evidence on hydrogen primarily concerned the production of hydrogen or its use in other applications such as vehicle fuel and in refinery hydrotreaters and hydrocrackers [20]. Hydrogen production technologies include steam-methane reforming (SMR), electrolysis [74] and chemical looping reforming (CLR) [75], though CCS is required for both SMR and CLR, and low-carbon electricity is required for electrolysis if CO_2 emission is to be avoided. Gasification, reforming and shift (coal or biomass) is another way to produce hydrogen [76].

The report by CCC produced in 2012 [21], indicates abatement costs for electricity and hydrogen combined (£2010 UK) post 2030: annualised capital cost 0.2-0.36 £/yr, annualised operating cost ~8-14 £/yr, total annualised cost ~9-14 £/yr, average per tonne CO_2 ~£200-£260. Care must always be taken to consider life cycle emissions and primary energy usage when considering shifting to electricity or hydrogen usage.

3.3 Review of the barriers and drivers

The findings above highlight that there is significant potential for the UK to decarbonise heat used in industrial processes. Many of these technologies are cost effective yet they are still not being taken up. This section reviews the literature on the barriers to and drivers for the uptake of energy efficiency in the industrial sector.

3.3.1 Overview of the literature on barriers and drivers

During the initial categorisation, 15 papers were classified as high relevance to research questions 3) and 4) on barriers and drivers. Of these, 12 papers were found to be useful for this study. These papers are summarised in Table 15 in Appendix 9, providing supporting evidence for the high level messages discussed below.

The sectors that were covered by the literature are summarised in Table 11. Most of the papers (11 papers) covered multiple sectors. One paper covered industry as a whole and was not sector specific. Additional sectors that are also covered but are not the focus of this report include: power (2 papers), metal processing (1 paper), machinery (2 papers), foundry (2 papers), textiles (3 papers) and automotive (1 paper).

Table 11: Sector coverage of the papers

Sector	Number of papers that referred to this sector
Refineries and petrochemicals	3
Chemicals	3
Metals	4
Pulp and paper	5
Food and drink	2
Non-metallic minerals	3

Table 14 in Appendix 8 gives a comprehensive list of the barriers and drivers that are referred to in the literature. At the highest level, these can be grouped into those that are internal (i.e. the company has some control over them) and external (outside the company's control). Within that, the barriers can be grouped into economic, organisational/behavioural, informational and technical.

The main method of studying the barriers and drivers in the literature investigated was through surveys and semi-structured interviews. Information from the semi-structured interviews is usually used to explore general themes or patterns or to supplement results from the surveys. The majority of papers reviewed in this report conducted surveys (7 papers) and only 3 papers report semi-structured or in-depth interviews. In addition, the analysis of the results in the majority of studies involved either qualitative discussion (3 papers) or descriptive statistics (4 papers), with only 3 papers performing a statistical regression analysis. It is important to note that without a complete regression analysis, studies cannot be fully conclusive and should only be seen as indicative and interpreted with caution.

3.3.2 High level messages from the literature

Table 12 presents the evidence for the most important barriers to and drivers for the adoption of energy efficient technologies in industry. Column 3 shows the ranking that each barrier or driver was given in a particular study followed by the paper reference. Based on this evidence, each barrier and driver was rated as having either high or low importance as shown in column 4.

Table 12: Evidence in the literature for the most important barriers and drivers

	Barrier/driver	Papers which ranked these barriers/drivers as being of importance	Additional information
Barriers	Technical risk*	[77–81]	
	Lack of capital	[77], [78], [81], [82]	Both privately owned (often smaller) companies and group owned (often larger) companies considered this to be an important barrier [78]. Relevant to both developed (e.g. UK) and developing (e.g. Pakistan) countries [82].
	Lack of prioritisation	[78–81]	Particularly relevant for SMEs [81]. This was also found to be more relevant for the textile industry (example of NEIC) compared to cement (example of EIC) [80].
	Lack of time	[77], [80], [81]	More relevant for SMEs and much less relevant for the larger companies [81].
	Unfavourable economic conditions	[79]	Relevant for the development of new processes [79]
	Shortage of staff	[79]	
	Lack of long term focus	[79]	Relevant for the development of new processes [79]
	Lack of awareness	[82]	
	Heterogeneity	[83]	
	Concern for job security	[79]	Relevant for the development of new processes [79]
	Non-availability of technology	[82]	
	Cost of obtaining information	[78]	
	Absence of government policies	[82]	
Drivers	Cost savings or economic gain	[79], [82–84]	
	People with real ambition, Willingness to improve energy efficiency	[79], [82–84]	Improving existing processes [79]
	Long-term energy strategy	[78], [83]	
	Competition	[78], [79]	Relevant for the development of new processes [79]
	Tight supply of gas feedstocks	[79]	
	Improved product quality	[80]	Relevant to Cement (example of EIC) [80]
	Environmental company profile	[78]	
	Broaden knowledge base	[79]	Relevant for the development of new processes [79]
	Improved staff H&S	[80]	Relevant to Cement (example of EIC) [80]
	Corporate targets	[82]	
	Policy/regulation	[82], [83]	
	Threat of rising energy prices	[83]	

*Includes: risk and/or cost of production disruptions; preference for known/proven configurations rather than new technologies; importance of guaranteeing continuity of the business.

3.3.2.1 Barriers

The most important barriers, based on evidence in the literature surveyed, are technical risk and continuity, lack of time and capital, and lack of prioritisation.

Technical risk and operational continuity was viewed as an important barrier by a number of studies [77–81]. A very high value is placed on operational continuity, i.e. risks to production are weighted heavily, even if the investment is highly profitable [45]. This is because the cost of a production disruption is very high [83]. This strong focus on core business is thought to be independent of the energy intensity of the firm, and often "makes requirements for energy investments tougher" [45].

Lack of time and capital was ranked as a highly relevant barrier by the majority of respondents in a survey of 65 European foundries using a combination of semi-structured interviews and questionnaires [81]. This evidence was supported by a number of other studies [77], [78], [80–82][78], [79], [81], [83][81], [82], [84], [86]. As mentioned above, energy efficiency improvements are usually not related to the core business; as a result employees are often unfamiliar with the suite of technologies that are available and so investigating the best option is often resource intensive (author's opinion).

Lack of prioritization is closely linked to the barrier above (lack of time and capital). Projects compete for attention both in terms of time and capital. Which projects are favoured depends on the priorities of the company. One study concludes that many barriers indicate that energy efficiency is often not prioritised highly in organisations [83]. Company organisation is likely to be of key importance for SMEs in particular, according to one study [81]. This study indicated that if management does not consider energy to be a main priority this could be a significant barrier.

3.3.2.2 Drivers

The most important drivers, based on evidence in the literature surveyed, are cost savings or economic gain, people with real ambition and willingness to improve energy efficiency.

Cost savings or economic gain was ranked as the most important driver by three studies. This is not surprising; particularly for energy intensive firms where energy costs make up a significant percentage of overall costs. However, Thollander et al. [83] argues that it is questionable whether this can really be considered as a driver of energy efficiency; rather that it is a 'prerequisite for the long-term survival of the firm'.

People with real ambition and willingness to improve energy efficiency were found to be a key driver according to a number of studies. Suk et al. [84] investigated the primary determinants of energy saving activity using regression analysis. The authors found that 'willingness to improve energy efficiency' showed a significant positive correlation with the level of energy saving activity with in a company ($P<0.01$). According to Thollander et al. [83] this characteristic is closely related to the values of the individual.

Other drivers that may have some importance are long-term energy strategy and competition [78], [79]. Finally, the author would like to point out that for long-term cross-industry activities (heat cascading, etc.), where very large potential savings lie, there is the requirement for different industries to work together very closely and considerations of whether industrial partners will remain in business to both supply and demand heat at the required temperatures are significant issues.

3.3.2.3 Determinants of barriers and drivers

A number of factors can influence which types of barriers pose the biggest hurdles and which drivers are most effective, including: company size, energy intensity, industrial sector and type of investment. The first three factors are often closely related and difficult to separate, as discussed below. Certain sectors such as steel or cement manufacture are, by their nature, very energy intensive. By comparison, food manufacturing or textiles are much less energy intensive. Final energy intensity of production varies considerably from 52.3 btu/$ (55.2 kJ/$) in cement production to 0.4 btu/$ (0.422 kJ/$) in computer assembly [85]. Additionally, because of economies of scale, highly energy intensive sectors are often made up of a few large companies, whilst less energy intensive sectors are made up of many smaller companies. However, this is not always the case and it is difficult to generalise.

Resource constraints in terms of time and capital are thought to be a bigger barrier for SMEs compared to larger companies [81]. This is because larger companies are able to have people with the right skills and the exclusive role of investigating energy issues. This was confirmed by another study, which indicated that often for non-energy intensive companies, the person responsible for energy is from maintenance, real estate or facilities and not close to production [45]. Another important point (author's opinion) is that the operators of buildings are frequently not the original constructors. Even where the same body is responsible for both construction and operation, energy saving measures may be costed under a different budget than energy usage, leading to failure to implement savings. Additionally, if the energy bill is a small portion of total costs (often the case for less energy-intensive, smaller companies) there is less incentive to use energy rationally. According to the above study, obtaining credit can be a particular problem for SMEs [81]. The type of ownership of the company may also be a factor. One study indicated that, in general, group owned firms face more organisational barriers whilst privately owned firms face more informational barriers [78].

The type of investment is a significant determinant of the barriers to investment. Large projects usually have very long lead times (particularly for energy intensive industries) and a lot of resources are put into making the decision; "An application for investment funds is made, submitted and then approved at different levels depending on the size of investment" [45]. A number of different criteria can be used to determine the economic feasibility of the project i.e. payback, Net Present Value (NPV) and Internal Rate of Return (IRR). NPV is considered the best but payback is used the most (particularly for smaller investments) because it is easy to understand [45].

Ren et al. [79] investigated the difference in barriers and drivers for two different investment categories, namely: 1) improving existing processes and 2) developing new processes. These were investigated from the perspective of the petrochemicals industry based on consultation with various employees from 8 out of 11 international petrochemical firms. The barriers and drivers for these categories were found to be quite different. *Improvements to existing processes* are driven by cost savings, tight supply of gas feedstocks and the personal commitment of individuals; and are hindered by staff shortages, lack of prioritization and preferring proven configurations over new technologies. By comparison, development of new processes is driven by possible economic gain from conversion of low cost feedstock to high value chemicals, competition between both producers and technology suppliers and knowledge expansion (regarding catalytic processes). Barriers include unfavourable economic conditions; inability of conventional decision-making tools and models to cope with longer-timescales, which are associated with higher uncertainties, and concern for job security. The main difference between these barriers and drivers was thought to arise from an inherent difference in the uncertainty of the reward-to-risk ratio of these two types of innovation. Improving existing processes generally has a low uncertainty; since the technologies, costs and market are relatively well known. By comparison, development of a new process has a highly uncertain reward-to-risk ratio since it requires a longer-term perspective.

3.4 Review of policies

UK energy-intensive industries are covered by a range of policies aimed at reducing their energy intensity and greenhouse gas emissions. The major policies covering these industries directly are the Climate Change Levy (CCL) with Climate Change Agreements

(CCAs), the European Union Emissions Trading System (EU ETS) and the Renewable Heat Incentive (RHI). Indirectly, through increased electricity prices, UK industries are also affected by the EU ETS applied to the power sector, the Renewables Obligation, Feed-in-Tariffs, the Electricity Market Reform, the Carbon Price Floor, and “Other” policies such as the Carbon Emissions Reduction Target (CERT).

There is broad evidence that the energy and CO_2 intensity of energy-intensive industries, not just in the UK but in other EU countries and the rest of the world, has decreased over the past decades [86], [87]. In describing the decarbonisation options for energy-intensive industries in the EU by 2050, the European Commission [88] shows that energy-intensive industry could reduce its emissions by 35% by 2030 and 85-90% by 2050 compared to 1990 levels. This would include an energy intensity reduction of almost 75% by 2050 on 1990 levels with CCS accounting for the rest. Decarbonisation of heat is not explicitly mentioned.

This section discusses what evidence there is in the literature, if any, that indicates whether or not these policies have been successful in achieving their desired goals, i.e. improving industrial energy efficiency and reducing CO_2 emissions from industrial processes.

3.4.1 Evidence of the effectiveness of policies

Analysis of the effectiveness of policies is extremely difficult since there is no counterfactual and it is difficult to isolate individual policies from other interventions and market factors. The methods that are typically employed to assess effectiveness include: economic modelling and econometrics based on interview data.

To date, the analysis of the effectiveness of UK policies applicable to industry has focused on the CCL and CCAs and there are only 3 key papers. Reconciliation between these views is required as they present two different pictures of the success of the CCA scheme. Macro-economic modelling of projections of Business As Usual (BAU) energy intensity for UK energy-intensive industries indicate that the CCA scheme resulted in most sectors significantly over-achieving against their targets by 2002 [1]. This was attributed by the authors to an announcement effect, which encouraged these industries to find energy efficiencies. The study however also asserts that the CCAs were set at levels that were not significantly different from BAU energy efficiency improvements (considering historical trend data). Martin et al [2] compared changes in firm-level energy use over time for plants in and out of CCAs. They demonstrate that in the UK the CCA actually led to an increase in energy intensity against levels that would have occurred without the policy, and that the full rate of CCL would have achieved a much more significant energy and CO_2 reduction. This suggests that CCA targets were lacking in stringency even compared to business-as-usual and that the CCL alone would have been preferable. Bailey et al [89] report results from a survey of 189 UK companies from the cement, aluminium and chemicals sectors and 23 interviews with sector associations and businesses from these and other energy-intensive industries. Overall the CCL and CCAs (as well as EU ETS) were seen as relatively weak instruments, compared to energy prices. The study cautions against relying purely on market instruments alone.

More recent policies such as the RHI have not been described in the literature reviewed. Where policies aimed specifically at heat are mentioned [67], these relate to historic government-supported R&D efforts in Western Europe, the USA and Japan, in the wake of the 1970s oil crisis, when the focus even for heat-related technologies like waste heat utilisation and CHP was primarily on using heat more efficiently rather than decarbonising it.

A recent paper [90], which analyses the energy efficiency impact on industry of the Energy Efficiency Demonstration Scheme (EEDS) in the UK over the period 1979-1989, holds interesting insight for current R&D programmes. The paper asserts that about one quarter of the energy savings directly due to efficiency (as opposed to changes in industrial structure or changes in industrial output) were a result of investments stimulated by this RD&D programme. EEDS included grants of up to 25% of capital cost for energy efficiency demonstration programs across mainly energy-intensive industries. The paper argues that EEDS's current successor, the Carbon Trust's Industrial Energy Efficiency Accelerator (IEEA) has had its funding cut, and that Public RD&D expenditure on energy efficiency in industry in 2010 was about £5m, compared to an annual average cost of EEDS of about £7m. This indicates that Government may be underinvesting in energy efficiency RD&D for energy-intensive industry.

Outside the UK, several energy tax schemes combined with voluntary targets allowing rebates or other concessions are described, broadly as having successfully driven energy efficiency. Geller et al [67] describe that German industries and utilities agreed to reduce CO_2 emissions intensity by 20% (subsequently increased to 28%) between 1990 and 2005, in return for low-interest loans on energy efficiency equipment purchases, delays in introducing regulatory measures and limits to new energy taxes. This reduction contributed to a 9% reduction in Germany's total CO_2 emissions by 1998. The Netherlands' Long Term Agreements programme with industries representing over 90% of industrial energy use offered technical and financial assistance from government for efficiency upgrades. This led to a 20% energy efficiency increase over the period 1989 to 2000.

Nevertheless, as in the UK analysis, there is some doubt as to whether energy efficiency and GHG emissions reducing investments have been made in response to policies or market factors. Rogge et al [91] assess how the regulatory framework has affected innovation activities in the German pulp and paper sector through surveying firms in the industry and its value chain. They conclude that at this stage innovation activities are driven by market factors (paper price, availability of raw materials, demand or paper products) and not affected by the EU ETS and other climate policies, but there is an expectation that the impact of these policies will increase by 2020 as the carbon price rises.

In addition, doubt has been cast on the cost-effectiveness of these policies. One study of the cost-effectiveness of voluntary energy efficiency programmes for the industrial sector in Sweden [92], noted that comparable policies in Denmark have been quite cost-ineffective due to administrative costs in financing the energy use assessments that firms have to undertake. However, this cost is reduced where firms signed agreements in groups. In addition, the lack of in-depth expert knowledge by the energy-auditing consultants meant that only relatively small, generic investments were identified (e.g. substitution of new pumps, fans and ventilation systems). The authors assert that rather than voluntary agreements, an energy tax may be more effective as an instrument for energy-intensive companies as they are likely to know about the energy-saving options already, and will be incentivised to implement them in response to increases in energy costs. It is less energy-intensive firms that would benefit from energy audits and energy management systems.

3.4.2 Impact of competitiveness issues on the UK industry sector's ability to investment in abatement technologies

The majority of the impact of policies on energy-intensive industry costs concerns the impact of the EU ETS on energy-intensive industry costs and the subsequent risk of competitiveness loss and leakage. The Environmental Audit Commission [93] investigates the energy intensive industries compensation scheme to prevent these industries relocating abroad. The most striking statement in the report is that:

> *"There continues to be a paucity of data to understand how the cost of electricity for energy intensive industries will affect them. Without reliable data on the risk of carbon leakage, it is impossible for the Government to demonstrate that its compensation package is proportionate. Getting the amount of compensation wrong risks creating further distortion and poor value for money for the taxpayer. Applications from companies for compensation will provide much needed data, but that will come too late to help design the current compensation package."*

The report shows DECC analysis on the impact of climate policies on electricity costs for energy intensive users, ranging from 11-16% in 2011, to 8-28% in 2020, and 27-41% in 2030. There is high uncertainty over the level of the EU ETS, which is the main component of this cost. The ICF [94] estimates that, assuming an EU ETS price of £27.7/tCO_2 by 2020 (in line with DECC carbon values), by 2020 the following cost increases (including direct and indirect electricity costs) would be seen for energy-intensive sectors.

- For steel, the UK would see production costs increase by about £20/t, less than Italy (about £22/tonne) but higher than France and Germany (about £13/tonne) and much higher than the rest of the world (with China at less than £5/tonne).
- For aluminium, the UK would see cost increases of close to £600/tonne, compared to about £300-400/tonne for other EU countries and £150/tonne in China.
- For cement, the UK and EU more generally would see production costs increase by about £8/tonne, compared to negligible levels elsewhere.

In addition, the literature also describes and analyses the effect of climate change policies covering the electricity sector on energy-intensive industry costs [94], [95]. CIVITAS [96] quote the Mineral Products Association to show that the combined cost of the EU ETS, Carbon Price Floor, Feed-in-Tariffs, RO, EMR, and CCL is £65m per year in 2013, or 10% of industry revenues. BCG [97] assesses the impact of Phase III of the EU ETS on the EU cement and clinker industry, asserting that at a carbon price of Euro 25/t, 80%+ of clinker is at risk of being offshored, and at Euro 35/t, 100%.

By contrast, the European Commission [88] uses energy system models to estimate that the impacts on production of energy intensive industries in a decarbonisation scenario (where the EU reduced its emissions by 25% on 1990 levels by 2020) could be at maximum around a 1% loss in 2020.

Outside the UK, doubt has been cast on the hypothesis that energy taxes can in theory increase firm productivity through realizing efficiencies that would have otherwise been missed. One study [98] analysed firm level data to assess the impact of a CO_2 tax on the profitability of Swedish industry over the period 1990-2004. They find that, for a number of energy intensive industries (mining, wood, pulp and paper, chemicals, rubber and plastic, stone and minerals, and iron and steel), only in the rubber and plastic industry is the tax correlated with increased productivity. The authors conclude that for most sectors the tax potentially diverts scarce resources from productive use.

The Minerals Product Association [95] in its submission to the EAC ETS review point out that the expectation for the 7 years of Phase III of the EU ETS is that the cement and lime industries will become more efficient through implementing new plant, whereas in reality the capital lifetime is 30-35 years. The submission asserts that there has been a 26% improvement in CO_2 intensity of production between 1990 and 2010, due to investment in more efficient kiln technology and substitution of fossil fuels. The submission also asserts that, given lack of available mitigation options, the EU ETS and energy taxes are effectively taxes on production, which divert investment away from longer-term low-carbon investment.

4 High level summary of the evidence

Table 13 summarises the strength of the evidence by sector, giving an indication of the number of papers that contributed to the knowledge base in this review and the relevance of these papers. This section below expands on this table and gives a brief discussion of the evidence by sector and technology.

Refineries – On an international level, evidence for the potential for energy efficiency and heat exchanger optimisation in the literature is strong with a number of papers in agreement. However, there is weak evidence of how this can be transferred to a UK setting. In addition, the evidence for CCS and other advanced technical improvements applied to, for example the distillation process, is weak for the UK. Much of the evidence for these long-term improvements is based on the academic literature and requires demonstration. There is weak-medium evidence for clustering; the basic idea is sound and well known, but there have been few detailed studies where plant integration has been studied.

Chemicals - The main weakness in the evidence base is that there is a variation in the way different countries treat feedstock energy use and the quality of data is poor. As a result, the data cannot be used adequately for target setting or country comparisons [25]. There is consistent evidence across all papers regarding the abatement technologies, which have been identified for this sector; however the cost and potential savings data for different technologies are very sparse. Additionally, most of the data in the papers are global and there are limited UK data.

Basic Metals - Most of the academic literature on post-2020 technologies for the iron and steel sector is ultimately based on the technical potential and cost data published in two key resources, i.e. IEA report or underlying US DoE Research Reports. There is very limited information on the foundries sector; however some papers on the iron and steel sector do cover some EAF measures. Coverage of the aluminium sector is weak and in particular there is no consideration of secondary aluminium production. There is no coverage of the rest of the non-ferrous metals in the literature.

Pulp and paper - Much of the research is more applicable to other countries for example the US and Sweden. In particular there is a lot of focus on chemical pulping, which is not carried out in the UK. From the available literature there is good consistency in the coverage of the main carbon reduction technologies. Most of these opportunities are explained in detail technically but there is only limited information on costs and payback and savings to a lesser extent.

Food and drink - The academic papers had very limited information on efficient technologies deployed in the sector and for many of the emerging technologies, environmental impact and operational efficiency information is still scarce or non-existent in the published literature.

Non-metallic minerals – The evidence on the actual technical opportunities is robust, in that there has been much attention on the technical options to reduce CO_2 in the cement industry. There is good agreement on what the opportunities are between information sources. Evidence on the technical abatement potential is also fairly robust in that the best CO_2 performance with current technology is well understood. This gives a good baseline against which to estimate savings. The evidence on costs is less robust, overall. Currently, the best resource for cost data for currently available technologies is the CSI/ECRA – Technology Paper. This paper collates real cost data from operators. However, for longer-term opportunities, the cost data will be less robust, as there is no actual implementation experience in the cement sector to inform these estimates.

There is good UK-relevant evidence on CO_2 saving potential and associated costs for the brick sector (68% of fuel for heat in the whole ceramics sector). Very little UK-relevant evidence was uncovered for CO_2 reduction potential and associated costs for the other sub-sectors in ceramics (sanitary ware, tableware, refractories, other).

The evidence on the abatement opportunities applicable for the glass sector is strong, in that there is broad agreement across the literature on what the opportunities are. The evidence on savings potential and capital costs draws heavily on two key reports [62], [63]. This is because the other literature identified in this project was weak in this regard. However, these two reports are expected to be well researched and comprehensive. The main weakness in the literature relates to the current uptake of technologies and, therefore, the remaining potential. For these only the AEA report has information on penetration in the UK context and these details are well embedded in the report and would require further work to extract.

Energy Efficiency – The main weaknesses in the evidence base are firstly that it tends to use ‘energy efficiency’ as a catch-all term for all past savings and projections for energy efficiency savings effectively double count savings from other technologies and sectors, and secondly that there is very little evidence on the most common industrial energy uses where efficiency would have the most impact on decarbonisation (namely boilers, burners and insulation).

CHP - CHP technology has been widely used in UK industrial sector but information relating to uptake of CHP was limited in the public literature. Although CHP is widely used in both the refineries and food and drinks sectors in the UK, there was very weak evidence of this in the high relevance papers for these sectors. In addition, there were no data on the use of CHP combined with novel technologies like fuel cells and CCS in the sectors covered by this study. The technical and economic potential for CHP across all sectors using conventional and renewable fuels has been published by DECC, in 2013.

Biomass - The information relating to biomass applications within the UK industrial sector is weak as most of the research was from other countries with a greater biomass production capacity. There were limited data available on CO_2 savings and costs for the UK.

Electricity – the academic literature provides very limited evidence on carbon savings through electrification and concentrates mainly on ways to reduce end-use electricity consumption in industry through measures such as efficient motors and drives, which in most cases have only limited impact on carbon emissions. The data on savings that do exist are often mixed with data for hydrogen, as the hydrogen is being generated using “carbon-free” electricity.

Drivers and barriers - There is a strong consensus regarding what the barriers and drivers are but there is very little UK specific research in this area. There is limited evidence regarding how the drivers and barriers vary by company size and type and geography. Additionally, in much of the literature only a descriptive analysis of the data was presented with only very few full regression analyses carried out. This limits the level of conclusions that can be drawn from the literature. One key area of weakness is that only one paper considered how to overcome the barriers and reinforce the drivers.

Policy – The policy evidence base is very weak. The two major papers on the effectiveness of the CCAs [1] [2] come to different conclusions. There is a great deal of analysis on the energy efficiency reductions made by various industry sectors across a range of countries since the early 1970s, but there is no clear attempt to link these to specific policies as opposed to purely energy price (or other) effects. The focus of the vast majority of policy analysis is on energy efficiency measures, with virtually nothing on policies to decarbonise industrial heat.

The analysis on the cost, competitiveness and leakage impact of the EU ETS and other UK climate change policies on the UK energy-intensive sector is also contended, with (in general) industry associations estimating much higher potential leakage rates (based on bottom-up analysis of cost increases) than energy and macro-modelling exercises.

It is difficult to summarise a consistent message across the evidence. Regarding energy taxes combined with voluntary agreements, the majority of the literature supports the view that these schemes are effective and help uncover energy efficiency options, but there are several papers, which question whether the asymmetry of information between governments and industries means that they are deliberately underestimating their energy efficiency potential.

A striking facet of this evidence is that it does not discuss policy effectiveness for measures other than energy efficiency, nor does it discuss the potential effectiveness of policies to achieve deep decarbonisation of the industrial sector by 2050.

Table 13: Summary of strength of evidence on industrial decarbonisation of heat

Sector/ Technology/ Theme	Number of high relevance papers reviewed					Strength of the evidence			
						International		UK-specific	
	Academic database searches	Directed website searches	Suggested by sector stake-holders	Expert reviewer additions[4]	Total[1]	Evidence on potential	Evidence on costs	Evidence on potential	Evidence on costs
Refineries	11	0	3	16	30 (26)	Strong	Medium	Medium	Weak
Chemicals	9	1	4	2	16 (6)	Strong	Medium	Medium	Weak
Iron & Steel	16	0	5	3	24 (6)	Medium	Strong	Strong	Medium
Aluminium	3	0	2	1	6 (5)	Medium	Medium	Weak	Weak
Paper & Pulp[2]	22	0	4	0	26 (8)	Medium	Weak	Weak	Weak
Food & Drink	6	1	2	5	14 (7)	Strong	Medium	Weak	Weak
Cement	8	0	9	3	20 (9)	Strong	Medium	Strong	Medium
Ceramics	5	0	5	1	11 (4)	Strong	Medium	Strong	Medium
Glass	3	0	1	4	8 (6)	Weak	Medium	Medium	Medium
Energy efficiency[3]	15	6	6	0	27 (3)	Medium	Weak	Weak	Weak
Biomass	6	2	9	2	19 (2)	Strong	Medium	Medium	Medium
CHP	10	1	1	3	15 (3)	Strong	Medium	Medium	Weak
Electrification	4	2	3	0	9 (2)	Weak	Weak	Medium	Weak
Hydrogen	2	2	2	2	8 (2)	Weak	Weak	Weak	Weak
						Evidence on barriers and drivers		Evidence on barriers and drivers	
Organisational	14	1	0	1	16 (13)	Medium		Weak	
						Evidence on effectiveness of interventions		Evidence on effectiveness of interventions	
Policy	26	1	8	1	36 (18)	Medium		Medium	

[1] First number is total number of papers rated as highly relevant during the categorisation process; of these only a few papers (represented by the number in brackets) were actually found to contain useful information by the expert reviewer. Note that, the initial categorisation was made based on a brief skim-read of the papers, hence when there was uncertainty over the ranking of the paper, the reviewers tended towards a higher ranking in order to avoid potentially excluding an important paper. As a result, when the high relevance papers were read in more detail a number were found to be less useful.
[2] Paper & pulp papers addressing chemical processing of pulp were excluded from this review as this is not done in the UK and is unlikely to be applied in the future.
[3] Crosscutting energy efficiency technologies only; sector-specific technologies are addressed under sectors.
[4] Assumed to all be high relevance

Key: Strong evidence = multiple papers written since 2010 that provide consistent, detailed and evidenced information on potential or costs

Medium evidence = multiple papers giving broadly consistent information or one credible recent paper with detailed and evidenced data
Weak evidence = some evidence but with inconsistent or missing data; or credible but very dated information
No evidence = no papers found that provide this information even after gap-filling with medium priority papers and secondary references

5 Gap analysis

Key findings

Based on the high level summary of evidence detail in Section 4 and the analysis of the metadata, outlined below, the following knowledge gaps were identified:

- There is a gap in the knowledge regarding the remaining potential for decarbonisation in the UK, particularly for the aluminium, ceramics (excluding brick), pulp and paper and food and drink sectors, and crosscutting industrial ecology/synergies, particularly in the UK.
- There is insufficient evidence for the costs of different technologies, within a UK context, particularly for the following sectors: refineries, chemicals, aluminium, ceramics (excluding brick), pulp and paper and food and drink.
- The longer term (post 2030) potential and costs for electrification and hydrogen to affect deep cuts in CO_2 emissions in UK industry are not clear based on the literature.
- There is a lack of peer-reviewed, independent research on the short term costs and potential for decarbonisation of industry
- There was no evidence in the literature on novel applications of CHP. For example, CHP combined with fuel cells and CCS.
- There was weak evidence on scope for further improvement of heat integration through co-location of different industry sectors and with power generation, e.g. co-locating power generation with Carbon Capture and Storage (CCS) with cement works or refineries.
- Whilst there are a number of studies on barriers and drivers, these are largely not specific to the UK. Additionally, there is limited research on the factors that determine what a company's more important barriers and drivers are.
- The evidence for the effectiveness of UK industry policy is inconclusive.

Based on the categorisation of papers described in the methodology section, a detailed analysis of the meta-data was performed in order to map the literature landscape and to gain a clearer picture of how the evidence is distributed across the areas of interest for this project. The results are presented using 'bubble plots' where the size of the bubble represents the number of papers from that category. **Figure 7** and **Figure 8** summarise these results whilst more detailed graphs showing technology relevance, cost relevance, policy relevance and barriers/drivers relevance by both industrial sector and geographical region are presented in Appendix 10.

As shown in **Figure 7** and **Figure 8** below, the majority of high-relevance papers in the database were applicable to the technical question, with significantly fewer papers of high-relevance for the policy and barrier/drivers questions. Of the papers with a technical focus there was quite an even spread of papers across the industrial sectors. Only the chemicals sector was particularly less well represented compared to the other sectors. This is possibly owing to the search terms chosen which did not search for specific chemical processes. In **Figure 7** there is clear evidence of the gap of costs related to these technologies. Very limited sector-specific cost data was found, with very few 'high relevance' papers. Overall there was some UK-relevant literature but the majority of the literature referred to global industry or did not specify a geographic region. For the policy and barriers/drivers sections, much of the literature refers to industry as a whole and there is very little sector-specific evidence.

The graphs in Appendix 10 reveal a number of additional points, which are highlighted as follows. Industry-specific energy efficiency options were the best covered of the different technologies. There are clear gaps in the literature regarding electrification, hydrogen, industrial synergies and CCS (this is likely to be because we did not search for CCS specifically). For the cost charts we have also included the papers, which were categorised as having a technical focus and yet did not mention any costs. This is to highlight the lack of cost data in the literature.

For the UK, much of the literature surrounding the remaining technical potential and costs of short-medium term technologies for industry is largely found in the grey literature and consultancy reports. There is also an ongoing dialogue between industry and equipment suppliers in the form of trade journals and other advertising mediums. Here, the potential energy savings of new equipment is often part of the sales pitch; however, the actual savings in practice are rarely confirmed and reported. Much of this information never reaches the academic literature. This is likely to be because much of the information is proprietary and difficult to obtain from the companies themselves. Additionally, this area is of limited interest to academia owing to the incentive to publish novel research and lack of funding for long-term studies. As a result there is the risk that the information may be biased and there is a lack of transparency regarding assumptions. There is motivation for incentivising research in this area to gather a clear picture of the remaining potential.

In contrast, for longer-term technologies, the majority of the literature is based on academic journals. There is often a disconnect between the costs reported in academic literature and those quoted from industry. There is an urgent need to move these projects out of the lab and to demonstration level and further development is necessary in order to resolve this. It is important that academia and industry continue to work together at this stage in order to ensure continued communication, improve the transparency and drive further research.

This review has also highlighted where the UK could benefit from learning from other countries where there has been significant R&D activity in particular areas. For example, in Scandinavian countries, district heating has generated a market for low-grade heat that can be recovered from industrial processes, which has in turn resulted in advanced heat integration on industrial plants. In the German cement industry, waste heat has been successfully recovery for power generation. There are also a number of international examples of successful industrial clusters, for example the Kalundborg eco-park in Denmark. Co-location of industries and exploiting industrial synergies will be a key step in decarbonising the UK industry.

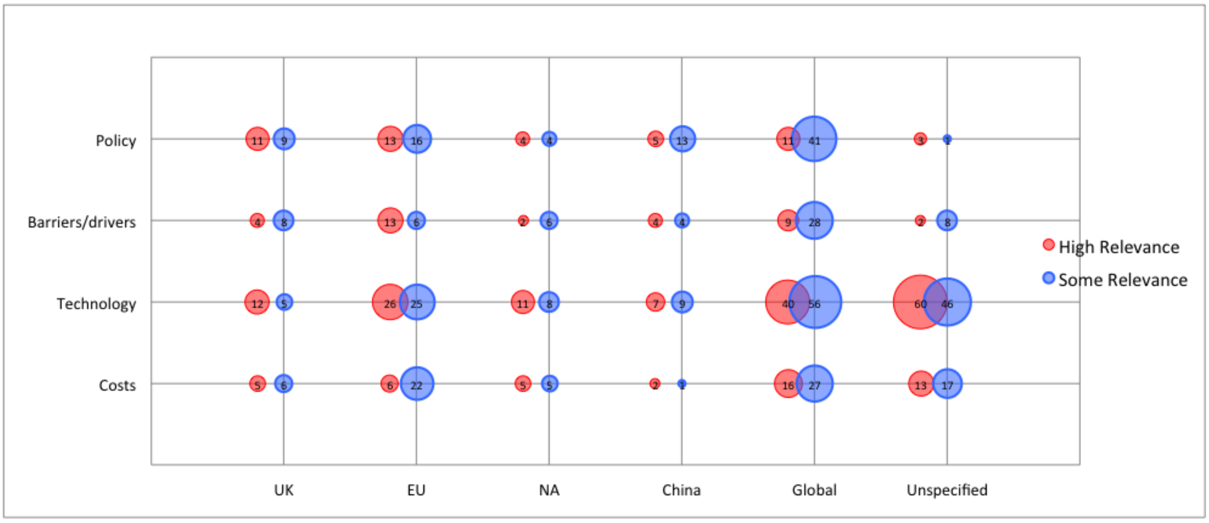


Figure 7: Summary of the literature by high-level category and geographical region

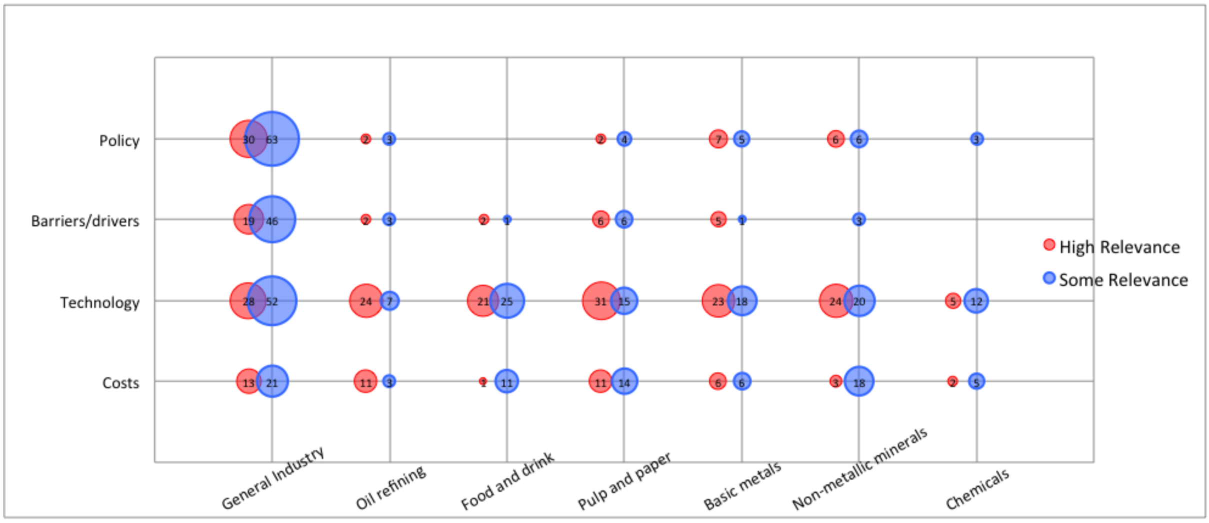


Figure 8: Summary of the literature by high-level category and industrial sector

6 Conclusions

Technologies and costs of decarbonizing heat in the UK industrial sector

There are short-term opportunities to reduce CO_2 emissions in many sectors through the further uptake of CHP, heat integration and heat networks. Other short-term opportunities appear to be limited as many of the energy efficiency improvements yet to be made in other countries have already been adopted in the UK. In the longer term, deeper emissions cuts may be possible through the introduction of novel technologies and fuel substitution. However these opportunities are likely to involve significant investment and will only be made during normal replacement cycles and if the regulatory and economic context is in place to incentivise such investment.

The lack of a robust and consistent evidence base on costs makes it difficult to draw firm conclusions for most sectors. In the literature there are some short-term measures claimed to reduce CO_2 emissions at low or negative costs but many are from international sources and the measures or costs may not be applicable to the UK. Evidence in the iron & steel sector is stronger and suggests that longer-term technologies combined with CCS could reduce sector emissions by about 50% at a cost of around £1.5 billion [34].

The barriers to and drivers for the uptake of technologies for decarbonizing heat

A key organisational driver is the willingness of top management to make climate change a priority. This is crucial as it affects the overall culture of the firm. The primary economic driver for industry to decarbonise, where decarbonisation involves more efficient use of energy is cost and the threat of rising energy prices. However, where low carbon options are not ultimately cost negative the current carbon price and its instability is insufficient to facilitate the uptake of these technologies.

Lack of resources, both in terms of time and capital, are considered to be major barriers by many firms. Another important barrier to the adoption of low carbon and energy efficient technologies is the risk of disruption to production. Continuity of production is of primary importance to firms. This is one of the reasons that energy efficiency technologies tend to have more stringent economic criteria compared to investments that are more closely related to the core business.

The effectiveness of policy and competitiveness

The evidence on the effectiveness of current policies is inconclusive and there is a real concern that rising energy prices could drive UK industry offshore. The only explicit indication from the literature reviewed that competitiveness loss is a barrier to investment in low-carbon technologies is from the Mineral Products Association [95], which claims that its members have already invested in energy efficient kilns and substitution of fossil fuels, resulting in a significant decrease in CO_2 intensity between 1990 and 2010, and which goes on to assert that the EU ETS and energy taxes will divert investment away from longer-term low-carbon investment. Aside from this, some analyses ([94], [96], [97]) show that there could be relatively high increases in production costs in energy-intensive sectors as a result of assumed 2020 EU ETS carbon prices, from which it could be inferred that the prospects for longer-term low-carbon investment could be harmed. However, the possibility that future assumed ETS prices could incentivise low-carbon investment (in order to reduce exposure to this price) is not discussed.

The gaps in the literature

The literature provides information on potential CO_2 savings from a range of short- and longer-term decarbonisation technologies in all of the sectors covered by this study, as detailed in Section 3.1. However for some sectors, such as paper and pulp, much of the information is based on non-UK case studies and so its relevance to the UK context may be limited. The academic literature tends to focus on a single technology in a single application while reports from international bodies (e.g. IEA, USDoE) and consultants (e.g. for the Carbon Trust or Committee on Climate Change) are more comprehensive but may not have been subject to rigorous peer review. While sector-specific technologies are relatively well covered in the literature, the same is not true of crosscutting technologies such as CHP, heat integration and more efficient boilers. There is a particular dearth of robust and consistent data on the costs of mitigation measures, even for shorter term technologies, with sporadic cost data often quoted as a single Capex value or as cost-effectiveness (£/tCO_2) without corresponding information on the baseline or discount rate applied.

In summary, analysis of the existing evidence base against the research questions for this project suggested a number of gaps in the evidence:

- The extent to which certain key short-term measures are really applicable in the UK. For example, what level of clinker substitution in cement production and fuel substitution in steel production is possible without adversely affecting product quality and customer confidence.
- The remaining potential for technology improvements and increased uptake in the UK of crosscutting technologies such as energy efficient boilers, burners and insulation.
- The longer term (post 2030) potential for electrification and hydrogen to effect deep cuts in CO_2 emissions in UK industry. An overview was provided in a CCC report last year. However, the applicability of these technologies at scale is disputed amongst experts.
- The likely capital and operating costs of abatement technologies in different sectors and on different timescales, using a systematic approach to ensure comparability.
- The scope for further improvement of heat integration through co-location of different industry sectors and with power generation, e.g. co-locating power generation with CCS with cement works or refineries and e.g. paper production.
- The barriers to and drivers for the decarbonisation of industrial heat within a UK context, together with building an understanding of the key factors which determine the most important barriers and drivers for a company.

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Appendices

Appendix 1 - List of databases identified and their priority for this study

Database	Coverage	Priority	Reasoning
ISI Web of Knowledge (WOK)	General database covering science and engineering (as well as some humanities and social sciences).	HIGH	Covers a wide range of multidisciplinary journals. We are familiar with the database.
Science Direct	Multidisciplinary journals published by Elsevier.	LOW	Only covers Elsevier publications
IDEAS	Database dedicated to Economics research.	MEDIUM	
Social Science Research Network	Covers social science research and is composed of a number of specialized research networks in each of the social sciences. Covers economics, management, policy and sustainability.	LOW	Useful for policy, economic and social science aspects. However, Imperial does not have access.
Google Scholar	Google Scholar provides a simple way to broadly search for scholarly literature. Can search across many disciplines and sources: articles, theses, books, abstracts and court opinions, from academic publishers, professional societies, online repositories, universities and other web sites.	HIGH	Covers very wide range of publications and captures grey literature well.
GreenFILE	Draws on the connections between the environment and a variety of disciplines such as agriculture, education, law, health and technology. Topics covered include global climate change, green building, pollution, sustainable agriculture, renewable energy, recycling and more.	MEDIUM	Might be useful if we have time.
ProQuest	Collection of multidisciplinary bibliographic databases. Provides access to a number of environment related	HIGH	Useful resource for the policy and barriers sections.

	databases, including: Environmental Impact Statements Ecology Abstracts Pollution Abstracts Water Resources Abstracts		
EBSCO	The key Business database. It includes academic journals, company profiles, country reports, market research and industry profiles.	HIGH	Useful for coverage of economic aspects.
Energy Citations	ECD includes scientific and technical research results in disciplines of interest to DOE such as chemistry, physics, materials, environmental science, geology, engineering, mathematics, climatology, oceanography, and computer science.	MEDIUM	Might be useful but very US focussed.

Appendix 2 - List of search terms used

Note: ‘?’ is a wild-card character which allows the search engine to search for different spelling conventions. ‘*’ means that the search engine will search for different variations in word endings e.g. electric* = electrical, electricity, electric etc.

<table>
<tr><th colspan="3">Technology focussed terms</th></tr>
<tr><th>Sector</th><th>NOT…</th><th>AND Carbon/energy</th></tr>
<tr><td>“Oil refining” OR
“Petroleum refining” OR
Refiner*</td><td></td><td rowspan="4">“Carbon abatement” OR
“Carbon management” OR
“Emissions reduction” OR
“Decarboni?ation” [excl. for iron and steel sector] OR
“Low carbon” [excl. for iron and steel sector] OR
“Carbon dioxide mitigation” OR
“CO2 mitigation” OR
“Energy efficiency” OR
“Energy saving” OR
“Energy intensity” OR
“Energy consumption” OR
“Energy demand reduction”
“Energy conservation”</td></tr>
<tr><td>“Food and drink*” OR
“Food and beverage*” OR
“Food process*” OR
“Food manufactur*”</td><td>agriculture OR
farming OR
crop* OR
animal OR
agro*</td></tr>
<tr><td>“Pulp and paper”</td><td></td></tr>
<tr><td>“Basic metals” OR
“Iron and steel production” OR
“steel production” OR
“iron production” OR
“iron and steel manufactur*” OR
“iron manufactur*” OR
“steel manufactur*” OR
“iron and steel indust*” OR
“steel industr**” OR</td><td></td></tr>
</table>

"iron industry*"		
"Non metallic minerals" OR Cement OR Clinker OR Concrete OR Glass OR Ceramic*		
Chemicals OR Plastics OR "Organic chemicals"		
Industr* OR "Energy intensive" OR Manufactur* OR "Heavy industry*" OR "Industrial sector" OR "High temperature indust*"	power OR "power generation" OR "electric* generation	

Policy focussed terms			
Industry	**NOT…**	**AND Carbon/energy**	**AND Policy**
Industr* OR "Energy intensive" OR Manufactur* OR "Heavy industry**" OR	power OR "power generation" OR "electric* generation	"Carbon abatement" OR "Carbon management" OR "Emissions reduction" OR "Decarbonisation" OR	Policy OR "EU ETS" OR "Emissions trading scheme" OR "Climate change agreements" OR

"Industrial sector" OR "High temperature indust*"		"Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation" OR "Energy management"	CCA OR "Carbon tax"

Organisational or behavioural and cost focussed			
Industry	**NOT…**	**AND Carbon/energy**	**AND Organisational/behavioural**
Industr* OR "Energy intensive" OR Manufactur* OR "Heavy industry**" OR "Industrial sector" OR "High temperature indust*" OR Heat	power OR "power generation" OR "electric* generation	"Carbon abatement" OR "Carbon management" OR "Emissions reduction" OR "Decarbonisation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR	"Behavi?r* change" "organi?ation* behave?r" Driver* Barrier* "decision making" Cost Technology cost Rate of return Payback Abatement cost curve

		"Energy consumption" OR "Energy demand reduction" "Energy conservation"	MACC Investment cost

Appendix 3 - Search results

Database	Date of search	Topic	Search term Part A	Search term Part B	Search term Part C	Search term Part D	Paper type	Timeline	Search in?	Sorted by	No. of hits	No. selected	Search order
			Industry	NOT	Carbon/energy	Other							
WOK	29/01/2013	Cost	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport OR agri* OR agro*	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation"	cost OR "technolog* cost" OR "rate of return" OR payback OR "abatement cost curve*" OR MAC OR MACC OR "Investment Cost*"	ONLY: Article or review	1990-2013	Topic		127	15	4
WOK	29/01/2013	Policy	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation" OR "energy us*" OR electrif*	policy OR "EU ETS" OR "emission* trading scheme" OR ETS OR "climate change agreement*" OR CCA OR "carbon tax*" OR "CO2 tax*"	ONLY: Article or review	1990-2013	Topic		126	47	1
WOK	29/01/2013	General industry	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation" OR "energy us*" OR electrif*	hydrogen OR biomass OR "steam production" OR boiler* OR refri*eration OR cooling OR heating	ONLY: Article or review	1990-2013	Topic		122	27	2
WOK	29/01/2013	Chemicals	chemical* production OR "chemical manufactur*" OR "plastic* production" OR "plastic manufactur*" OR "ammonia production" OR "fertili?er production"		carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation" OR "energy us*" OR electrif*		ONLY: Article or review	1990-2013	Topic		113	14	3
WOK	29/01/2013	Behaviour change	energy intensive industr* OR "manufactur*" OR "heavy industr*" OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" or "emission* reduction" or decarboni?ation or "low carbon" or "carbon dioxide mitigation" or "co2 mitigation" or "energy efficiency" or "energy saving" or "energy intensity" or "energy consumption" or "energy demand reduction" or "energy conservation"	behavi*r* change or "organi?ation* behavi*r" or driver* or barrier* or "decision making"	ONLY: Article or review	1990-2013	Topic		98	16	5
WOK	29/01/2013	Oil refining	oil refining OR "Petroleum refining" OR "Diesel production" OR "Petro* production"		Carbon abatement OR "Carbon management" OR "Emissions reduction" OR "Decarboni?ation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		55	30	6
WOK	29/01/2013	Food and Drink	Food and drink* indust* OR "Food and beverage* indust*" OR "Food process*" OR "Food manufactur*"	power OR "power generation" OR "electricity generation" OR "model*" OR "simulat*" OR "agricultur*" OR "farm*" OR "crop" OR "animal" OR "agro*"	carbon abatement OR "Carbon management" OR "Emissions reduction" OR "Decarboni?ation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption reduction" OR "reduction in energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		124	52	
WOK	29/01/2013	Pulp and Paper	pulp and paper OR "Pulp production" OR "Paper production" OR "pulp manufactur*" OR "paper manufactur*" OR "pulp process*" OR "paper process*"	"power" OR "power generation" OR "electricity generation" OR "model*" OR "simulat*" OR "paper properti*" OR "paper structure" OR "pulp properti*"	carbon abatement OR "Carbon management" OR "Emissions reduction" OR "Decarboni?ation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		155	68	
WOK	29/01/2013	Non metalic minerals	Non metallic minerals OR "Cement production" OR "Cement manufactur*" OR "Cement indust*" OR "Clinker production" OR "Clinker manufactur*" OR "Glass production" OR "Glass manufactur*" OR "Glass indust*" OR "Ceramic* manufactur*" OR "Ceramic* production"	build* OR"construction" OR "transport*" OR "power" OR "power generation" OR "electricity generation" OR "model*" OR "simulat*"	carbon abatement OR "Carbon management" OR "Emissions reduction" OR "Decarboni?ation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		105	40	
WOK	29/01/2013	Basic Metals	Basic Metals OR "Iron and steel production" OR "steel production" OR "iron production" OR "iron and steel manufactur*" OR "iron manufactur*" OR "steel manufactur*" OR "iron and steel indust*" OR "steel indust*" OR "steel	"power" OR "power generation" OR "electric*" OR "model*" OR "simulat*"	Carbon abatement OR "Carbon management" OR "CO2 Emissions reduction" OR "Carbon Dioxide Emissions reduction" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		110	42	
EBSCO	29/01/2013	Cost	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport OR agri* OR agro*	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation"	cost OR "technolog* cost" OR "rate of return" OR payback OR "abatement cost curve*" OR MAC OR MACC OR "Investment Cost*"	ONLY: Article or review	1990-2013	Topic		22	5	
EBSCO	29/01/2013	Policy	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation" OR "energy us*" OR electrif*	policy OR "EU ETS" OR "emission* trading scheme" OR ETS OR "climate change agreement*" OR CCA OR "carbon tax*" OR "CO2 tax*"	ONLY: Article or review	1990-2013	Topic		61	22	
EBSCO	29/01/2013	General industry	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation" OR "energy us*" OR electrif*	hydrogen OR biomass OR "steam production" OR boiler* OR refri*eration OR cooling OR heating	ONLY: Article or review	1990-2013	Topic		14	2	
EBSCO	29/01/2013	Chemicals	chemical* production OR "chemical manufactur*" OR "plastic* production" OR "plastic manufactur*" OR "ammonia production" OR "fertili?er production"		carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation" OR "energy us*" OR electrif*		ONLY: Article or review	1990-2013	Topic		43	3	

EBSCO	29/01/2013	Behaviour change	energy intensive industr* OR "manufactur*" OR "heavy industr*" OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" or "emission* reduction" or decarboni?ation or "low carbon" or "carbon dioxide mitigation" or "co2 mitigation" or "energy efficiency" or "energy saving" or "energy intensity" or "energy consumption" or "energy demand reduction" or "energy conservation"	behavi*r* change or "organi?ation* behavi*r" or driver* or barrier* or "decision making"	ONLY: Article or review	1990-2013	Topic		54	3
EBSCO	29/01/2013	Oil refining	oil refining OR "Petroleum refining" OR "Diesel production" OR "Petro* production"		Carbon abatement OR "Carbon management" OR "Emissions reduction" OR "Decarboni?ation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		22	6
EBSCO	29/01/2013	Food and Drink	Food and drink* indust* OR "Food and beverage* indust*" OR "Food process*" OR "Food manufactur*"	power OR "power generation" OR "electricity generation" OR "model*" OR "simulat*" OR "agricultur*" OR "farm*" OR "crop" OR "animal" OR "agro*"	carbon abatement OR "Carbon management" OR "Emissions reduction" OR "Decarboni?ation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption reduction" OR "reduction in energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		18	5
EBSCO	29/01/2013	Pulp and Paper	pulp and paper OR "Pulp production" OR "Paper production" OR "pulp manufactur*" OR "paper manufactur*" OR "pulp process*" OR "paper process*"	"power" OR "power generation" OR "electricity generation" OR "model*" OR "simulat*" OR "paper properti*" OR "paper structure" OR "pulp properti*"	carbon abatement OR "Carbon management" OR "Emissions reduction" OR "Decarboni?ation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		21	5
EBSCO	29/01/2013	Non metalic minerals	Non metallic minerals OR "Cement production" OR "Cement manufactur*" OR "Cement indust*" OR "Clinker production" OR "Clinker manufactur*" OR "Glass production" OR "Glass manufactur*" OR "Glass indust*" OR "Ceramic* manufactur*" OR "Ceramic* production"	build* OR"construction" OR "transport*" OR "power" OR "power generation" OR "electricity generation" OR "model*" OR "simulat*"	carbon abatement OR "Carbon management" OR "Emissions reduction" OR "Decarboni?ation" OR "Low carbon" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		9	3
EBSCO	29/01/2013	Basic Metals	Basic Metals OR "Iron and steel production" OR "steel production" OR "iron production" OR "iron and steel manufactur*" OR "iron manufactur*" OR "steel manufactur*" OR "iron and steel indust*" OR "steel indust*" OR "steel	"power" OR "power generation" OR "electric*" OR "model*" OR "simulat*"	Carbon abatement OR "Carbon management" OR "CO2 Emissions reduction" OR "Carbon Dioxide Emissions reduction" OR "Carbon dioxide mitigation" OR "CO2 mitigation" OR "Energy efficiency" OR "Energy saving" OR "Energy intensity" OR "Energy consumption" OR "Energy demand reduction" OR "Energy conservation"		ONLY: Article or review	1990-2013	Topic		30	11
Google scholar	30/01/2013	General industry	"energy intensive" AND		"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	36
Google scholar	30/01/2013	General industry	manufacturing AND		"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	14
Google scholar	31/01/2013	General industry	"industrial sector"		"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	34
Google scholar	31/01/2013	Non metalic minerals	cement		"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	40
Google scholar	31/01/2013	Basic Metals	"iron and steel"		"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	25
Google scholar	31/01/2013	Pulp and Paper	"pulp and paper"		"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	38
Google scholar	31/01/2013	Food and Drink	"food and drink"		"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	4
Google scholar	31/01/2013	Oil refining	refining	sugar OR pulp OR steel	"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	10
Google scholar	31/01/2013	Chemicals	chemical		"energy efficiency" OR "carbon abatement" OR "emission reduction" OR "low carbon" "carbon dioxide mitigation" OR "co2 mitigation" OR "energy intensity" OR "energy saving" OR "energy consumption"		EXCLUDED: Patents and citations	1990-2013	Anywhere in text	Relevance	100	9
ProQuest Social Science	01/02/2013	Cost	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport OR agri* OR agro*	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation"	cost OR "technolog* cost" OR "rate of return" OR payback OR "abatement cost curve*" OR MAC OR MACC OR "Investment Cost*"		1990-2013			5	1
ProQuest Social Science	01/02/2013	Policy	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation" OR "energy us*" OR electrif*	policy OR "EU ETS" OR "emission* trading scheme" OR ETS OR "climate change agreement*" OR CCA OR "carbon tax*" OR "CO2 tax*"		1990-2013			16	9
ProQuest Social Science	01/02/2013	General industry	energy intensive OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" OR "emission* reduction" OR decarboni?ation OR "low carbon" OR "carbon dioxide mitigation" OR "co2 mitigation" OR "energy efficiency" OR "energy saving" OR "energy intensity" OR "energy consumption" OR "energy demand reduction" OR "energy conservation" OR "energy us*" OR electrif*	hydrogen OR biomass OR "steam production" OR boiler* OR refri*eration OR cooling OR heating		1990-2013			2	0
ProQuest Social Science	01/02/2013	Behaviour change	energy intensive industr* OR "manufactur*" OR "heavy industr*" OR "industrial sector" OR "high temperature industr*"	power OR "power generation" OR "electric* generation" OR hous* OR accommodation OR residential OR "renewable energ*" OR "renewable electric*" OR "renewable power" OR transport	carbon abatement OR "carbon management" or "emission* reduction" or decarboni?ation or "low carbon" or "carbon dioxide mitigation" or "co2 mitigation" or "energy efficiency" or "energy saving" or "energy intensity" or "energy consumption" or "energy demand reduction" or "energy conservation"	behavi*r* change or "organi?ation* behavi*r" or driver* or barrier* or "decision making"		1990-2013			16	2
								Total number of hits				2368
								Total no. of papers selected				638
								Recovery percentage before duplicate removal				27%
								Total no. of papers after duplicate removal				432
								Recovery percentage after duplicate removal				18%

Appendix 4 - High-level selection criteria

	Considerations	Final criteria
Time period to be covered	The most significant improvement in UK industrial energy intensity was seen in the two decades after the 1970s oil shocks. Policies targeting energy efficiency in the UK industrial sector were also introduced around this time period. However, more recently published papers will be more relevant to this study as these will give a better picture of the abatement potential and effectiveness of current policies.	Papers published after 1990 to be included. Selected papers published between 1970 and 1990 to be retained for a high level analysis of historical trends
Geographical area	Whilst this study is largely interested in the decarbonisation potential of UK industries, many UK plants are owned by international companies. Additionally, new technologies may have been developed and implemented in countries outside the UK.	No geographical exclusion criteria.
Industrial sector	There is often a conflation between the power 'industry' and the manufacturing industry. Papers may refer to industry as a whole or may be sector specific.	Only papers which relate to the industrial sector (as defined by the ISIC definition) to be included; Papers relate to the industrial sector as a whole or to the following selected sectors: Oil refining, Food and drink, Pulp and paper, Basic metals, Non-metallic minerals, Chemicals
Language	Although some relevant papers may have been published in other languages we expect that these are minimal compared to the vast quantity of papers published in English.	Limit papers to only those published in English[11]

[11] Ricardo-AEA staff have the capability to work with reports in many other languages, should this be required, but we anticipate the key literature for this study will be available in English.

Appendix 5 - Google form used for categorisation of papers

Industry review: Paper categorisation

* Required

Top of Form

1. ALL PAPERS: Paper title *

2. ALL PAPERS: Paper Category *

What is the main focus of the paper?

- ○ Technology
- ○ Organisational/behavioural
- ○ Policy

3. ALL PAPERS: Does the paper have sections which refer to any of the other above categories? *

This is to flag up the paper in case there is a section that is worth reading for an expert covering a different section.

- ☐ Technology
- ☐ Organisational/behavioural
- ☐ Policy
- ☐ No, only focuses on primary category stated above

4. ALL PAPERS: Industry sector *

Which industry sector does the paper cover? Select all that apply.

- ☐ Industry as a whole
- ☐ Oil refining
- ☐ Food and drink
- ☐ Pulp and paper
- ☐ Basic metals
- ☐ Non-metallic minerals
- ☐ Chemicals

- [ ] Other: [ ]

5. ALL PAPERS: Geographical region *

Which geographical region does the paper refer to?

- ( ) UK
- ( ) EU
- ( ) China
- ( ) North America
- ( ) Global
- ( ) Not specified
- ( ) Other: [ ]

6.1 TECHNOLOGY PAPERS ONLY:

Which of the following best describes the paper?

- [ ] Detailed discussion of specific technologies/measures (gives energy savings, TRL etc.) - HIGH RELEVANCE
- [ ] Projection of future technical abatement potential - HIGH RELEVANCE
- [ ] Overview of different technologies but not much detail - SOME RELEVANCE
- [ ] Exergy analysis - SOME RELEVANCE
- [ ] Benchmarking - SOME RELEVANCE
- [ ] Analysis of historical trends of energy use/emissions - NO RELEVANCE
- [ ] Decomposition analysis - NO RELEVANCE
- [ ] Other: [ ]

6.2. TECHNOLOGY PAPERS ONLY: Energy efficiency

What sort of energy efficiency technologies are covered in this paper?

- [ ] Process- or sector- specific energy efficiency options
- [ ] Cross-cutting energy efficiency options (steam systems, compression, motor systems etc.)
- [ ] Heat integration, pinch analysis
- [ ] Process optimisation
- [ ] Combined heat and power (CHP)

- [ ] Significant focus on electrical energy efficiency (e.g. VSDs) - NO RELEVANCE
- [ ] None
- [ ] Other: ______

6.3. TECHNOLOGY PAPERS ONLY: Fuel switching

How would you describe the 'fuel switching analysis'

- [ ] Detailed discussion of the technical challenges of fuel switching - HIGH RELEVANCE
- [ ] Sporadic mention of fuel switching options - SOME RELEVANCE
- [ ] Econometric analysis of fuel substitution (i.e. price elasticities etc.) - NO RELEVANCE
- [ ] No fuel switching discussed
- [ ] Other: ______

6.4. TECHNOLOGY PAPERS ONLY: Fuel switching

Which of the following fuel switching options are dicussed in this paper?

- [ ] Switching to gas
- [ ] Biomass or wastes
- [ ] Hydrogen
- [ ] Electrification
- [ ] None
- [ ] Other: ______

6.5. TECHNOLOGY PAPERS ONLY: Other low carbon options

Which of the following other low carbon technologies are discussed in this paper?

- [ ] Industrial synergies or clustering or heat networks
- [ ] Carbon capture and storage (CCS) - NO RELEVANCE (if paper too focussed on CCS)
- [ ] Novel processes, innovations
- [ ] None
- [ ] Other: ______

6.6. TECHNOLOGY PAPERS ONLY: Research Q1 - Does this paper refer to specific technical measures?

What existing research is there on the technical potential for decarbonising energy use, and in particular heat demand in industry to 2050? What generic and specific technical measures does decarbonisation involve, and which heat-intensive industries are those measures applicable to?

7.1 TECHNOLOGY PAPERS ONLY: Costs

What cost details are provided?

- ☐ Detailed technology specific costs - HIGH RELEVANCE
- ☐ Marginal abatement cost curve - HIGH RELEVANCE
- ☐ A few sporadic costs mentioned - SOME RELEVANCE
- ☐ No cost details - NO RELEVANCE
- ☐ Other:

7.2. TECHNOLOGY PAPERS ONLY: Research Q2 - Costs

What research is there on the costs of these technical measures?

8.1. ORG/BEH PAPERS ONLY:

Which of the following best describes this paper?

- ☐ Detailed discussion/analysis of decision-making or barriers and drivers to uptake of low C technologies based on real industry data (surveys/case studies etc) - HIGH RELEVANCE
- ☐ Discussion/analysis of decision-making or barriers and drivers to uptake of low C technologies based on theories or models (no real industry data) - SOME RELEVANCE
- ☐ Brief mention of barriers and drivers - SOME RELEVANCE
- ☐ Review of economic or social theories - NO RELEVANCE
- ☐ Other:

8.2. ORG/BEH PAPERS ONLY: Type of drivers/barriers considered

Select all that apply

- ☐ Economic
- ☐ Organisational
- ☐ Technical
- ☐ Other:

8.3. ORG/BEH PAPERS ONLY: Research Q3 & 4 - barriers and drivers

What does research tell us about the economic and organisational drivers or barriers for industrial organisations in the six sectors to decarbonise their heat use? What are the perceived benefits for industrial organisations to decarbonise their heat use?

[▾]

9.1. POLICY PAPERS ONLY:

Which of the following best describes the paper?

- ☐ Analysis of policy effectiveness - HIGH RELEVANCE
- ☐ Discussion/Review/Analysis of policies by country/region - SOME RELEVANCE
- ☐ Discussion/Review/Analysis of one or more policies - SOME RELEVANCE
- ☐ Policy theory - NO RELEVANCE
- ☐ Other: [ ]

9.2. POLICY PAPERS ONLY:

Which policy measures are covered in this paper?

- ☐ Tax or carbon price (e.g. Emissions trading scheme (ETS))
- ☐ Targets (e.g. emissions targets, energy intensity targets)
- ☐ Tariff
- ☐ Regulation
- ☐ International (e.g. Clean Development Mechanism (CDM),
- ☐ Other: [ ]

9.3. POLICY PAPERS ONLY: Research Q5 - policy interventions

What evaluations exist of the effectiveness of past and present interventions (including UK government policies) in influencing industry decision making to drive decarbonisation of heat in the six sectors? Which interventions have been most effective and why?

[▾]

9.4. POLICY PAPERS ONLY: Competitiveness

Are competitiveness or carbon leakage issues discussed in the paper?

- ○ Yes
- ○ No

10. ALL PAPERS: Does the paper have any relevance to the other questions that you would like to flag up?

Select all that apply.

- [ ] 1
- [ ] 2
- [ ] 3 and 4
- [ ] 5
- [ ] 6

11. ALL PAPERS: Overall, how would you rate the paper in terms of relevance to the study? *

12. Any other relevant information that you feel should be noted?

13. Do we have a full text for this paper? *

- ( ) Yes
- ( ) No

▯¶ 0

Submit

Bottom of Form

Appendix 6 – Quality and Relevance Criteria

	Technical	Cost	Barriers/Drivers	Policy
Minimum quality criteria	Peer-reviewed, or otherwise from a known, reputable institution The study must clearly describe its methodology All data inputs and assumptions must be clearly stated and cited where relevant			
	Clear justification of the technical potential and costs Paper rejected if the figures are unsubstantiated or vary widely from expected values		Explicitly states the method of data collection and analysis (e.g. survey/econometrics/model) and justification of conclusions Paper rejected if claim is unsubstantiated	
High relevance	Detailed discussion of specific technologies/measures (gives energy savings, TRL etc.) Projection of future technical abatement potential Detailed discussion of the technical challenges of fuel switching	Detailed technology specific costs Marginal abatement cost curve	Detailed discussion/analysis of decision-making or barriers and drivers to uptake of low carbon technologies based on real industry data (surveys/case studies etc)	Analysis of policy effectiveness
Some relevance	Overview of different technologies but not much detail Exergy analysis Benchmarking Sporadic mention of fuel switching options	A few sporadic costs mentioned	Discussion/analysis of decision-making or barriers and drivers to uptake of low C technologies based on theories or models (no real industry data) Brief mention of barriers and drivers	Discussion/Review/Analysis of policies by country/region Discussion/Review/Analysis of one or more policies
No relevance	Analysis of historical trends of energy use/emissions Decomposition analysis Significant focus on electrical energy efficiency (e.g. VSDs) Econometric analysis of fuel substitution (i.e. price elasticities etc.) Wholly focussed on Carbon Capture and Storage (CCS)	No cost details	Review of economic or social theories	Policy theory

Appendix 7 – Guidance questions for experts

	Guidance Questions for Experts
Sectoral review	**What are the abatement options in the short term (<2020)?** List abatement options addressed in the literature, focusing on process- and sector-specific options. **What are the longer-term abatement options (2020-2050)?** List abatement options addressed in the literature, indicating nature of innovation and when they might become available. **What is the technical potential for decarbonisation in this sector?** What is the remaining scope for energy efficiency improvements? What is the scope for fuel switching, and which fuels are applicable to which processes? What is the scope for other technologies? Any UK-specific challenges in implementing these technologies? Any lessons the UK can learn from other countries? What % or absolute CO_2 savings are considered possible from different abatement options, noting whether these figures apply specifically to the UK context and to what year they apply. **What are the costs of different abatement technologies in this sector?** Include capital and operating costs, where available. Note which geography the costs relate to, e.g. UK, EU, China, global. Use original currencies and base year e.g. £1995 or $US2000. If £/t$CO_2$ figures are given, note the assumed lifetime and discount rate. It will be assumed that these are costs for high volume manufacture if not stated **How strong is the evidence base for this sector?** Which aspects are well covered, which are not? Is there any contradictory evidence? What are the key gaps?
Technology review	**What is the technical potential for these technologies?** What is the scope for applying these technologies to decarbonise heat in each of the key industry sectors? What are the constraints on their use, e.g. process type, scale, resource availability? What new innovations might become available, and when? What % or absolute CO_2 savings are considered possible in different sectors, noting whether these figures apply specifically to the UK context and to what year they apply. **What are the costs of these technologies?** Include capital and operating costs, where available. Note which geography the costs relate to, e.g. UK, EU, China, global. Use original currencies and base year e.g. £1995 or $US2000. If £/t$CO_2$ figures are given, note the assumed lifetime and discount rate. It will be assumed that these are costs for high volume manufacture if not stated **How strong is the evidence base for these technologies?** Which aspects are well covered, which are not? Is there any contradictory evidence? What are the key gaps?
Barriers/drivers review	**What are the barriers and drivers to the adoption of abatement options?** List the typical barriers and drivers and describe whether they are broadly economic, organisational or technical. **Can these barriers and drivers be grouped into themes?** **Are these barriers/drivers sector specific or independent?** Identify

	whether these barriers and drivers are consistent across all sectors or are sector specific. Highlight the barriers/drivers encountered by sector/by technology/by organisational characteristics (e.g. size, location) etc. **How strong is the evidence base for these barriers/drivers?** Which aspects are well covered, which are not? Is there any contradictory evidence? What are the key gaps?
Policy review	**Describe the current suite of policies facing the UK industry.** Describe the policies. Give details regarding the effect of these policies on the industrial sector (both direct and indirect). Include discussion of non-policy interventions such as voluntary agreements. **What evidence is there that these interventions have been effective in increasing energy efficiency/reducing emissions?** **How have these policies or interventions affected costs for industry?** Discuss the evidence in the literature. **How do competitiveness issues affect the UK industry sector's investment in abatement technologies?** Discuss the evidence in the literature. **How strong is the evidence base for the effectiveness of interventions?** Which aspects are well covered, which are not? Is there any contradictory evidence? What are the key gaps?

Appendix 8 – Theoretical barriers and drivers

Table 14: Drivers and barriers to the adoption of energy efficient technologies in industry collected from a range of literature sources [78], [79], [81–85]

	Driver	Barrier
Internal	Economic • Reduced energy costs Organisational/behavioural • Recognition/reputation • Top manager support • Willingness to improve energy efficiency • Improved staff health and safety Technical • Co-benefit of improvement in product quality or yield • Expected longer equipment life and reduced maintenance requirements (not this is not always the case in reality)	Economic • Lack of access to capital/capital constraints • Split incentives • Ownership transfer issue • Hidden cost/transaction cost/disruption cost • Upfront cost vs. lifetime cost • Adverse bundling • Heterogeneity Information • Lack of awareness/information Organisational/behavioural • Principal-agent relationship • Bounded rationality • Lack of focus from top-management • Concerns over health and safety risks of new equipment • Custom/habit Technical • Concerns over tech operation of new equipment • Retrofit vs. new build • Concerns over impact on product quality
External	Compliance with Government policy Export rate of product Influence of industrial association Competitor EM levels Threat of rising energy prices Third-party financing Organisational growth	Price uncertainty Price distortions Insufficient supply channels/procurement constraints Uncertainty regarding policies

Appendix 9 – Summary of barriers and drivers studies

Table 15: Summary of the high relevance literature on barriers to and drivers for the adoption of energy efficient technologies

Study	Methodology	Description of respondents	Main findings
Suk et al. 2013 [84]	Questionnaire based survey of 66 energy-intensive businesses. Uses regression analysis to relate the company's level of Energy Saving Activity to a number of independent variables (regulation, export ratio, influence of competitors and industry organisations, willingness to change etc.).	Sectors covered include: steel, power, petro-chemical, pulp and paper, cement, non-ferrous, metal processing, machinery, oil refining. Majority (77.3%) of companies were medium-sized. Geography: Republic of Korea	The main driver of energy saving activity was found to be 'willingness to improve energy efficiency'.
Thollander et al. 2008 [83]	Investigates the barriers to energy efficiency investments. Survey of Swedish pulp and paper mills. Questionnaire was answered by the energy manager or equivalent. Participants were asked to rate barriers/drivers according to importance.	Pulp and paper Geography: Sweden	Top 5 barriers: Risk of production disruptions, cost of production disruption. Heterogeneity (i.e. different plants require different equipment), lack of time and lack of capital. The barriers are largely related to non-market failures. EE is not prioritised highly in organisations. Top 5 drivers: Cost, people with real ambition, long-term energy strategy, threat of rising energy prices, Electricity Certificate System (Swedish policy) The drivers are largely related to company organisation.
Ren 2009 [79] [79]	Interviewed 30 experts from petrochemical manufacturers, engineering firms, consultancies, universities and governmental bodies.	Petrochemical Geography: International	Compared the drivers and barriers for two types of investments: 1. improving existing processes Drivers: cost savings, tight supply of gas feedstocks, personal commitment of individuals Barriers: shortage of staff, lack of prioritisation, preference for known proven configurations rather than risky new technologies (despite the potential benefits)

			2. developing new processes. Drivers: economic gain, competition, broaden the knowledge on catalytic processes Barriers: unfavourable economic conditions, financial tools unable to deal with uncertainties of longer-term timescales, concern for job security
Rohdin et al. 2007 [78]	59 members of the Swedish Foundry Association answered a questionnaire.	Geography: Sweden	Top 5 barriers: Lack of access to capital, Technical risk (e.g. product disruption), Lack of budget funding, Cost of obtaining information, other priorities for capital investment Top 5 drivers: people with real ambitions, long-term strategies, environmental company profile, environmental management systems, international competition Lack of access to capital applied to both privately owned (often smaller) companies and group owned (often larger) companies. In general, group owned firms faced more organisational barriers whilst privately owned firms faced more informational barriers.
Hasanbeigi et al. 2009 [80]	Literature review, questionnaire and semi-structured interview. Respondents: Cement (3), Textiles (13).	Cement (representing large energy intensive companies), Textiles (representing smaller less energy intensive companies) Geography: Thailand	Compared the drivers and barriers for two types of investments: 1. Cement Drivers: reduced energy costs, improve product quality, improve staff health and safety Barriers: management concern re investment cost, management finds production more important, management concerns re time required to improve energy efficiency 2. Textiles Drivers: reduced energy costs, improve staff health and safety, improve product quality Barriers: management finds production more important, technology will become cheaper, concern that new tech will not satisfy future safety standards
Trianni et al. 2013 [81]	Questionnaire completed by 65 companies. The results were analysed quantitatively for	Foundry: covered a range of company size and alloy type	The two main barriers : 1) lack of resources in terms of time and capital and 2) importance of guaranteeing continuity of the business. First barrier was more relevant for SMEs and much less

	significance.	Geography: EU	relevant for the larger companies. This is because larger companies are able to have people with the right skills and the exclusive role of investigating energy issues. Additionally, for SMEs company organization is of key importance. If management does not consider energy to be a main priority then this is a significant barrier. The study also indicated that for SMEs access to capital is a barrier and obtaining credit in particular was cited as being a problem. Interestingly, the study also found that firms which had previously conducted an energy audit were more aware of the barriers and difficulties to investment in energy efficiency technologies than those who had not.
Sardinou 2008 [44]	Survey of 50 industrial firms	Sectors: Metals, machinery, food and drink, chemicals, paper and textiles Geography: Greece	
Jeswani et al. 2008 [82]	Aims to assess the activity level (operational and management) of companies in response to climate change. Companies were classified as either indifferent, beginner, emerging or active. Survey of 180 companies.	Sectors covered: oil and gas, chemical, automotive, power, steel, cement, paper, textile, food and drink. Geography: Compares the UK (108 companies) and Pakistan (72 companies)	75% of Pakistan companies were either 'indifferent' or 'beginner' 40% of UK firms were 'emerging' and 30% are 'active'. 'Indifferent' or 'beginner' companies tended to be non-multinational corporations, small in size and not regulated by the EU ETS (UK relevant only) Drivers: cost savings, management commitment, corporate targets, compliance and regulations (both countries) Barriers: high cost and lack of financial resources (both UK and Pakistan), lack of awareness, non-availability of technology, absence of government policies (Pakistan)
Sandberg and Soderstrom 2003 [45]	14 in-depth interviews. Qualitative analysis of the results according to 4 high level topics: energy auditing, monitoring and benchmarking; investment routines; follow-up and knowledge transfer; and risk management and uncertainty	Sectors: Pulp and paper (2 companies, 4 respondents), steel (1 company, 1 respondent) and chemicals (1 company, 1 respondent) Geography: Sweden	Energy auditing, monitoring and benchmarking: EIC - Degree of energy measurement is highly variable across companies. Energy audits are sometimes performed in-house in details; other companies hire consultants. NEIC - Limited energy monitoring and measurement; Energy audits seldom lead to investment, because it is considered more profitable to do nothing; little energy benchmarking performed largely because factory activities too heterogeneous, limited

			resources BOTH - Electricity is better metered than steam (because it is easier) Investment routines: EIC – “an application for investment funds is made, submitted and then approved at different levels depending on the size of investment”. Early lobbying makes it more likely for the project to be accepted timely. Large projects – long lead time, lots of resources put into making the decision. NEIC – Person responsible for energy is often maintenance, real estate or facilities and not close to production. Tendency to delay replacement as this is the most profitable alternative. Energy efficiency is seldom the sole reason for an investment going ahead. BOTH - NPV is considered the best but payback is used the most (particularly for smaller investments) because it is easy to understand. Strong focus on ‘core business’ “makes requirements for energy investments tougher”. Follow-up and knowledge transfer: EIC – Most activity is done on a factory level and only large investments are reviewed at corporate level. Respondents agreed that learning from projects could be improved. Some, but limited, knowledge transfer between factories, usually overseen at corporate level. NEIC – All respondents thought post-project follow-up can be improved. Follow-up is largely done at corporate level, if at all. Communication between factories is normally very rare Risk management and uncertainty: EIC – Different types of risks are handled at different places in the organisation. High value placed on good information as this reduces risk; the information should be reliable and at reasonable cost NEIC – High variability in product range so flexibility is very

			important. BOTH - Very high value placed on operational continuity, i.e. risk to production are weighted more heavily, even if the investment is highly profitable. Environmental risks are also weighted quite highly as the company does not want to lose face.
Granade et al 2009 [85]	Several hundred interviews with representatives from government agencies, public and private companies, academic institutions, research foundations and independent experts.	Industrial sector as a whole (as well as the residential and commercial sectors). <u>Geography</u>: US	

Appendix 10 – Gap analysis using meta-data

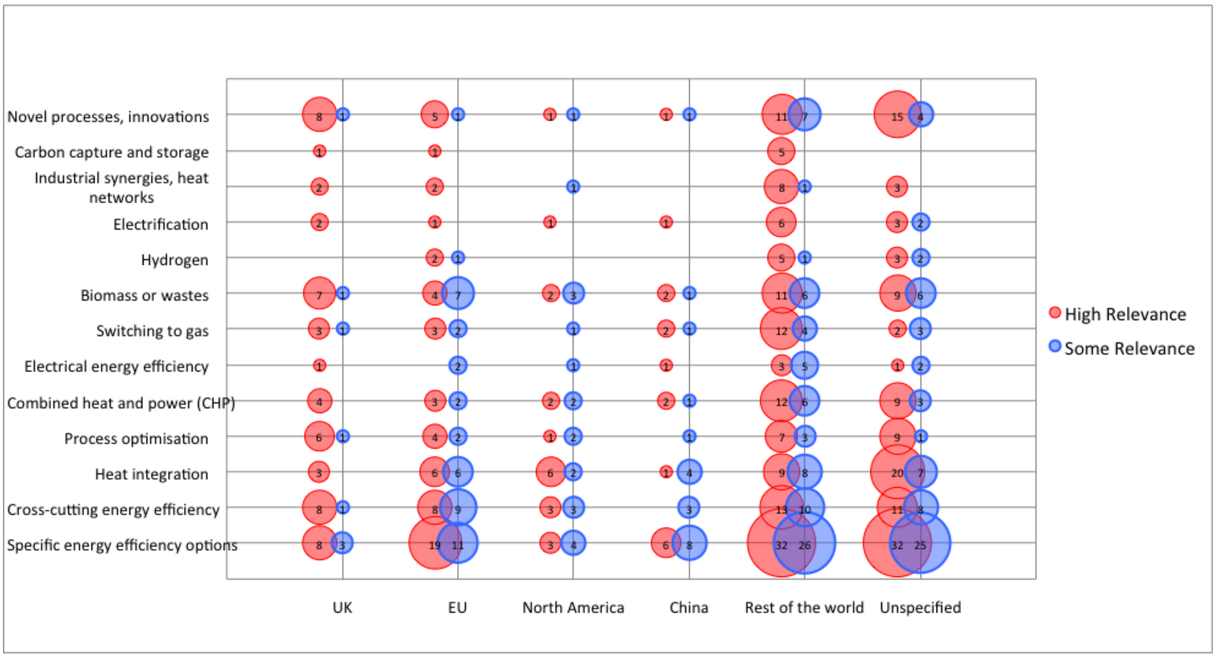


Figure 9: Map of the technical literature showing measure by region

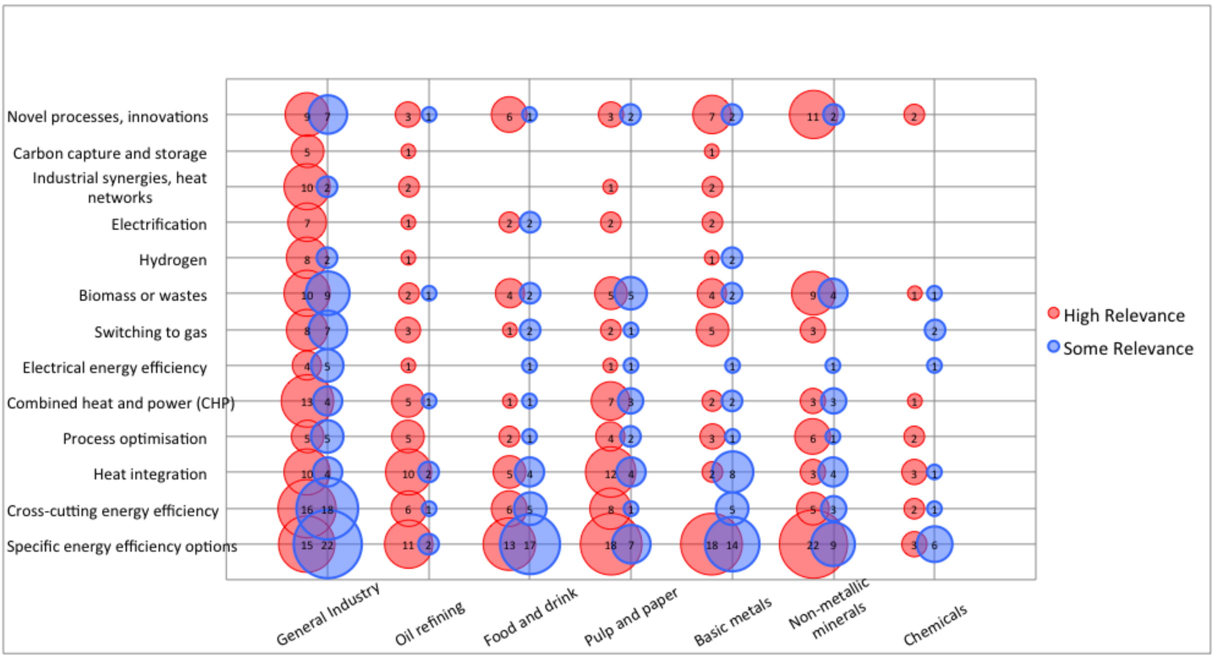


Figure 9: Map of the technical literature showing measure by industrial sector

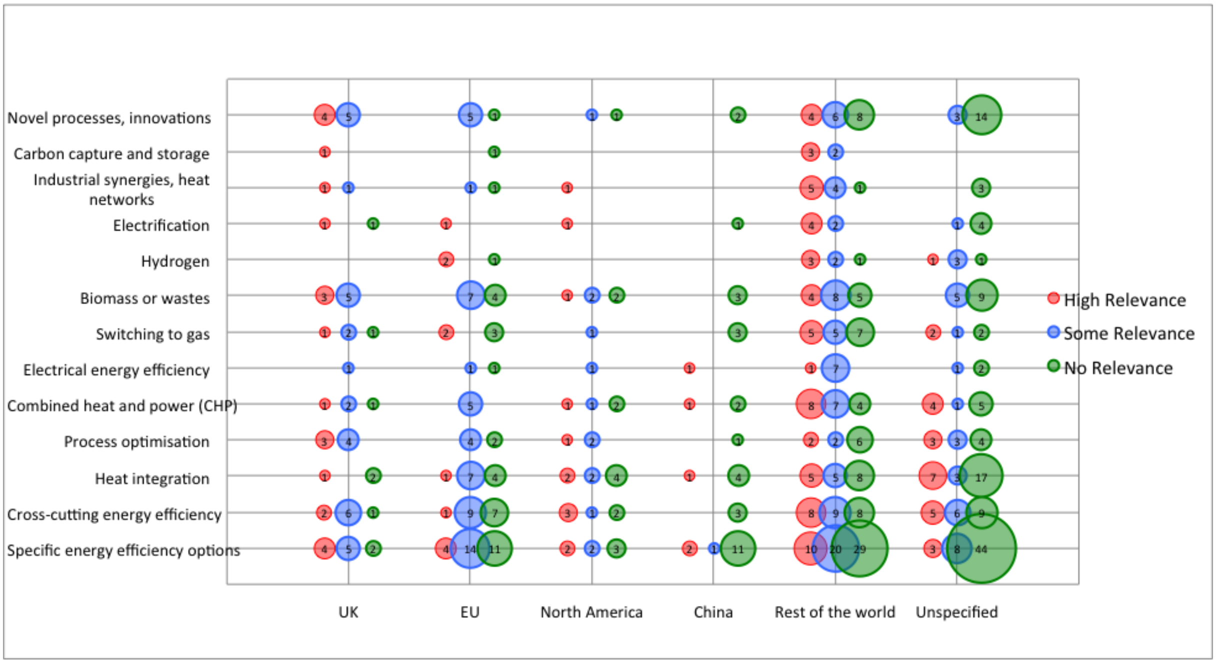


Figure 10: Map of the cost literature showing measure by region

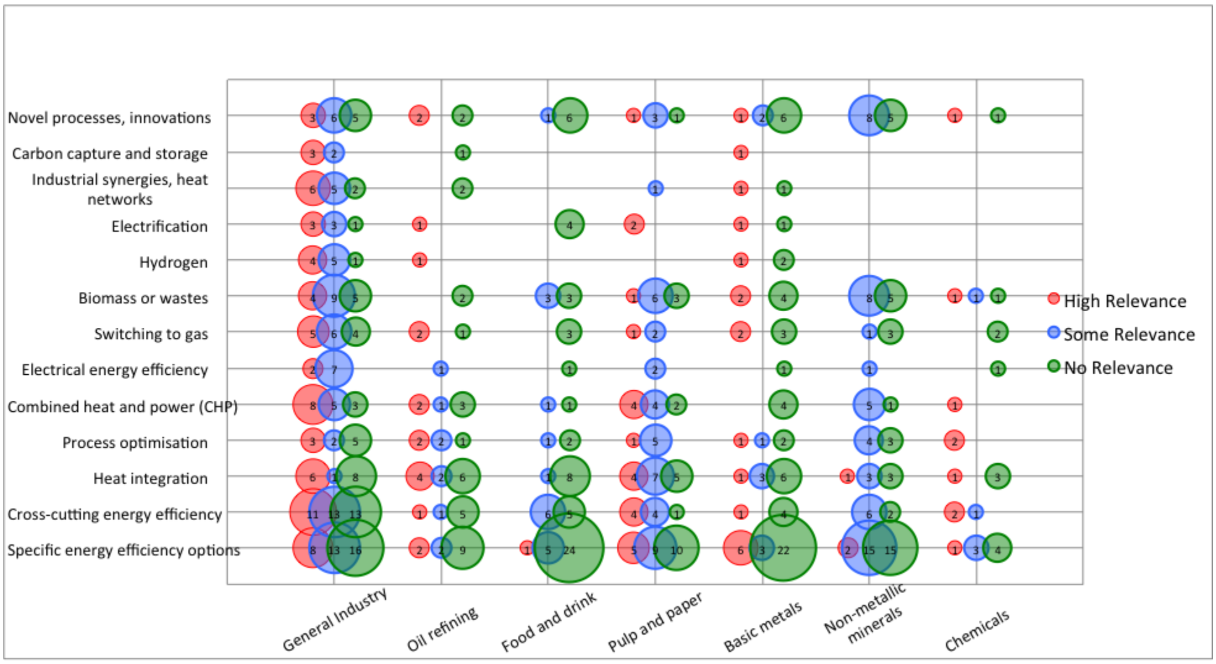


Figure 11: Map of the cost literature showing measure by industrial sector

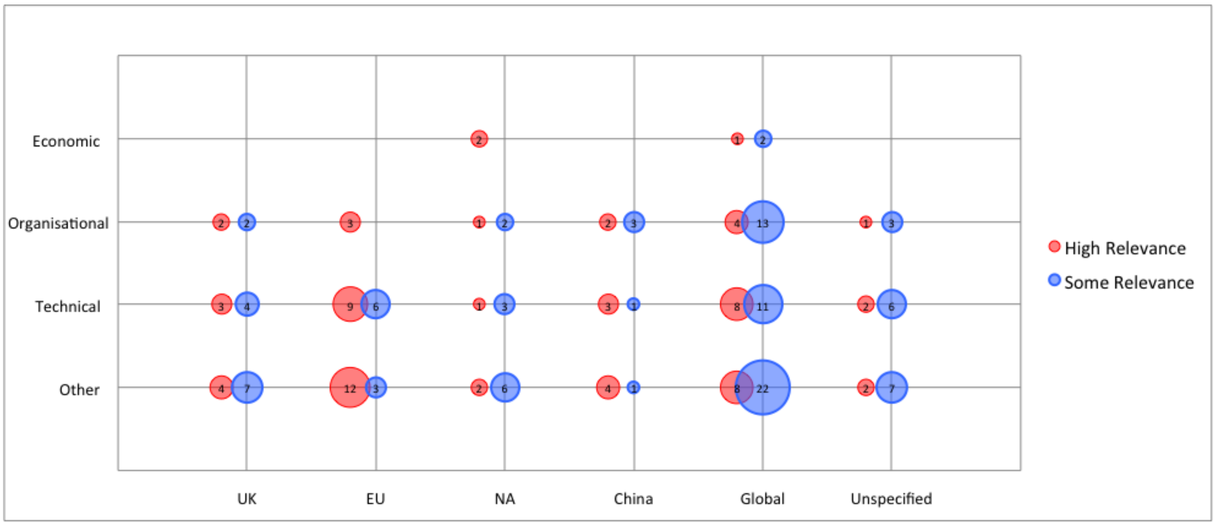


Figure 12: Map of the barriers/drivers literature showing measure by region

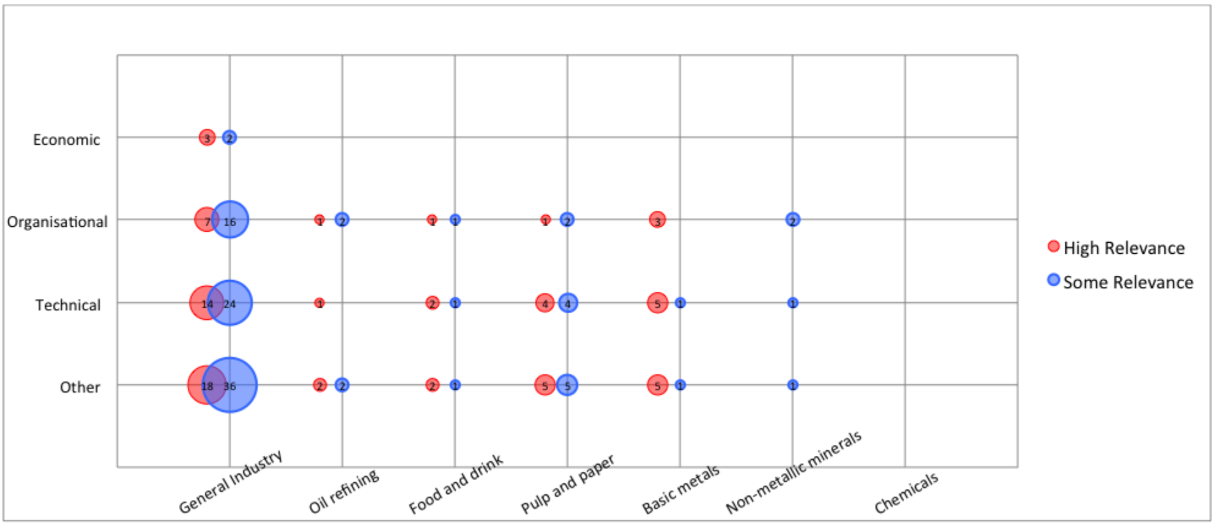


Figure 13: Map of the barriers/drivers literature showing measure by industrial sector

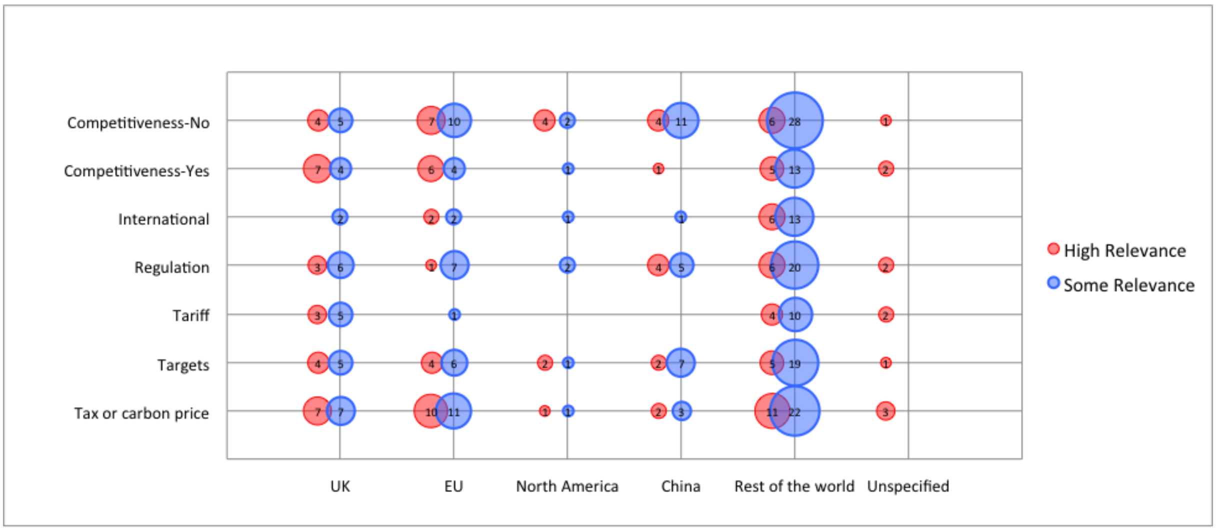


Figure 14: Map of the policy literature showing measure by region

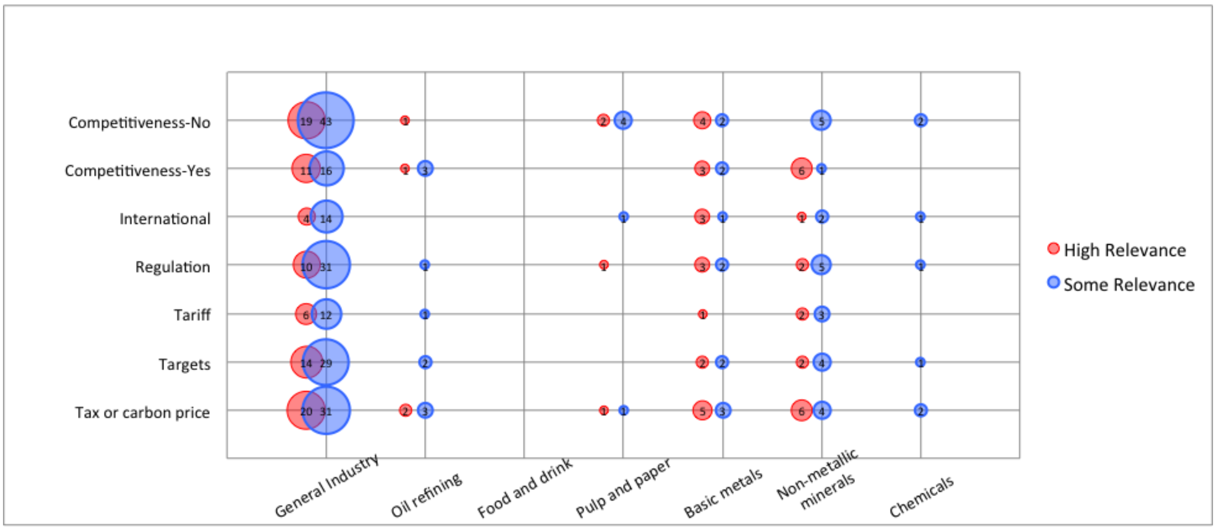


Figure 15: Map of the policy literature showing measure by industrial sector

Appendix 11 – CHP technologies

Reciprocating Gas Engines

Reciprocating gas Engines can run on both conventional and renewable fuels. The electrical efficiency ranges from around 30% for smaller gas engines around 100kWe up to around 40% for 4MWe gas engines based on Gross Calorific Value Fuel Input (GCV). The amount of waste heat available for use is approximately proportional to the fuel input and electrical output so to avoid wasting heat, the engine needs to be modulated (fuel input and electrical output reduced) to suit the heat demand (Heat Led Operation). However if the value of power is high compared to the cost of fuel it may be more economic to generate maximum power and waste excess heat.

Bio-liquids such as biodiesel and bioethanol can be burned in reciprocating engines with the same technology as diesel and petrol car engines. Most small scale renewable CHP schemes are bio-liquid engines operating on the diesel cycles. The efficiency is slightly higher than for natural gas engines due to the more efficient diesel cycle

Gas Turbines

The electrical efficiency is lower than similarly sized gas engines (typically between around 25% (GCV) for small turbines below 1MWe up to around 36% for very large turbines over 100MWe but they are usually smaller and have less maintenance and vibration than reciprocating engines and all the waste heat can be used to provide steam and so gas turbines tend to be more practical for larger applications of several MW.

Gas turbines used in isolation are referred to as Open Cycle Gas Turbines as opposed to Combined Cycle Gas Turbines where they are coupled with Steam Turbines as explained below. As with gas engines, waste heat availability from open cycle gas turbines is approximately proportional to electrical output so energy efficient operation will mean heat led modulation, but economics may make it preferable to generate more power and waste excess heat.

Steam Turbines

In steam turbines, high-pressure steam is fed into a turbine which consists of several different sets of turbine blades or stages, each with angles optimised to capture power from steam with a decreasing density. In a condensing steam turbine, power generation is maximised by minimising the output pressure of the steam to sub atmospheric pressures around 0.1Bara (-0.09barg) before condensing and pumping the water back to the boiler.

A back-pressure steam turbine is designed as a CHP such that the steam leaves the final stage of turbine at a higher pressure corresponding to the temperature demand. As the exhaust steam has a higher amount of potential energy, less power is generated than in a condensing steam turbine, but the overall efficiency is higher if the heat can be used.

A pass-out condensing steam turbine is designed with outlets between turbine stages to allow steam to be diverted to serve heat loads. Extracting steam to meet thermal demands in this way reduces the volume of steam going to downstream turbine stages and thus the power generation.

Biomass Boiler Driven Steam Turbines is the most commonly employed technology for renewable CHP schemes, over 3MWe in size. Smaller steam turbines are very inefficient, particularly in CHP mode, and therefore uncommon.

Combined Cycle Gas Turbines (CCGT)

In a CCGT residual heat from a gas turbine is used to generate steam which is then used to drive a steam turbine which can either be back pressure or condensing. CCGT with fully condensing steam turbines can achieve very high electrical efficiencies (typically around 45%

for industrial CCGT schemes but over 50% for power stations) (GCV), but this is reduced in CHP operation where the turbine is designed as a pass-out steam turbine allowing steam to be extracted from the turbine to meet the site's steam demand. This results in a drop in power generation. It is also possible to form a CCGT scheme by coupling reciprocating engines and steam turbines but this is uncommon.

Biomass Indirect Air Turbines

This is a relatively new technology for small applications up to around 100kWe where steam turbines would be very inefficient with small but growing market penetration to date.

An indirect air turbine operates on a similar same principle to the conventional gas turbine except that the working fluid which moves the turbine is clean air heated by combustion gases in a heat exchanger as biomass combustion products contain tar and other chemicals which present problems for gas turbine operation. Hot water can be generated from residual heat in the clean air and/or combustion gases.

Organic Rankine Cycles

Organic Rankine cycles operate on the same principle as steam turbines except that the working fluid is not water, but either a fluid with a relatively low boiling point, such as a refrigerant, or with a relatively high boiling point such as oil. Low temperature fluids allow power to be generated at lower temperatures than conventional steam turbines and can achieve higher electrical efficiencies for smaller capacities below 1MWe. Organic Rankine cycles are a relatively new technology with little operating experience in the CHP market.

Direct Combustion

The technologies available for the direct combustion of solid fuels (biomass) are very mature and reliability is high. Depending on the prime mover technology used systems are available from >300 kWe, although smaller systems are now beginning to come to the market. There are two main direct combustion technologies suitable for solid fuel fired renewable CHP; moving grates and fluidised beds. These technologies differ on how the fuel is introduced, fuel and air are mixed and how the fuel moves within the combustion chamber.

Fuel Cell CHP (beyond 2030)

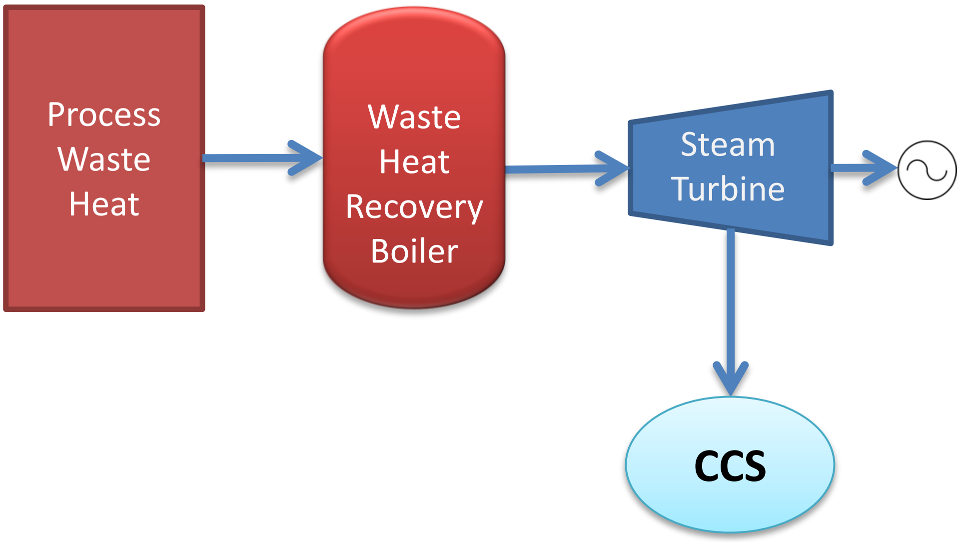
A fuel cell converts chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent and large amount of heat is released. This heat is captured to generate power could significantly .increase the efficiency of the system. In UK this technology is available and has scope of decarbonising the industrial sector beyond 2030.

Waste Heat Recovery Systems with CCS (beyond 2030)

High heat intensive processes have significant amount of waste heat which is usually rejected. The waste heat from industrial process can be recovered in a heat recovery boiler to generate steam. The steam can be utilised in a steam turbine coupled with a generating set to produce electrical power as shown in schematic diagram in **Figure 17**. For example, additional waste heat is available from the kiln gases (preheater exit gas) and cooler exhaust air. This heat can be used for electricity production which can be produced by using a steam cycle, an organic rankine cycle. However, heat recovery for power production may not be feasible in plants where the waste heat is used in raw mills to extensively dry the raw material.

Additionally, the low-grade heat/steam from the steam turbine can be utilised in a Carbon Capture and Storage system which has demand for such heat or in a community district heating system. This efficient system could potentially result in significant reduction of CO_2.

Figure 16: Waste heat Recovery System



RICARDO-AEA

The Gemini Building
Fermi Avenue
Harwell
Didcot
Oxfordshire
OX11 0QR

Tel: 01235 75 3000

www.ricardo-aea.com